DEFORMATION CONTROL OF A FLEXIBLE BEAM UNDER LOW FREQUENCY LOADING USING Ni-Ti-Cu SMA WIRE ACTUATOR

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Abstract. *In this article the development of an experimental platform to analyze and control the deformation of a flexible aluminum beam subjected to external disturbances is described. In the proposed platform, strain-gauges are used to measure the deformation of the beam in a simply clamped mode while Shape Memory Alloy (SMA) wires, presenting a nonlinear behavior, are used as force actuators. Data acquisition and control are implemented with an ADuC microcontroller based card. The system answer in open-loop was used to identify the mathematical model of the mechanical system. To find the appropriate controller and to reach the best performance of the system, it was used techniques of direct tunning (pole-zero cancellation) in the identified model. The PI controller has been used to control the deformation of the beam for different types of reference signals as square, sinusoidal and triangular. The frequencies of the reference signals has been varied to observe the bandwidth that the system answers. The microcontroller card is connected to a computer running LabView software to visualize the measurements in a graphic user interface. Experimental results are used to demonstrate the usefulness of the PI controller in the proposed platform.*

Keywords: *deformation, strain-gauge, control, shape memory alloy, actuators*

1. INTRODUCTION

Mechanical systems are frequently prone to suffer both internal and external disturbances, which gives rise to deformation and/or undesirable mechanical vibrations putting at risk the very structural integrity of these systems. The problems involving deformation and/or vibrations in structural systems may be solved by employing conventional control techniques such as those used in conventional actuators (electrical, hydraulic and pneumatic). These actuators find it difficult to generate sufficient power when their sizes and weights are somehow reduced. However, non-conventional actuators, such as the shape memory alloy (SMA) have become a highly attractive alternative to conventional actuators. This is mostly due to its unique capacity of recovering from deformations, that it can be used to generate great forces and great displacements, mainly when low frequencies are required (Lima *et al.*, 2007).

Some applications carry out an on-off control when they use shape memory alloys as actuators (Khidir *et al.*, 2007). For more complex applications, one is advised to implement control techniques capable of controlling the SMA actuator's force and temperature so as to secure better performance and more stability. The lack of an accurate control technique is one the factors that most frequently impede a great number of actuators from being employed.

Song and Ma (2007) points towards the viability of using 2 (two) SMA wires in order to control an aircraft flap (one wire to move the flap upwards, the other to move it downwards) by means of a robust non-linear controller in place of the conventional actuators.

Khidir *et al.* (2007) have demonstrated that it is possible to use SMA wires along a flexible beam, dividing it into equally spaced segments so as to make possible to establish a linear movement by means of an on-off control.

Moallem and Lu (2005) demonstrate the viability of using SMA wires for non-linear control of force so as to control the position of the flexible beam by using a linearized feedback by means of the non-linear system theory.

This work describes the development of a platform to measure and control the deformation on a simply supported flexible aluminum beam, on which is subjected to a static mechanical load and external disturbances stemming from an electro-dynamic exciter. On the developed platform, electric-resistant extensometers were employed to measure beam deformation. Wires made from a Ni-Ti-Cu shape memory alloy were used as force actuators. Both data acquisition and control are implemented with an ADuC microcontroller based card. An open loop response was used to identify the system's mathematical model. In order to find the ideal controller and obtain the best performance possible for the system, the technique known as direct tuning (pole-zero cancellation) was used in the identified model. Finally, a PI controller was used in order to control the deformation in a variety of reference signals such as quadratic and triangular signals, where the frequency was changed to identify the bandwidth to which the system responds.

2. EXPERIMENTAL PROCEDURE

Figure 1 shows the experimental platform diagram developed in order to apply the deformation control on a flexible beam that has been submitted to low frequency external disturbance.

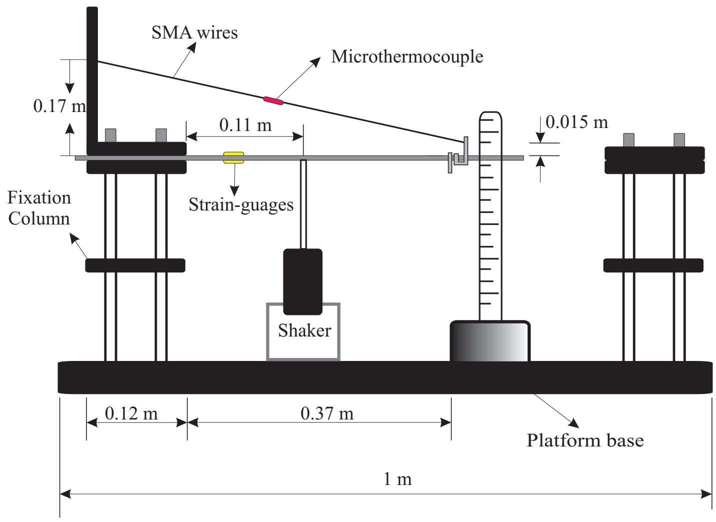

Figure 1. Schematic diagram of the developed experimental platform.

