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MEASUREMENT AND CONTROL OF DEFORMATION ON A FLEXIBLE BEAM USING SHAPE MEMORY ALLOY

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Abstract. *This article describes the development of an experimental platform which analyzes and controls mechanical systems subjected to internal and external disturbances. On the proposed platform, strain-gauges are used to measure the deformation of a flexible aluminum beam that is fixed on a rigid column. NiTi shape memory alloy (NiTinol) wires attached to the beam and column are used as force actuators. Data acquisition and control are implemented with an ADuC microcontroller based card (PD-ADuC). Standard P and PI controllers have been used to control the deformation of the flexible beam. The microcontroller card is connected to a personal computer (PC) running LabVIEW software to visualize the real-time measurements in a graphic user interface (GUI). Selected experimental results are used to demonstrate the usefulness of the proposed test platform.*

Keywords: *intelligent materials, strain gauge, control, shape memory alloys*

1. INTRODUCTION

Mechanical systems are frequently subjected to internal and external disturbances, causing undesirable deformations and/or mechanical vibrations, which in some cases put at risk the structural integrity of the system (Teixeira, 2001). The deformation analysis of mechanical elements subjected to applied stresses is of great importance in various applications. Through this analysis, it can be determined the internal efforts involved in a mechanical component or structure (Kelly, 1998; Leuckert, 2000).

With the purpose of measuring deformations, specialists have developed methods based on mechanical, optical and/or electrical principles. By the advent of transducers, capable of converting small mechanical displacements in variation of electrical resistance, greater development in the methods of deformation measurements have taken place. These transducers are called strain gauge and have contributed to the development of measurement techniques for deformation and mechanical stress analysis (Leuckert, 2000).

Mechanical problems involving deformation and/or vibration in structural systems have been recently solved by using conventional control techniques and the addition of new actuators named shape memory alloys (SMA). Due its deformation recovery, SMA has been considered a good and attractive actuator alternative for systems where high forces, high deformations and low frequencies are requested. When used as a thermomechanical actuator, heating is mainly accomplished by Joule effect (Nascimento, 2002).

This work describes the development of an experimental platform for analysis and control of the deformation of flexible metallic beams. At the experimental test bench, strain gauges are used to measure the deformation of an aluminum beam, and SMA wires are used as force actuators. Data acquisition and controllers (P and PI) are implemented with an ADuC842 microcontroller-based card (PD-ADuC) connected to a personal computer (PC) running a LabVIEW software to visualize measurements in real-time on a graphic user interface (GUI). This platform is a prototype which can be used for several other mechanical analyses.

2. LABVIEW

The National Instruments (NI) has revolutionized the way engineers and scientists have been working since the LabVIEW software (Virtual Laboratory Instrument Engineering Workbench) was developed as an environment of programming directed towards the development of applications based on virtual instrumentation that allows fast technological and commercial advance (NI, 2007).

LabVIEW creates a graphic user interface through a graphical programming language. This language is composed of a set of instructions which does not use commands in text form to generate code lines. In other words, the program is made up of block diagrams. These blocks present libraries of prompt functions to be used for any type of specific applications like: spectral and statistical analysis, signal filtering, among others. Tools for development of data acquisition and control, communication with I/O instruments, Bluetooth and TCP are also available (NI, 1996).

With a programming structure guided by data flow and hierarchy, the LabVIEW greatly simplifies the implementation of complex systems, including data acquisition, instrumentation, and control of equipments by means of a personal computer (NI, 1996, 2003b).

LabVIEW recognizes several buses connected to PC as: GPIB, Ethernet, USB, RS-232, RS-485, PCI, CAN, among others. Moreover, this software works with programs from other areas, such as MATLAB and Excel. It also accesses and controls programs on the Internet by using the Web Publishing tool (NI, 2003a).

