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

Walber Medeiros Lima, baljp@ibest.com.br
José Sérgio da Rocha Neto, zesergio@dee.ufcg.edu.br
Antônio Marcus Nogueira Lima, amnlima@dee.ufcg.edu.br
Universidade Federal de Campina Grande - Department of Electric Engineering
Rua: Aprígio Veloso, 822 - Bodocongó - CEP: 58109-970 - Campina Grande - PB

Carlos José de Araújo, carlos@dem.ufcg.edu.br
Universidade Federal de Campina Grande - Department of Mechanical Engineering

Walter Andrés Vermehren Valenzuela, wal_v@yahoo.com.br
Universidade do Estado do Amazonas - Department of Mechanical Engineering

Abstract. *This article describes the development of an experimental platform which analyzes and controls mechanical systems subjected to internal and external disturbances. In the proposed platform, strain-gauges are used to measure the deformation of a flexible aluminum beam that is fixed in a rigid column. 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 in risk the structural integrity of the system (Teixeira, 2001).

The deformations analysis in an element that is subjected to mechanical stresses is of great importance in diverse applications. Through this analysis, it can be determined the efforts involved in a mechanical component or structure (Kelly, 1998; Leuckert, 2000).

With the intention of being able to measure deformations, it has been developed through time some methods of measurements based on mechanical, optical or electrical principles. The advent of a transducer capable to convert mechanical deformations in variation of electrical resistance has caused a great development in the methods of electrical measurements. Such transducer is named of strain gauge that has been allowing the development of measurement techniques for deformation and mechanical stress analysis (Leuckert, 2000).

The mechanical problems involving deformation and/or vibration in structural systems have been for a long time dealt with by conventional techniques of control through the addition of new actuator denominated shape memory alloy (SMA). This alloy have been revealed as a good attractive alternative, due to its great deformation and good recovery, for systems where great forces, great deformations and low frequency are requested. And when used as thermomechanical actuator, where the heating is accomplished by Joule effect, must be applied certain electric current intensity (Nascimento, 2002).

This article describes the development of an experimental platform for analysis and control of the deformation of the flexible aluminum beam. In the platform, strain gauges are used to measure the deformation in the beam and the SMA wires are used as force actuators. The data acquisition and the controllers (P and PI) are implemented with an ADuC842 microcontroller based card (PD-ADuC), developed by Analog Device, where is connected to the personal computer (PC) running LabVIEW software to visualize measurements in real-time in a graphic user interface (GUI). This platform serves as prototype for several other mechanical systems.

2. LABVIEW

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

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

Using a structure of programming guided by data flow and hierarchical, the LabVIEW becomes simple the complex systems implementation that include data acquisition, instrumentation and control of equipments through a personal computer (Instruments, 1996, 2003b).

LabVIEW recognizes several connected buses to PC as: GPIB, Ethernet, USB, RS-232, RS-485, PCI, CAN, among others. Moreover, this software works with programs of other areas as MATLAB and Excel. It also access and control programs developed in the internet using the Web Publishing tool (Instruments, 2003a).

3. EXTENSOMETER OF ELECTRIC RESISTANCE

The extensometer of electric resistance (EER), also known as strain gauge, is a small grating formed by fine metallic lamina that can be glued on the surface of a component or structure. The EER has a fine adhesive coating that serves to transmit the deformation of the structure to the strain gauge, besides serving as electrical insulator. This sensor converts small displacements of the structure in equivalent changes of electrical resistance (Leuckert, 2000; Magalhães, 2003)

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

The main EER characteristics can be summarized in high precision, small size, low weight, low cost, excellent linearity, installation easiness, excellent static and dynamic response, excellent 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 extensometers of electric resistance ($R_G + \Delta R_G$ and $R_G - \Delta R_G$), where must be added the resistance of the wire (R_L) for the obtainment of accurate measures of deformation.

The strain gauges must be glued on 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.