To assemble the platform, a flexible aluminum beam - 0.7 m long, 0.0025 m wide and 0.003 m thick - was used. On the beam surface, two electric-resistance extensometers with self-temperature-compensation of 350 Ω and with a sensitivity factor of 2.1 were installed to measure the deformation. Two NiTiCu SMA wires, measuring 0.515 m in length and 0.29 mm in diameter, were utilized to act in the deformation control. A micro-thermocouple of the kind K with a diameter of 100 μm was also used to measure the temperature on the SMA wires. An ET-132 shaker from the Labworks was employed to create a low frequency external disturbance on the beam.

A deformation measuring circuit was projected for obtaining the deformation value on the beam when some static mechanical load is applied to the free end of the flexible beam. For this circuit uses a Wheatstone bridge with two electric-resistance extensometers along with two electric resistances of 350 and 315 Ω, respectively. The bridge output signal travels through a conditioning circuit made up of a high precision instrumentation amplifier, projected to amplify low-level signals, and a low-pass filter to eliminate any undesirable components that may come from the signal being verified. A driver circuit was also introduced to control the output voltage from the feeding source, by means of a PWM signal, that it adjusts the resistive heating from the SMA wires. Finally, a circuit to measure temperature was installed in order to read the SMA wires temperatures. For this circuit was used an instrumentation amplifier with a cool-joint compensator to the thermocouple on a monolithic micro-plate (Lima *et al.*, 2008, 2009).

3. MODEL IDENTIFICATION

In order to develop and identify the mathematical model for the system shown in Figure 1 with a static mechanical load of 7 N applied to the free end of the flexible beam, an open loop control system was used, as illustrated in Figure 2.

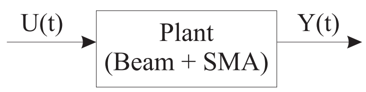

Figure 2. Block diagram of the open loop control system.

Figure 3 exhibits the response for the open loop control system. This was obtained by applying the voltage of 6.5 V by means of a feeding source that was connected to the driver circuit with a signal PWM of 100% (U(t)). This electric voltage produces a current of approximately 1.14 A, making the SMA wires to warm up as a result of Joule effect. This made the wires to contract, creating a deflection of 0.065 m on the built-in beam, which corresponded to a deformation of 763 $\mu m/m$ on the beam (Y(t)).

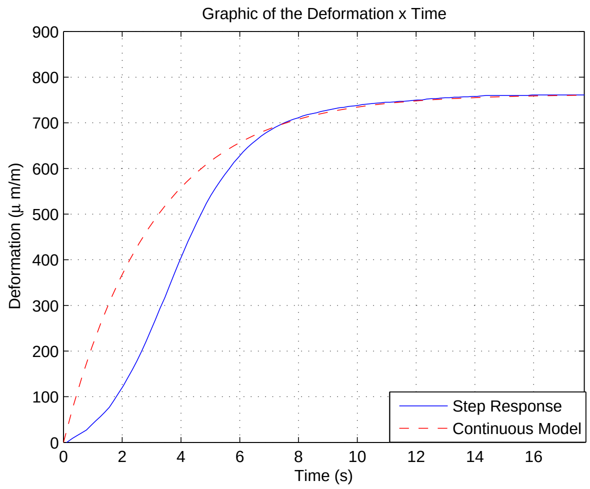

Figure 3. Response of the open loop control system to a voltage degree of 6.5 V.

The data acquisition and control are implemented on an ADuC microcontroller based card, together with a computer that runs the LabVIEW program that allows us to visualize the measurements in a graphic interface with a sampling time of approximately 0.214 s.

The model identification, as derived from the input and output data of the open loop control system, was carried out by means of the MatLab ident function, which led to a first order continuous model, as defined by Equation 1. Figure 3 shows the expected output of the model with a sampling time of 0.156 s.

$$G(s) = \frac{7.63}{1 + 3.04s} \qquad (1)$$

4. THE CONTROLLER'S PROJECT

According to the projected model and the use of the direct tuning technique (pole-zero cancellation), the choice of the Proportional-Integral (PI) controller seems to be most appropriate for the perfect performance of the system (Chau, 2002). Figure 4 shows the control system block diagram in closed loop for which the system input is R(t), which is the reference value for the beam deformation. Y(t) represents the present output of the system, which corresponds to the value of deformation on the beam, where the extensometers have been installed. E(t) represents the error and corresponds to the difference between Y(t) and R(t). U(t) is the control variable generated by the PI controller which corresponds to a duty cycle value.