3. ELECTRICAL RESISTANCE EXTENSOMETER

The electrical resistance extensometer (ERE), extensively named as strain gauge, is a small grating formed by a fine metallic lamina that can be glued on to the surface of a component or structure. The ERE has a fine adhesive coating that transmits the deformation of the structure on to the strain gauge, by serving as electrical insulator. This sensor converts small displacements into equivalent changes of electrical resistance (Leuckert, 2000; Magalhães, 2003)

The strain gauges are used for the experimental analysis of deformations in machines, bridges, locomotives, ships and for the construction of transducers for force, stress, pressure, flow, acceleration and other measurements (Leuckert, 2000; Magalhães, 2003).

The main ERE characteristics can be summarized as high precision, small size, low weight, low cost, excellent linearity, installation easiness, excellent static and dynamic response, large temperature range and application under severe conditions (Andolfato *et al.*, 2004; Magalhães, 2003).

3.1 Wheatstone bridge

The Wheatstone bridge with two active elements, illustrated in the Fig. 1, is a circuit composed of two equivalent resistances (R) and two electrical resistance extensometers ($R_G + \Delta R_G$ and $R_G - \Delta R_G$), which must be added the resistance of the wire (R_L) for an accurate deformation measurement.

The strain gauges must be glued on to the faces of the specimen submitted to opposing deformations. Whereas one is contracted, the other is extended in the same proportion. In this way, the electrical resistances will be submitted to the same alterations, with temperature compensation.

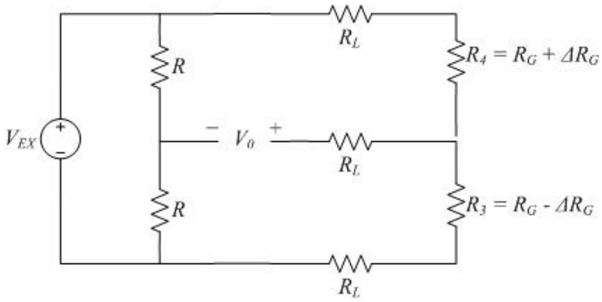


Figure 1. Electrical design of the Wheatstone bridge.

The functioning principle defined in Fig. 1 originates the Eq. 1. In this equation, if the sensibility factor of the strain gauge (K), the input voltage (V_{EX}) of the Wheatstone bridge, the resistance of the wire (R_L), the resistance of the strain gauge (R_G) are known and measured the output voltage of the Wheatstone bridge (V_0), the deformation can be determined, at the point where the strain gauge was installed (Leuckert, 2000; Magalhães, 2003).

$$\varepsilon = \frac{2}{K}\frac{V_0}{V_{EX}}(1 + \frac{R_L}{R_G}) \tag{1}$$

The magnitude of the deformation is, in general, very small; therefore, it is frequently multiplied by 10^6 and expressed in $\mu m/m$.

4. SHAPE MEMORY ALLOYS

The shape memory alloys (SMA's) are active materials that - when plastically deformed - can return to its original geometric shape if submitted to a variation of temperature and/or mechanical stress. This shape memory phenomenon reveals the capacity that these materials possess on assuming different crystalline structures at distinct temperatures throughout its phase of transformations. This phenomenon can be seen in several alloys, as for example: NiTi, NiAl, CuZn, CuZnAl, CuZnGa, CuZnSn, CuZnSi, CuAlNi, CuAuZn, CuSn, AuCd, FePt, among others (Nascimento, 2002; Valenzuela, 2005).

The SMA's are manufactured in the forms of wires, ribbons, plates and bars. The form of wire is the most used, by presenting reversible axial deformations that reaches up to 10%, where 7% of that go to the NiTi alloys (Song and Ma, 2003).

Due to their non-conventional properties, the SMA's can be used as sensors or actuators in the automobile and aerospace industries, orthodontics, and in orthopedic and robotic applications (Auricchio, 1995; Nascimento, 2002; Paiva *et al.*, 2003). When used as thermomechanical actuators, as illustrated in Fig. 2, the heating is obtained through Joule effect by applying some electrical current intensity. SMA's have been revealed as good and attractive actuators. This is because of its great deformation and good recovery capacity in systems where greater forces, greater deformations and lower frequency are required (Kelly, 1998; Nascimento, 2002; Song and Ma, 2003).