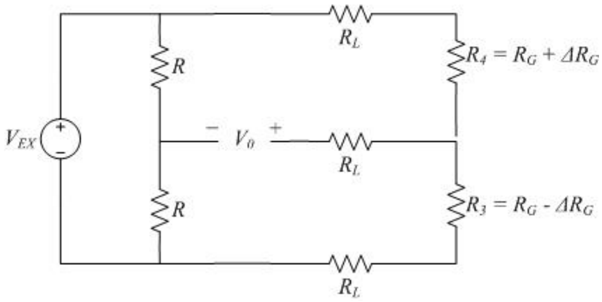


Figure 1. Electrical design of the Wheatstone bridge.

The functioning principle defined in Fig. 1 originates 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 measuring the output voltage of the Wheatstone bridge (V_0), the deformation in the point where the strain gauge was installed can be determined (Leuckert, 2000; Magalhães, 2003).

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

The magnitude of the deformation, in general, is 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 demonstrates the capacity that these materials possess in assuming different crystalline structures to distinct temperatures through its phase transformations. This phenomenon is exhibited in the alloys of NiTi, NiAl, CuZn, CuZnAl, CuZnGa, CuZnSn, CuZnSi, CuAlNi, CuAuZn, CuSn, AuCd, FePt, among others (Nascimento, 2002; Valenzuela, 2005).

The alloys are manufactured in the forms of wires, pipes, plates and bars in which the wire form is most used, presenting reversible deformations that reach about 10%, being 7% for the NiTi alloys (Song and Ma, 2003).

Due to their odd properties, the SMA's can be used as sensors or actuators in automobile, petroliferous and aerospace industry, orthodontic, orthopedical and robotic applications (Auricchio, 1995; Nascimento, 2002; Paiva *et al.*, 2003). When used as thermomechanical actuators as illustrated in the Fig. 2, the heating is accomplished by effect Joule applying certain electric current intensity, which has been revealed as a good attractive alternative, due to its great deformation and good recovery, for systems where great forces, great deformations and low frequency are required (Kelly, 1998; Nascimento, 2002; Song and Ma, 2003).

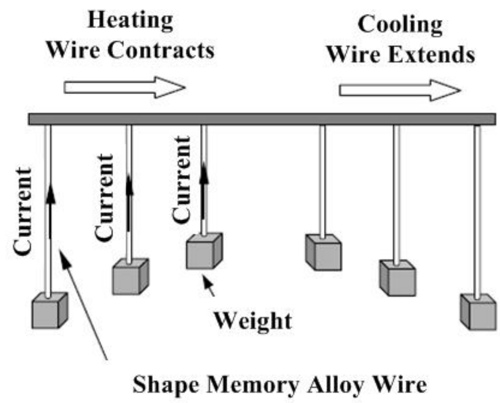


Figure 2. SMA wire working as an actuator.

4.1 Process of training and treatment

The two SMA wires of NiTi, with 1 m of length and 0.29 mm of diameter, of the type *Alloy* M of company Memory-Metalle used in the experimental platform were dealt with by a thermal process in the Laboratory LaMMEA (Laboratório Multidisciplinar de Materiais e Estruturas Ativas) from the Department of Mechanical Engineering (DEM) at UFCG (Universidade Federal de Campina Grande). This process consists in putting the wires in a stove to a constant temperature of 500 °C for a period of 20 minutes. After that, they are removed for a fast cooling thus liberating the phase transformation that originates the shape memory phenomenon, because these wires are supplied without such phenomenon.

The Figure 3 illustrates the experimental platform developed to a process of thermomechanical training of SMA wires that is loaded axially by means of one constant weight. It must be observed that the wires generate approximately a force for unit of area of 180 MN/m^2, thus according to the diameter of the wires, it has been put a load of 2 Kg in the edge of the SMA wires. After that, it has been applied an electric signal of amplitude equal to 13 V that has been supplied by a powering source of Agilent E3632A and controlled for a microcontroller system developed in LEMCAD (Laboratório de Ensaio, Manutenção, Calibração, Aferição e Desenvolvimento) from the Department of Electric Engineering (DEE) at UFCG. This signal has the form of a square wave with a period of 30 s and *duty-cycle* of 16.67% allowing thus a contraction of wires during 5 s.