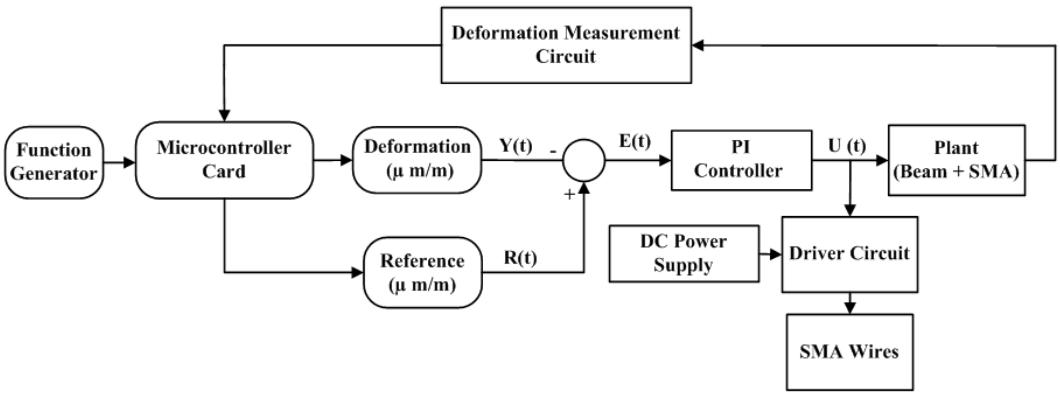

Figure 4. Block diagram for the closed loop control system.

Control action uses the transfer function $G_c(s)$, defined by Equation 2, for the PI controller, where K_p (Proportional Gain) and T_i (Integrative Time) represent the controller's parameters. These parameters have been calculated using the direct tuning technique and by taking into account, as the project's main parameter, the time constant of the system in closed loop, which equals to 0.32 s. In this way, the following values were obtained: K_p = 1.25 and T_i = 3.04.

$$G_c(s) = K_p(1 + \frac{1}{T_i s}) \tag{2}$$

In order to facilitate programming on the ADuC microcontroller based card, the PI controller was recursively discretized. This implies that the calculation of the control at an instant $u(k)$ rests upon a previous instant value $u(k-1)$ added to the correctors' terms as defined in Equation 3. The term $u(k)$ represents the controller's output signal, $u(k-1)$ represents the output signal with a sample delay, whereas $e(k)$ is the system's error signal, $e(k-1)$ represents the error signal with a sample delay, and T_0 corresponds to the sampling time of the system (de Souza and Filho, 2001).

$$u(k) = u(k-1) + K_p e(k) - K_p(1 - \frac{T_0}{T_i})e(k-1) \tag{3}$$

5. RESULTS AND DISCUSSIONS

On the PI control system of deformation, two experiments were carried out with a static mechanical load of 7 N applied to the free end of the flexible beam. The first experiment had the purpose of controlling deformation on the beam with a squared, sinusoidal and triangular reference signal, by varying the frequencies so as to observe the bandwidth to which the system responds. The second experiment was a repetition of the first with the added external disturbance on the control system caused by an electro-dynamic shaker as shown in Figure 1.

Figures 5 and 6 show the results of the control system behavior without external disturbance on a squared reference signal of 70 and 90 mHz, respectively; however, with a deformation of the beam varying from 75 to 580 μm/m. On examining Figures 5 and 6, one can see an ascending and descending time of about 5 s. By varying the reference signal frequency, one can see that the control action worked properly up to a frequency of 90 mHz, revealing a maximum error of about 5% and 2%, when the squared reference presented extreme deformations corresponding to 75 and 580 μm/m, respectively. However, due to the necessity of following the reference demand the application of pulses of electric current, the error, out of the positions corresponding the extreme deformations, becomes large. The value of the electric current on the SMA wires varied from 0 to 1.1 A, causing a temperature variation from 25 to 60 °C, which is sufficient to trigger the actuators.

Figures 7 and 8 show the results of the control system behavior without external disturbance for a signal of sinusoidal reference of 40 and 90 mHz, respectively; however, with a deformation of the beam varying from 75 to 580 μm/m. On varying the frequency of the reference signal, one notices that the control action works well up to a frequency of 40 mHz, revealing a maximum error of around 2% on external deformations, reaching its peak of 10% at the point of cycle inversion, when the sinusoidal reference value reaches 75 μm/m. For a frequency of 90 mHz, the maximum error at the inversion point reached 45%. The value of the electric current on the SMA wire varied from 0 to 1.1 A, causing a temperature variation from 25 to 60 °C, which is sufficient to trigger the actuators.

Figure 9 and 10 show the results of the control system behavior without external disturbance for a signal of triangular reference of 10 and 90 mHz, respectively; however, with a deformation of the beam varying from 75 to 580 μm/m. On altering the reference signal, one can see that the control action performed well up to a frequency of 10 mHz, presenting a maximum error of around 4%, and reaching its peak of 10% at the inversion point of the cycle, when the reference value reaches 75 μm/m. For a frequency of 90 mHz, the maximum error at the point of the cycle inversion, when the reference value reaches 75 μm/m, may go up to 50%. The value of the electric current on the SMA wire varied from 0 to 1.1 A, causing a temperature variation from 27 to 65 °C, which is sufficient to trigger the actuators.