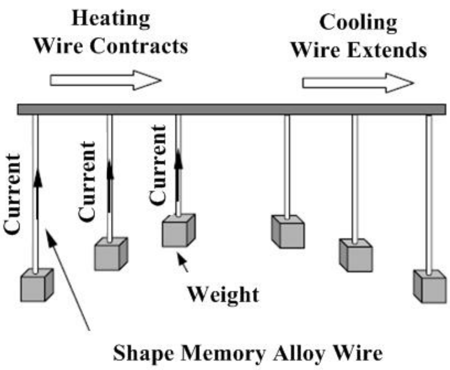


Figure 2. SMA wire working as an actuator.

4.1 Heat treatment and training procedures

In this work, the two NiTi SMA wires - 1 m in length and 0.29 mm in diameter - used in the experimental platform were supplied by Memory-Metalle Inc (Germany). These SMA wire actuators were heat-treated at 500°C for a period of 20 minutes, followed by a fast cooling (air quench), which triggers the phase transformation that originates the shape memory phenomenon. This is because these wires are supplied in a cold-worked state - without the observance of such phenomena.

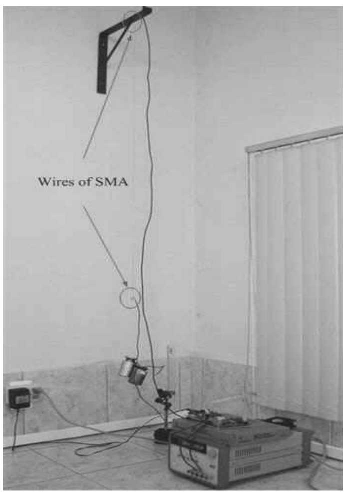


Figure 3. Experimental set-up for thermomechanical training of the SMA wire.

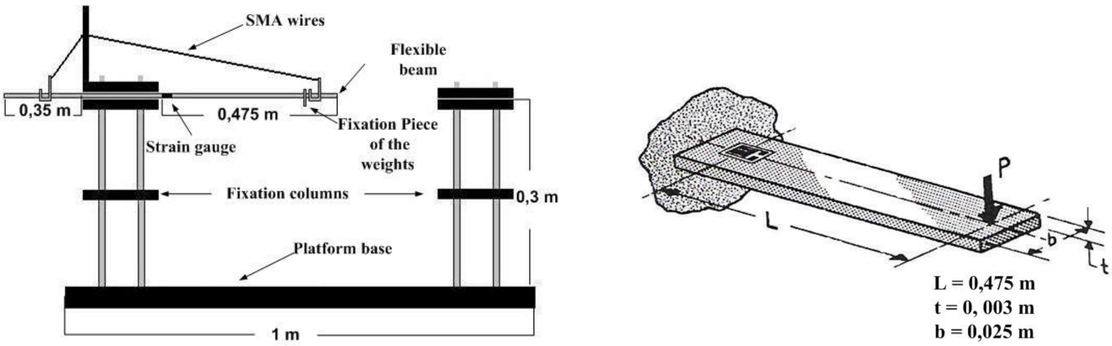
Figure 3 illustrates the experimental set-up for the thermomechanical training of the SMA wire, which is loaded axially by means of a dead weight. It must be observed that a load of 2 kg has been deployed at the extremity of the SMA wire, generating a stress of about 180 MPa. To heat the SMA wire, it was applied an electrical tension of 13 V, supplied by a powering source (Agilent E3632A), controlled by a microcontroller system specially developed for this purpose. This tension has the form of a square wave with a period of 30 s and duty-cycle of 16.7% allowing, as a result, a contraction of the SMA wire for a period of 5 s.

The thermal cycle for training was initiated with the SMA wire, stretched under load (∼180 MPa) along a martensitic phase, corresponding to the cooling step where the electrical current is zero for 25 s. After this, an electrical current pulse was applied for 5 s, during which the SMA wires are contracted due to the heating by Joule effect; therefore, reaching an austenitic phase that corresponds to the heating step. This pulse activates the shape memory effect, attributing, in this way, a form to each phase transformation. This procedure was repeated for 1500 cycles.