The cycle of thermal training was initiated with relaxed wires in a martensitic phase, cooling cycle, where the electric current is zero for 25 s. After that, a electric current pulse was applied during 5 s in which the wires are contracted due to the heating of wires for Joule effect reaching an austenitic phase, heating cycle. This pulse increases the temperature of wires reaching its effect of shape memory, thus associating a form to each phase transformation. This procedure was repeated by 1500 cycles.

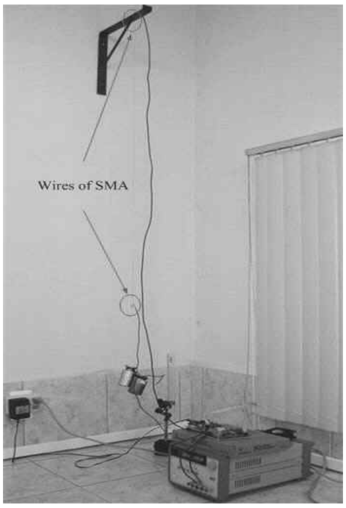
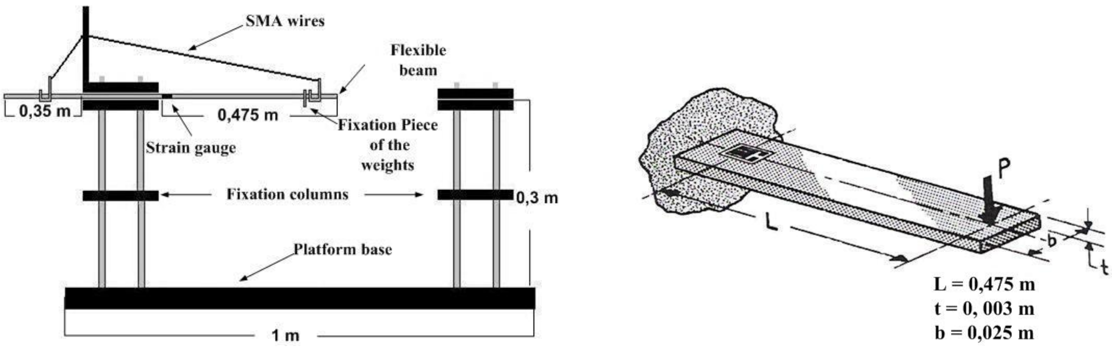


Figure 3. Experimental platform for the thermal training of the SMA wire.

5. EXPERIMENTAL PLATFORM FOR THE MEASUREMENT AND CONTROL

The Figure 4 illustrates the diagram of the experimental platform developed in LEMCAD to accomplish the control of the deformation in a flexible beam. In the platform the strain gauges are used in the measurement of the deformation of such beam. Furthermore, the SMA wires are used as force actuators in the deformation control of the beam to a determined reference value.

It was glued in a flexible aluminum beam, with a fine adhesive coating, two strain gauges of company Excel Sensores with auto-compensation of temperature of 350 Ω and sensibility factor of 2.1 in the faces of the beam.



(a) Experimental platform (b) Flexible beam

Figure 4. Diagram of the experimental platform.

A Wheatstone bridge circuit was mounted with two strain gauges of 350 Ω and two electric resistances of 330 Ω, according to section 3.1, due to its linearity and by presenting a sensibility twice larger than a circuit that uses only one strain gauge. The output signal of this bridge passes for a signal conditioning circuit composed for an instrumentation amplifier of high precision (INA101) with a gain of 201, projected to amplify the low-level signal, and of a filter low-pass, with a frequency of 106 Hz, to eliminate undesirable components of the measured signal.

A ADuC842 microcontroller based card developed by the Analog Device was used for data acquisition and control. After that, with the KEIL software of the μVision was developed a program to execute a P or PI control of the beam deformation as illustrated in the Fig. 5. Firstly, this program realizes the acquisition of the output voltage value of the Wheatstone bridge circuit, with canal 0 of the A/D converter of the microcontroller, and convert in a deformation value, in agreement with Eq. 1 of the section 3.1. Secondly, realizes the acquisition of the output voltage value of the Agilent 33120A function generator, with canal 1 of the A/D converter of the microcontroller, and convert in a deformation value that will be used as a reference value. Finally, the control action will be related to the selected controller. This steps are executed by microcontroller and, after that, it sends an information package that contains the deformation value in the beam and the reference deformation value, in which the beam will have to assume, for serial communication port (RS232) of PC to each 31.25 ms.