Figure 11 shows the results of the control system behavior with external disturbances, produced by an electro-dynamic shaker at a frequency of the 3.5 Hz, for a signal of squared reference of 20 mHz; however, with the deformation of the beam varying from 75 to 580 μm/m. Here one sees an ascending and descending time of around 6 s. It is worth noticing that the flexible beam is only submitted to an external disturbance when it reaches a deformation point smaller than 200 μm/m, and that the external disturbance does not interfere in the action of the PI controller, revealing a maximum error of about 30% and 2%, when the squared reference presented external deformations of 75 μm/m and 580 μm/m. However, due to the necessity of following the reference demand the application of pulses of electric current, the error, out of the positions corresponding the extreme deformations becomes large. The value of the electric current on the SMA wire varied from 0 to 1.1 A, causing a temperature variation from 25 to 65 °C, which is sufficient to trigger the actuators.

Figures 12 and 13 show the results of the control system behavior with an external disturbance, caused by an electro-dynamic shaker at a frequency of 3.5 Hz, for a signal of sinusoidal and triangular reference of 20 mHz, respectively; however, with a deformation beam varying from 75 to 580 μm/m. Here one can see that a flexible beam can only go through an external disturbance when it reaches a deformation smaller than 200 μm/m, and that the external disturbance does not interfere in the action of the PI controller; thus presenting a maximum error of around 2% on external deformations, and reaching its peak of 40% at the inversion point of the cycle, when the reference value reaches 75 μm/m. The value of the electric current on the SMA wire varied from 0 to 1.1 A, causing a temperature variation from 25 to 65 °C, which is sufficient to trigger the actuators.

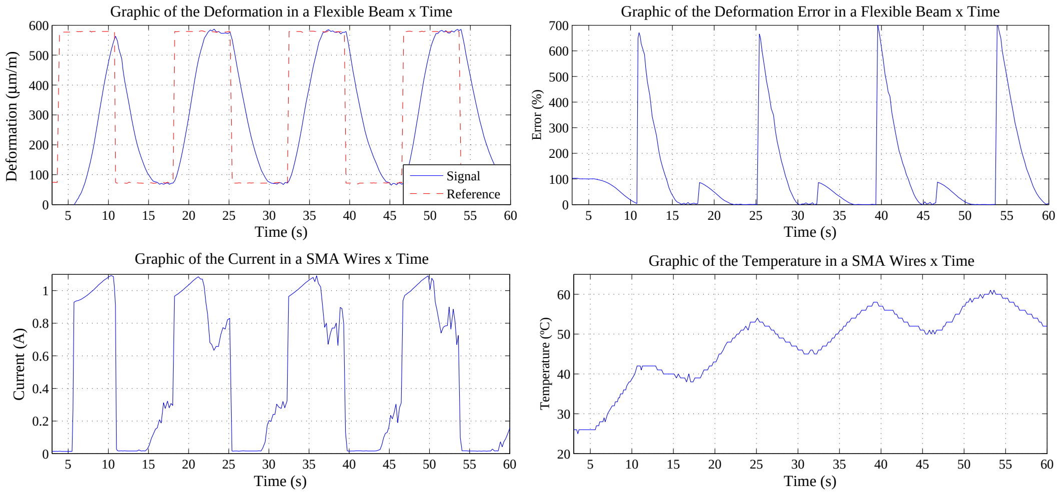

Figure 5. Deformation behavior, current, error and temperature for a squared reference of 70 mHz in the absence of external disturbances.

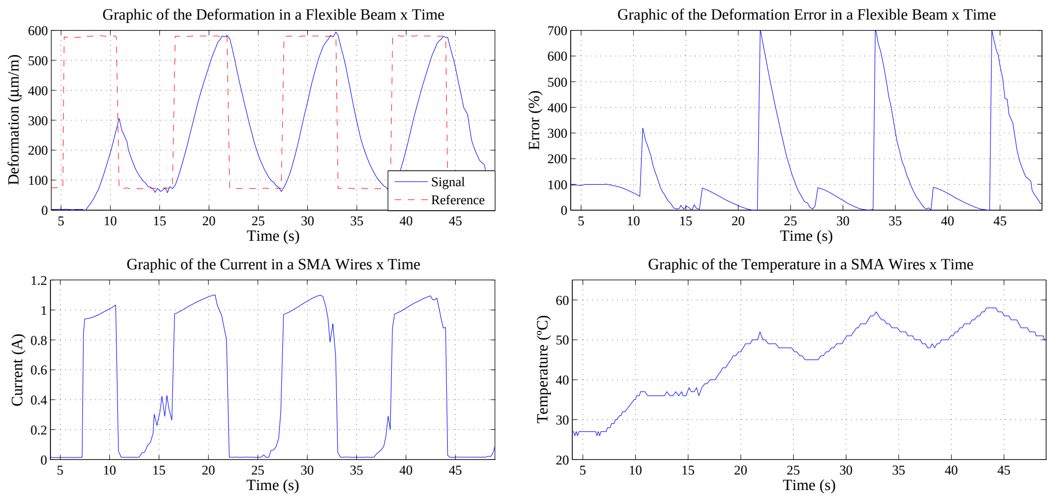

Figure 6. Deformation behavior, current, error and temperature for a squared reference of 90 mHz in the absence of external disturbance.