5. EXPERIMENTAL PLATFORM FOR MEASUREMENT AND CONTROL

Figure 4 illustrates a schematic drawing of the experimental platform developed to control the deformation on a supported flexible aluminum beam, which can be seen on the left-hand side. On the platform, the strain gauges are used to carry out the measurement of the deformation that takes place in the beam. Furthermore, the SMA wires are used as force actuators for the deformation control of the beam up to a determined reference value.

Attached to the faces of the flexible aluminum beam by means of a fine adhesive coating were two strain gauges of 350 Ω, with a temperature auto-compensation and sensibility factor of 2.1 supplied by Excel Sensores Inc (Brazil).



(a) Experimental platform (b) Flexible beam

Figure 4. Diagram of the experimental platform.

Because of its superior linearity and sensitivity - twice as large as that of the circuit which has only one strain gauge - a Wheatstone bridge circuit, with the two strain gauges of 350 Ω and two electrical resistances of 330 Ω, was installed. The output signal of this bridge runs through a signal conditioning circuit made up of a high precision instrumentation amplifier (INA101) with a gain of 201, designed to amplify the low-level signal, and a low-pass filter with a frequency of 106 Hz to eliminate the undesirable components of the measured signal.

The ADuC842 microcontroller-based card developed by the Analog Devices Inc (USA) was used for data acquisition and control, after which the KEIL software of the μVision - a program to execute a P or PI control of beam deformation - was developed, as illustrated in the Fig. 5. Let us consider the microcontroller's following steps: Firstly, it establishes the output voltage value of the Wheatstone bridge circuit with the canal 0 of the A/D microcontroller converter, and converts it into a deformation value, in agreement with Eq. 1 in Section 3.1. Secondly, it establishes the output voltage value of the Agilent 33120A function generator, with the canal 1 of the A/D microcontroller converter, and converts it into a deformation value that will be used as a reference value. Finally, it conveys the control action to the selected controller. Following these steps, the microcontroller sends an information package containing the beam deformation value and the reference deformation value to the serial communication port (RS232) of PC to each 31.25 ms.

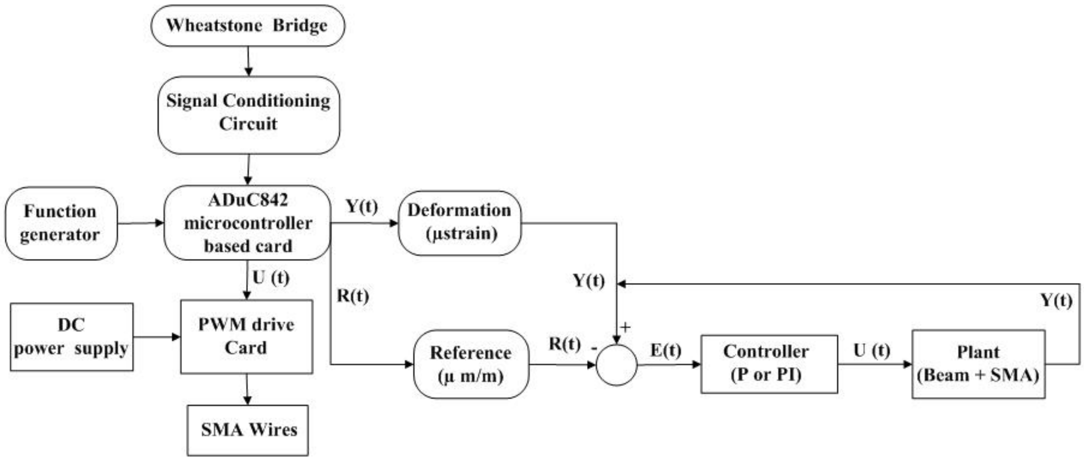


Figure 5. Blocks diagram of the system of acquisition and control of the deformation.

In the block diagram of the deformation control system, illustrated in Fig. 5, the control system input is R(t). This is the reference value for the beam deformation. Y(t) is the actual output of the control system. This variable corresponds to the beam deformation value, where the strain gauge is located. E(t) is the control error and corresponds to the difference between Y(t) and R(t). U(t) is the control variable generated by the selected controller (P or PI). This variable corresponds to the PWM signal that the microcontroller sends to the PWM drive card responsible for the force actuators drive; thus liberating an electrical current value for the SMA wires.