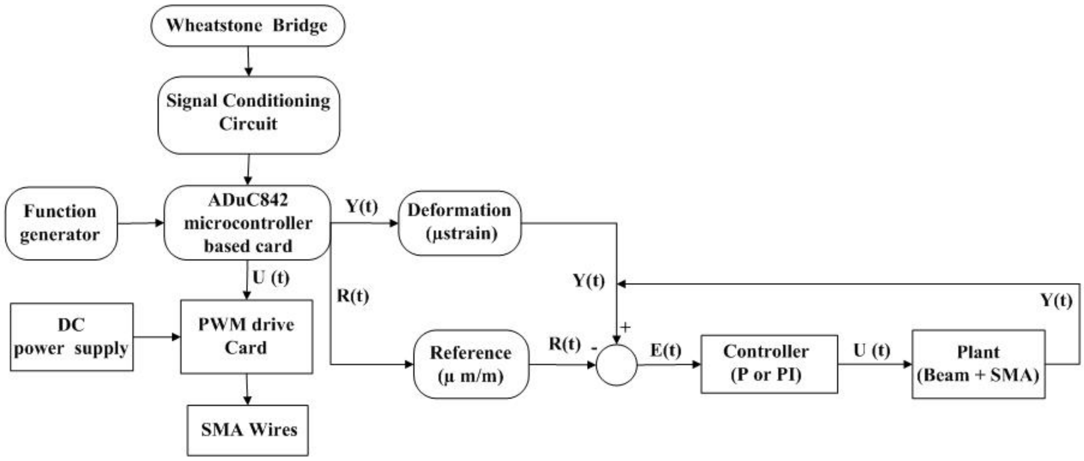


Figure 5. Blocks diagram of the system of acquisition and control of the deformation.

In the blocks diagram of the deformation control system, illustrated in the Fig. 5, the input of the control system is R(t). This is the reference value for the deformation in the beam. Y(t) is for the actual output of the control system. This variable corresponds to the deformation value in the beam, where the strain gauge is located. E(t) is the control error and corresponds 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 in which the microcontroller should send for PWM drive card that is responsible for the drive of force actuators. Thus liberating a value of electric current for the SMA wires.

The PWM drive card was developed and used to control the force actuators. This card makes use of a transistor (IRFZ44) to trigger the DC power supply correctly of the Agilent/HP E3632A, in which is limited in 5.5 V and 1.1 A. The trigger is accomplished by the PWM signal of 2.05 kHz sent from the ADuC microcontroller to PWM drive card.

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

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

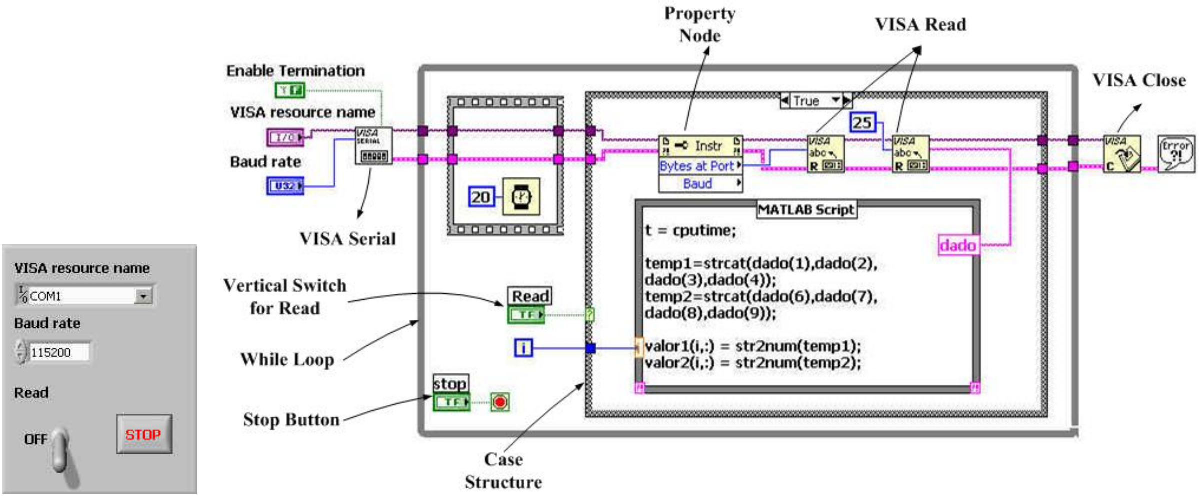
$$G_{CI}(s) = K_p(1 + \frac{1}{T_i s}) \tag{3}$$