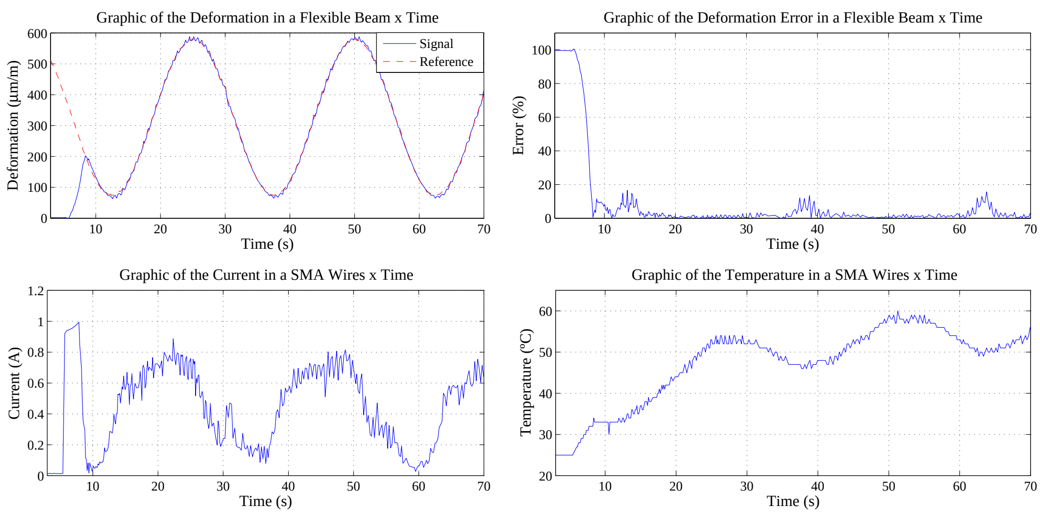

Figure 7. Deformation behavior, current, error and temperature for a sinusoidal reference of 40 mHz in the absence of external disturbance.

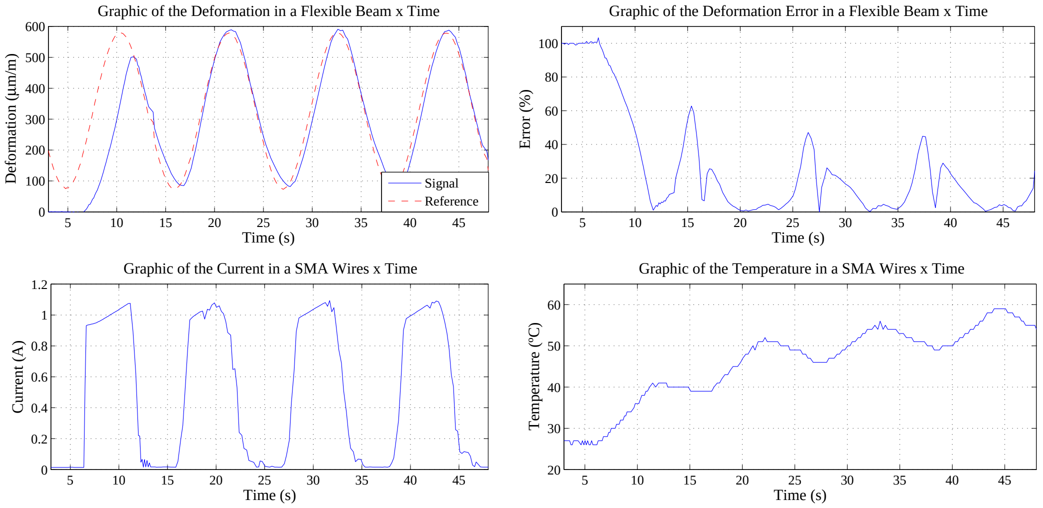

Figure 8. Deformation behavior, current, error and temperature for a sinusoidal reference of 90 mHz in the absence of external disturbance.