The PWM drive card has been developed and used to control force actuators. This card utilizes a transistor (IRFZ44) in order to trigger the DC Agilent E3632A power supply correctly, which is kept to a limit of 5.5 V and 1.1 A. The triggering is accomplished by the PWM signal of 2.05 kHz emitted from the ADuC microcontroller onto PWM drive card.

The control action uses the transference function $G_{CP}(s)$, defined by Eq. 2, for the P controller, and $G_{CI}(s)$, defined by Eq. 3, for the PI controller, in which K_p (proportional gain) and $T_i s$ (integrative time) are the controllers' parameters.

$$G_{CP}(s) = K_p \tag{2}$$

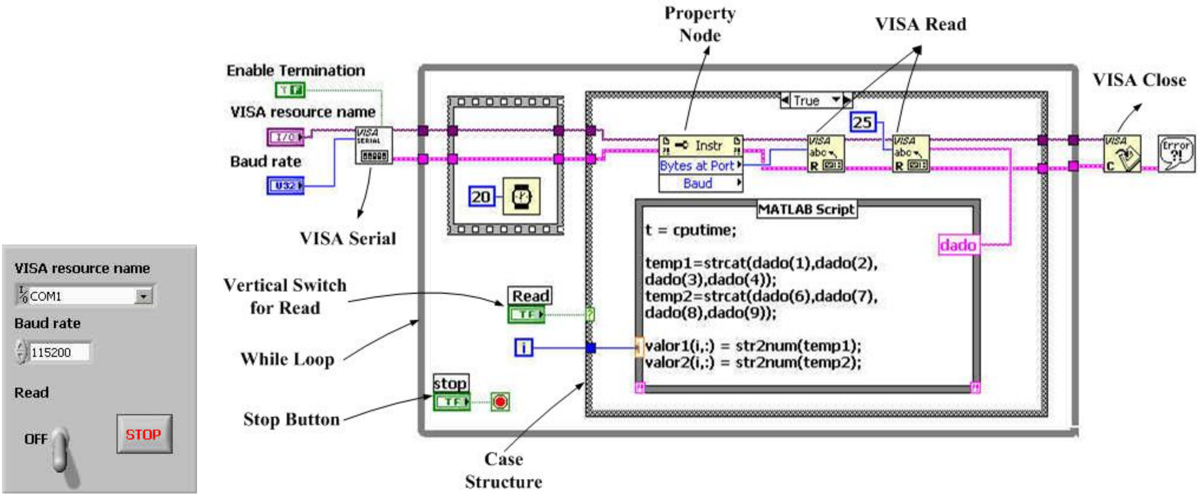
$$G_{CI}(s) = K_p(1 + \frac{1}{T_i s}) \tag{3}$$

To facilitate the programming in the ADuC microcontroller, a recursive form discrete-time PI controller was used. This means that the control calculation in one instant $u(k)$ is based on the value of a previous instant $u(k-1)$ plus the term correctors as shown in the Eq. 4. The term $u(k)$ is the output signal for the controller, $u(k-1)$ is the output signal for the controller with a delayed sample, $e(k)$ is the system error signal, $e(k-1)$ is the system error signal with a delayed sample, and T_0 is the process sampling time (de Souza and Filho, 2001).

$$u(k) = u(k-1) + K_p e(k) - K_p(1 - \frac{T_0}{T_i})e(k-1) \tag{4}$$

All programs developed in the LabVIEW have been named virtual instrument (VI), because its appearance and operation resembles a physical instrument, such as an oscilloscope or a multimeter. A VI is basically made up of a frontal panel and a blocks diagram.