To facilitate the programming in the ADuC microcontroller, the PI controller was discrete-time of recursive form. This means that the calculation of the control in one instant $u(k)$ is based on the value of a previous instant $u(k-1)$ plus the terms correctors as shown in Eq. 4. The term $u(k)$ is the output signal of the controller, $u(k-1)$ is the output signal of the controller with a delayed sample, $e(k)$ is the error signal of the system, $e(k-1)$ is the error signal of the system with a delayed sample and T_0 is the sampling time of the process (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 is called virtual instrument (VI), because its appearance and operation resembles a physical instrument, such as an oscilloscope and a multimeter. One VI is composed basically for: 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 to separate the information contained in such package. The separation is made by the MATLAB Script to visualize the real-time information in a graphic of the beam deformation along with the reference deformation versus the time. 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, it must be informed 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. After that, the program enters in *While Loop* with interactions of each 20 ms until the *Vertical Switch for Read* is on, in the frontal panel, and to enable the *Case Structure* truly. In the *Case Structure*, the *Property Node* identifies the amount of bytes that were sent for the serial port and sends for the first VISA Read. To eliminate error in the reading was inserted one more *VISA Read* that reads only 25 bytes. The data read by the second *VISA Read* are sent in the form of strings to the MATLAB Script. To finish the communication, the button *Stop Button* must be pressed in the frontal panel so that it gets out from the *While Loop* and finishes the communication with the *Visa Close*.



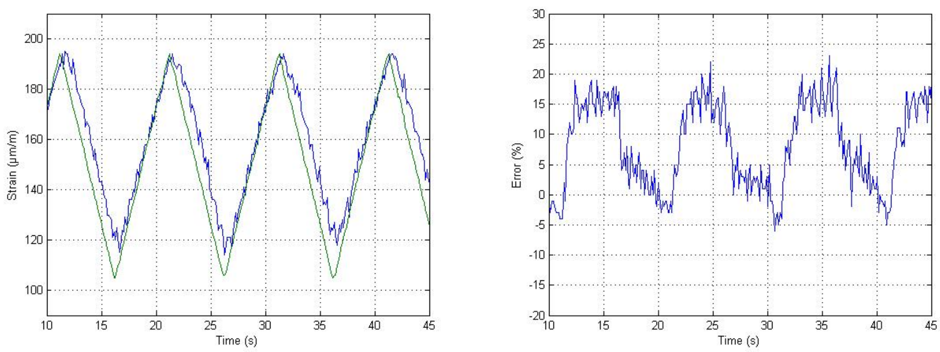
(a) Frontal panel (b) Blocks diagram

Figure 6. Windows developed in the LabVIEW software.