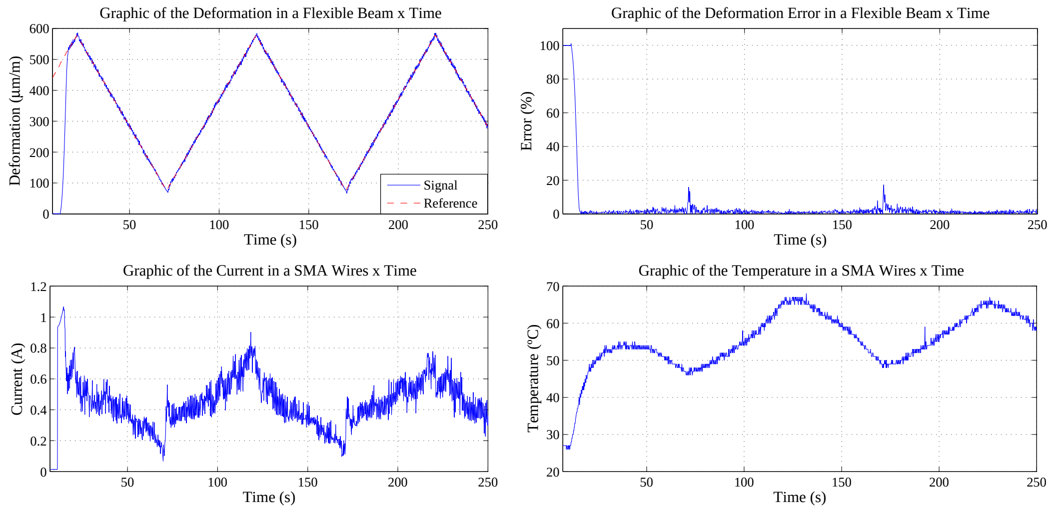

Figure 9. Deformation behavior, current, error and temperature for a triangular reference of 10 mHz in the absence of external disturbance.

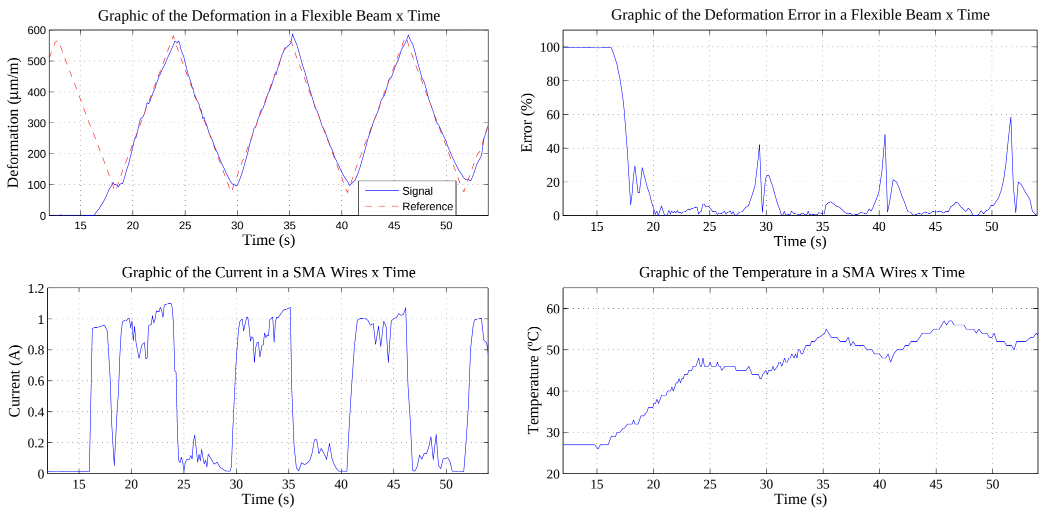

Figure 10. Deformation behavior, current, error and temperature for a triangular reference of 90 mHz in the absence of external disturbance.

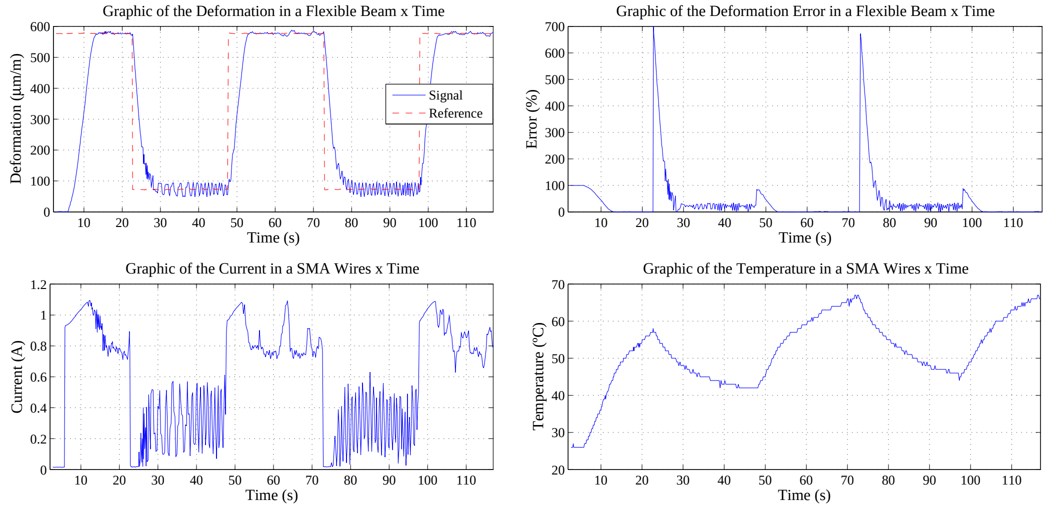

Figure 11. Deformation behavior, current, error and temperature for a squared reference of 20 mHz in the presence of an external disturbance of 3.5 Hz