The program illustrated in the Fig. 6 was created in the LabVIEW to receive the information package sent by the microcontroller, and separate the information contained in this package. The separation is made by means of the MATLAB Script so that real-time information of the beam deformation along with the reference deformation versus the time can be visualized through a graph. In this program, the *VISA* (Virtual Instrument Software Architecture) is a driver used to communicate with the serial communication port (RS-232) of PC. Therefore, one must inform the communication port and the baud rate in the inputs *VISA resource name* and *Baud rate*, in the frontal panel so that the *VISA Serial* initializes the communication with the serial port. Next, the program enters a *While Loop* with interactions at every 20 ms until the *Vertical Switch for Read* in the frontal panel is switched on, enabling the *Case Structure*. In the *Case Structure*, the *Property Node* identifies the amount of bytes that are sent to the serial port and sends to the first *VISA Read*. To prevent reading errors another *VISA Read* capable of reading only 25 bytes was inserted. The data read by the second *VISA Read* are sent, in the form of strings, to the MATLAB Script. To finish communication, the button *Stop Button* must be pressed in the frontal panel so that the system gets out from the *While Loop* and finishes the communication with the *Visa Close*.



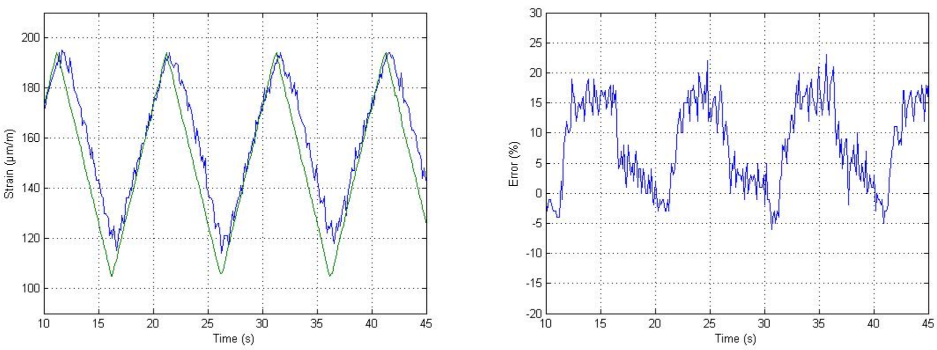
(a) Frontal panel (b) Blocks diagram

Figure 6. Windows developed in the LabVIEW software.

6. RESULTS

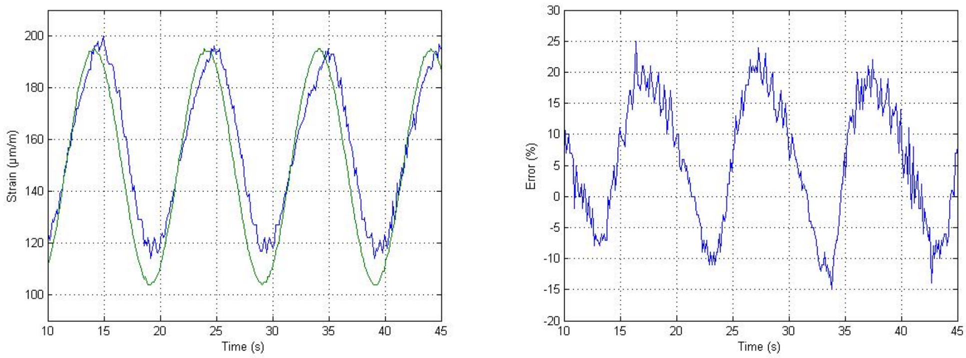
With the experimental platform for a P and PI control of deformation on a flexible beam, two experiments, with a weight of 500 g at the free edge of the beam, have been accomplished. The first experiment seeks, as its main objective, the control of the beam by means of a triangular reference of 10 mHz; and the second experiment, the control of the beam by means of a sinusoidal reference of 10 mHz. In these experiments, the SMA wires received a maximum power of 6.05 W, supplied by a power supply of Agilent E3632A.

For the P controller experiments, a triangular and sinusoidal reference with a peak amplitude of 90 $\mu m/m$, and an offset of 150 $\mu m/m$ have been used. After this, some parameter values for the P controller (K_p), for which the best parameter in both references was $K_p = 4$, have been tested. It has been observed that in the experimental results illustrated in the Fig. 7 and 8, the control action does follow the triangular and sinusoidal references: neither in the heating cycle nor in the alloy cooling cycle. Moreover, the control action was observed to cause a small vibration on the beam.