6. RESULTS

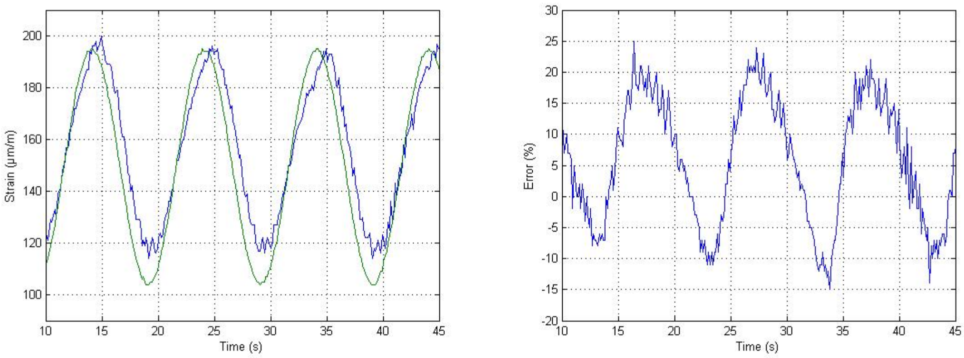
With the experimental platform for a P and PI control of the deformation in a flexible beam, it has been accomplished two experiments that had a weight of 500 g in the free edge of the beam. The first experiment had as its objective to control the beam with a triangular reference and the second with a sinusoidal reference of 10 mHz. In these experiments, the SMA wires received a maximum power of 6.05 W supplied for a power supply of Agilent E3632A.

For the experiments of the P controller, it has been used a triangular and sinusoidal reference with an amplitude of peak the peak of 90 $\mu m/m$ and offset of 150 $\mu m/m$. After that, it has been tested some values for the parameter of the P controller, K_p, in which the best parameter for both references was $K_p = 4$. It is observed that in the experimental results, illustrated in the Fig. 7 and 8, the control action does not get to follow the triangular and sinusoidal references neither in the heating cycle nor in the cycle of cooling of alloy. Moreover, it causes a small vibration in the beam.



(a) (b)

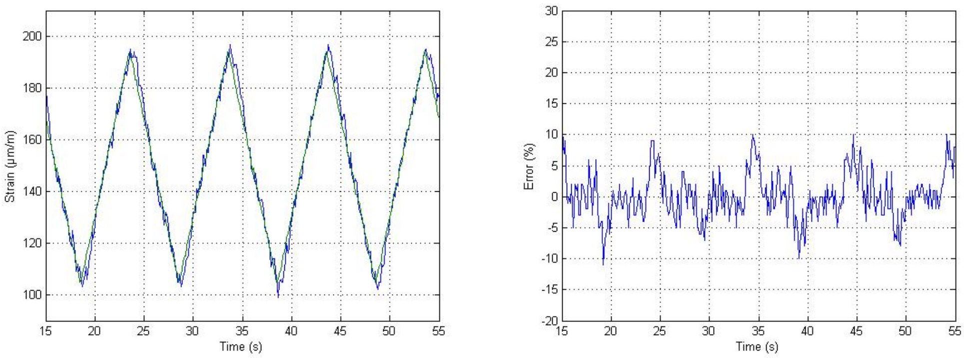
Figure 7. Experimental results using controller P for triangular reference.



(a) (b)

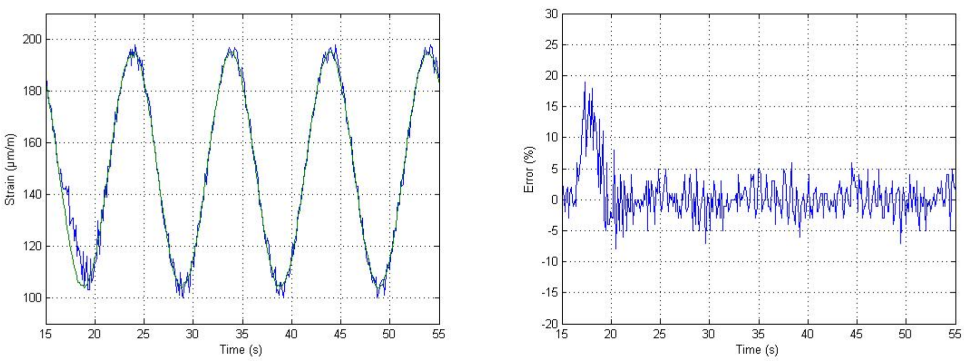
Figure 8. Experimental results using controller P for sinusoidal reference.