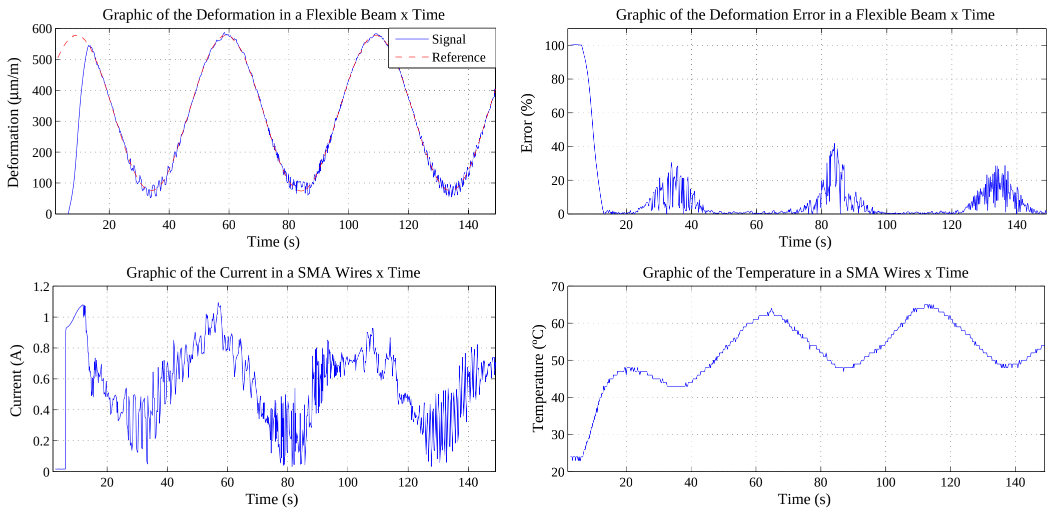

Figure 12. Deformation behavior, current, error and temperature for a sinusoidal reference of 20 mHz in the presence of an external disturbance of 3.5 Hz.

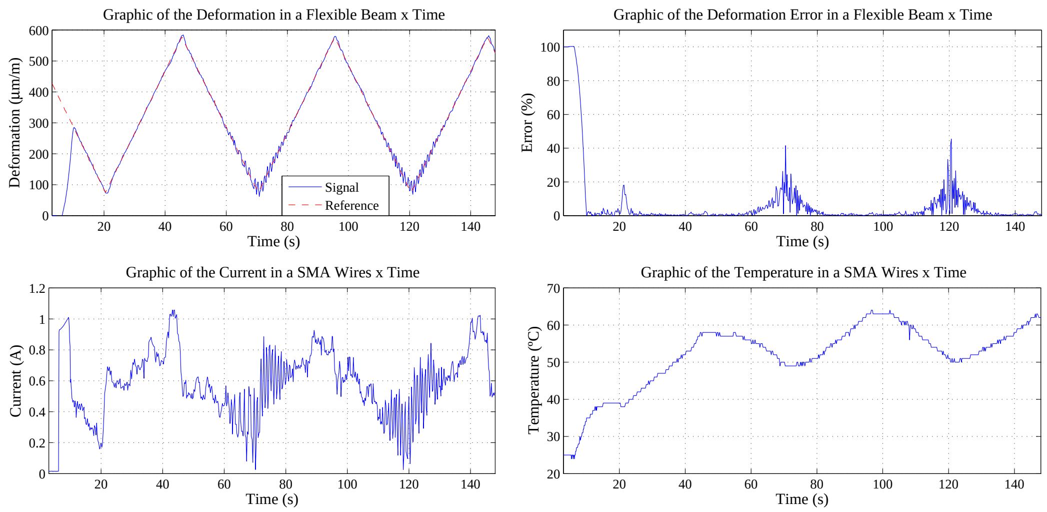

Figure 13. Deformation behavior, current, error and temperature for a triangular reference of 20 mHz in the presence of an external disturbance of 3.5 Hz.

Figures 14 and 15 show the results of the control system behavior with an external disturbance, caused by an electrodynamic shaker at a frequency of 4.5 Hz, for a signal of sinusoidal and triangular reference of 20 mHz, respectively; however, with a deformation beam varying from 75 to 580 μm/m. Here one can see that a flexible beam can only go through an external disturbance when it reaches a deformation smaller than 200 μm/m, and that the external disturbance interferes in the action of the PI controller; thus presenting a maximum error of around 3% on external deformations, and reaching its peak of 200% at the inversion point of the cycle, when the reference value reaches 75 μm/m. The value of the electric current on the SMA wire varied from 0 to 1.1 A, causing a temperature variation from 25 to 65 °C, which is sufficient to trigger the actuators.