(a) (b)

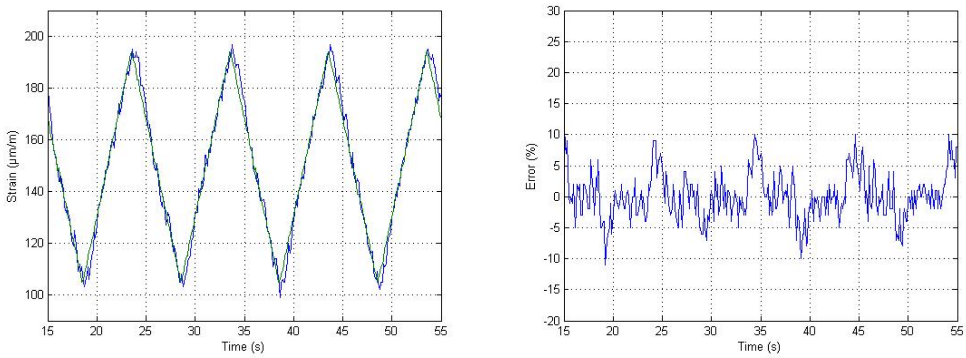
Figure 7. Experimental results using controller P for triangular reference.



(a) (b)

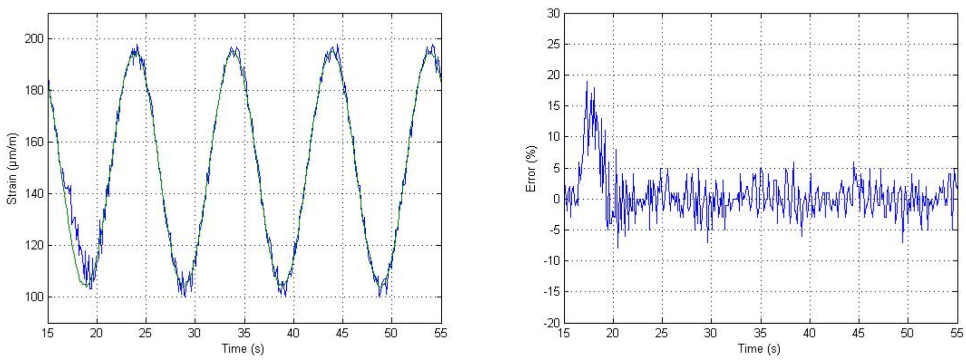
Figure 8. Experimental results using controller P for sinusoidal reference.

For experiments involving the PI controller, it has been used a triangular and sinusoidal reference with the same amplitude used for the P controller. After that, several values have been tested for the PI controller parameter (K_p and T_i), the best parameters being $K_p = 4$ and $T_i = 0,5$ for the triangular reference, and $K_p = 3,3$ and $T_i = 0,1$ for a sinusoidal reference. It has been observed that from the experimental results illustrated in Fig. 9 and 10, the control action followed the triangular and sinusoidal references in the heating cycle and in the alloy cooling cycle with maximum error of 10 % at the points of the cycle inversion. Furthermore, no vibration was observed along the beam.



(a) (b)

Figure 9. Experimental results using controller PI for triangular reference.



(a) (b)

Figure 10. Experimental results using controller PI for sinusoidal reference.

7. CONCLUSIONS

The process of deformations and/or vibrations analysis in mechanical systems is of great importance in diverse industrial applications because, in some cases, it may put at risk the structural integrity of the system.

In the experimental results obtained from an experimental platform for measurement and control of deformation of a flexible beam in which it was used strain gauges to measure the deformation on the beam and SMA wires for the control of the deformation, it has been observed that PI controllers presented an excellent performance for the triangular and sinusoidal references, compared to P controllers with a maximum error of 10 % at the points of the cycle inversion with no vibration along the beam.

To further improve the action of control, techniques capable of controlling the temperature and the force in the SMA wires must be developed so as to secure good performance and stability.

8. ACKNOWLEDGEMENTS

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