For the experiments of the PI controller, it has been used a triangular and sinusoidal reference with the same amplitude used in the P controller. After that, it has been tested several values for parameter of PI controller, K_p and T_i, in which the best parameters were $K_p = 4$ and $T_i = 0,5$ for the triangular reference and $K_p = 3,3$ and $T_i = 0,1$ for a sinusoidal reference. It is observed that in the experimental results, illustrated in the Fig. 9 and 10, the control action gets to follow the triangular and sinusoidal references in the heating cycle and in the cycle of cooling of the alloy with maximum error of 10 % in the points of cycle inversion. Furthermore, it does not even cause any vibration in 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 can place at risk the structural integrity of the system.

In the experimental results obtained of the experimental platform for measurement and control of the deformation of a flexible beam, in which it was used strain gauges to measure the deformation in the beam and SMA wires for the control of the deformation, it was observed that PI controller had a good action of control for the triangular and sinusoidal references compared to the P controller with a maximum error of 10 % in the points of cycle inversion without causing any vibration in the beam.

To improve even more the action of control it must be elaborated control techniques that could be capable of controlling the temperature and the force in the SMA wires as a guarantee of performance and stability.

8. ACKNOWLEDGEMENTS

The authors would like to thank CNPQ (Conselho Nacional de Desenvolvimento Científico e Tecnológico).

9. REFERENCES

Andolfato, R. P., J. S. Camacho, and G. A. de Brito, 2004, *Extensometria Básica*, Universidade Estadual Paulista, Ilha Solteira - SP, Brasil, http://www.nepae.feis.unesp.br/Apostilas/Extensometria20basica.pdf.

Auricchio, F., 1995, *Shape Memory alloy: Applications, Macromodeling and Numerical Simulations*, Thesis of doctorate in civil engineering, University of California at Berkeley, California, USA.

Instruments, N., 1996, *LabVIEW Tutorial*, http://www.physics.utoledo.edu/~alukasz/labview_tutorial.PDF.

Instruments, N., 2003a, *LabVIEW Getting Started*, http://www.sfu.ca/phys/231/063/data_sheets/LabView%20tutorial.pdf.

Instruments, N., 2003b, *LabVIEW User Manual*, http://www.ni.com/pdf/manuals/320999e.pdf.

Instruments, N., 2007, National instruments brasil - officeinfo, http://www.ni.com/brazil.

Kelly, B. L., 1998, *Bean Shape Control Using Shape Memory Alloys*, Dissertation of master's degree in aeronautic engineering, Naval Postgraduate School, Monterey, California, USA.

Leuckert, C., 2000, *Sistema Portátil de Aquisição de Dados para Análise Dinâmica de Estruturas Mecânicas*, Dissertation of master's degree in electric engineering, UFRGS, Porto Alegre - RS, Brasil.

Magalhães, E. P., 2003, *Comportamento Experimental de uma Cortina de Estaca Prancha Assente em Solo Poroso do DF*, Dissertation of master's degree in geotecnia, UnB, Brasília - DF, Brasil.

Nascimento, M. M. S. F., 2002, *Contribuição ao Estudo da Histerese em Ligas com Memória de Forma*, Dissertation of master's degree in electric engineering, UFCG, Campina Grande - PB, Brasil.

Paiva, A., M. A. Savi, and P. M. C. L. Pacheco, 2003, *Modelos Constitutivos para Ligas com Memória de Forma*, 2° Congresso Temático de Aplicações de Dinâmica e Controle (DINCOM), São José dos Campos, SP, Brasil.

Song, G., and N. Ma, 2003, *Control of Shape Memory Alloy Actuators Using Pulse– Width Pulse-Frequency (PWPF) Modulation*, journal of Intelligent Material Systems and Structures.

de Souza, C. P., and J. T. C. Filho, 2001, *Controle por conputador: Desenvolvend Sistema de Aquisição de Dados para PC* (EDUFMA), ISBN 85-85048-31-X.

Teixeira, R. L., 2001, *Uma Metodologia de Projetos de Controladores Híbridos Inteligentes com Aplicações no Controle Ativo de Vibrações Mecânicas*, Dissertation of master's degree in mechanical engineering, UFU, Uberlândia - MG, Brasil.

Valenzuela, W. A. V., 2005, *Sistema de Articulação Inteligente por Meio da Liga com Memória de Forma*, Dissertation of master's degree in electric engineering, UFCG, Campina Grande - PB, Brasil.