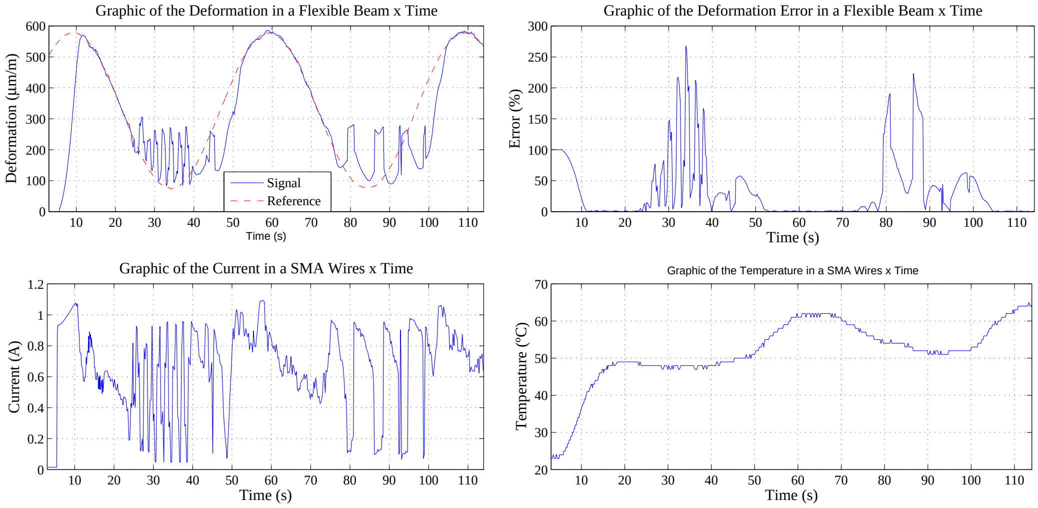

Figure 14. Deformation behavior, current, error and temperature for a sinusoidal reference of 20 mHz in the presence of an external disturbance of 4.5 Hz.

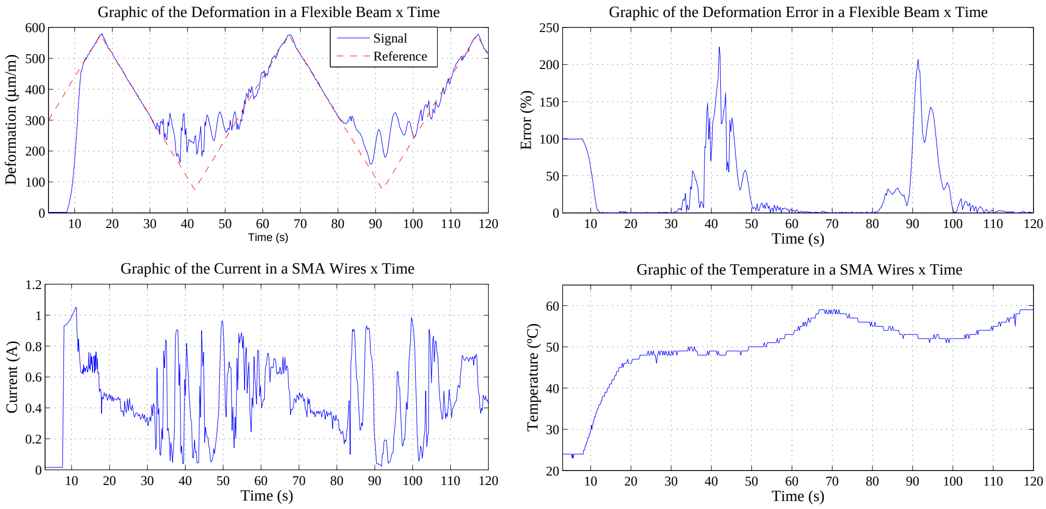

Figure 15. Deformation behavior, current, error and temperature for a triangular reference of 20 mHz in the presence of an external disturbance of 4.5 Hz.

6. CONCLUSIONS

On an experimental platform that has been developed to measure and control deformations on a simply supported flexible aluminum beam, submitted to a static mechanical load of 7 N, enabled it to obtain a PI controller of deformation of the beam from a first order model obtained from the response of the open loop control system, by the utilization of the direct tuning technique (pole-zero cancellation).

The PI controller worked very well without external disturbances for signals of squared, sinusoidal and triangular references with maximum frequencies of 90, 40 and 10 mHz, respectively. It presented a maximum error that varied from 2% to 4% and reaching its peak of 10% at the inversion point of the cycle, when the reference value reaches 75 μm/m.

Furthermore, the PI controller held a good performance under external disturbance, caused by the electro-dynamic shaker at a frequency of 3.5 Hz, for a signal of squared, sinusoidal and triangular reference of 20 mHz.

7. ACKNOWLEDGEMENTS

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