ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

ADAPTIVE AIRFOIL ACTUATED BY SHAPE MEMORY ALLOY(NITI)

Marcelo Francisco Maesta
Univ Estadual Paulista - UNESP, Department of Mechanical Engineering, GMSINT, Av. Brasil, 56, 15385-000 Ilha Solteira, SP, Brazil.
mfmaesta@gmail.com

Gustavo Luiz, C. M. Abreu
Univ Estadual Paulista - UNESP, Department of Mechanical Engineering, GMSINT, Av. Brasil, 56, 15385-000 Ilha Solteira, SP, Brazil.
gustavo@dem.feis.unesp.br

Cássio Thome de Faria
Univ Estadual Paulista - UNESP, Department of Mechanical Engineering, GMSINT, Av. Brasil, 56, 15385-000 Ilha Solteira, SP, Brazil
cassiofar@dem.feis.unesp.br

Carlos DeMarqui Junior
Department of Aeronautical Engineering, Engineering School of São Carlos-EESC, University of São Paulo, São Carlos, SP, 13566-000, Brazil.
demarqui@sc.usp.br

Vicente Lopes Junior
Univ Estadual Paulista - UNESP, Department of Mechanical Engineering, GMSINT, Av. Brasil, 56, 15385-000 Ilha Solteira, SP, Brazil.
vicente@dem.feis.unesp.br

Abstract. Morphing wings are structures that can change its shape to allow greater controllability of aircraft maneuvers. Aircraft with a capacity to adapt can have great advantages over conventional aircraft, being able to fly in different types of missions and perform extreme maneuvers. The main objective of this work is to illustrate an application of angular active control in morphing wings using shape memory alloys. In the proposed wing model, one wants to establish the shape of the airfoil based on the determination of an angle between two sections of the wing. This angle is obtained by the effect of the shape memory of the alloy by heating the wire through electric current. The function of the electric current is to change the temperature of the wire through the Joule effect, changing the shape of the alloy. This kind of alloy is capable of converting thermal energy into mechanical energy and once deformed, the material can return to its original shape by heating. Due to the presence of nonlinear effects, especially in the mathematical model of the alloy, this work proposes the application of a control system based on fuzzy logic. The performance of the fuzzy controller type Mandani is compared with an on-off controller experimentally in a built aerofoil prototype.

Keywords: Active Angular Control, Morphing Wings, Fuzzy Logic, Shape Memory Alloys.

1. INTRODUCTION

The aircraft design has been developed in an extraordinary way since the first manned flight in 1903. In just a century, engineers built aircraft that can travel beyond the speed of sound, crossing the circumference of the earth without making refueling and even crossing the atmosphere into space.
Modern aircraft are able to transport large load, landing and takeoff vertically, achieving high speeds and have high ability to execute maneuvers. For each flight condition, aircraft are required in specific geometric features that allow this condition to achieve maximum efficiency. It is a problem, since there is not a project that meets all aircraft flying possible conditions. Thus, a proposed solution is the aircraft being able to modify its main geometric features (modifying the shape of its wing) to meet all phases of the mission with maximum efficiency (Seigler et al, 2007). Within this scenario emerged the concept of Adaptive or Morphing Wings that are structures able to change its shape to enable greater controllability of the aircraft mainly maneuvers (Viana et al, 2009; Faria, 2010; Bilgen et al, 2011). Aircrafts with the ability for adapting promise a distinct advantage compared to conventional aircrafts, since they are able to fly in different types of missions and perform extreme maneuvers. The first aircraft to use the concept of adaptive wings was X-5 in 1951. After that came the F-111 and F14 that were equipped with such wings.

Several mechanisms were proposed to create an adaptive wing. The main difficulty of trying to recreate artificially such system is to find a lightweight actuator, as efficient as the muscles, able to perform such and still deform considerably. A synthetic material that has this characteristic is the Shape Memory Alloy (SMA) (Paiva and Savi, 2006). This material is capable of converting thermal energy into mechanical energy and once deformed the material can return to its original shape by heating. There are a large number of research works carried out in recent years

ISSN 2176-5480

focusing on the use of shape memory alloys in aeronautical wings adaptive (Léchevin and Rabbath, 2005; Feng et al, 2010; Faria, 2010; Bilgen et al, 2011). It proves the scientific and technological relevance of the subject.

However, because it is a relatively new topic of study, which are being continuously incorporated technological developments and new possibilities for practical applications, much research effort still has to be done. For this purpose, the control of aeronautic adaptive profiles should be developed, including, particularly, the application of control techniques based on artificial intelligence for adaptive wings.

The presence of nonlinear effects, especially in the mathematical model of the SMA (Paiva and Savi, 2006), this paper proposes an angular control system based on Fuzzy Logic type Mandani (Driankov et al, 1996). This control technique accepts as a basic assumption the uncertain nature of the processes. These uncertainties arise from parametric variations, disturbance dynamics, environmental change, ignorance of the models, etc. This control design allows reducing the complexity of project and implementation, obtaining the solution of these control problems until then untreatable by conventional techniques (Léchevin and Rabbath, 2005; Feng et al, 2010).

In this paper, the fuzzy controllers are chosen as the object of study for three main reasons: a) are essentially nonlinear and therefore have great potential to control more complex systems outperforming conventional controllers b) present facility for incorporation of expert knowledge through linguistic rules and c) doesn't need detailed knowledge of the models of the elements of the process to be controlled (plant, sensors and actuators).

The work is organized as following: Section 2 presents the prototype of the airfoil; Section 3 presents the experimental setup used to evaluate the performance of the fuzzy controller; Section 4 presents the theoretical concepts and the main features of fuzzy controller; Section 5 presents the results of the closed loop system with controllers: fuzzy and on/off. The paper concludes with Section 6, which presents the comments, conclusions and perspectives relevant to the issues studied.

2. PROTOTYPE AIRFOIL

This paper focuses on the study of an angle control system for an adaptive structural systems based on fuzzy logic type Mandani. The positions of the adaptive wing are obtained through SMA actuators. In this paper, we used the prototype airfoil illustrated in Figure 1. This airfoil is characterized by its greater thickness corresponding to 12% of the chord of the profile (NACA-0012 model), which has 500 mm of chord and 60 mm thick.

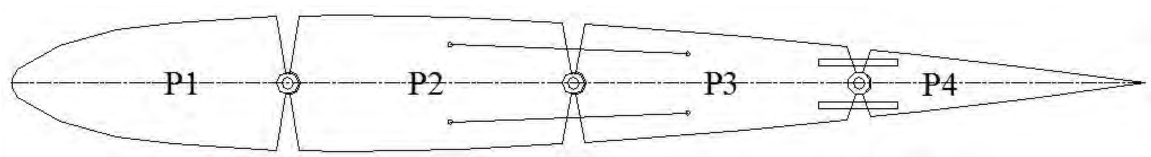
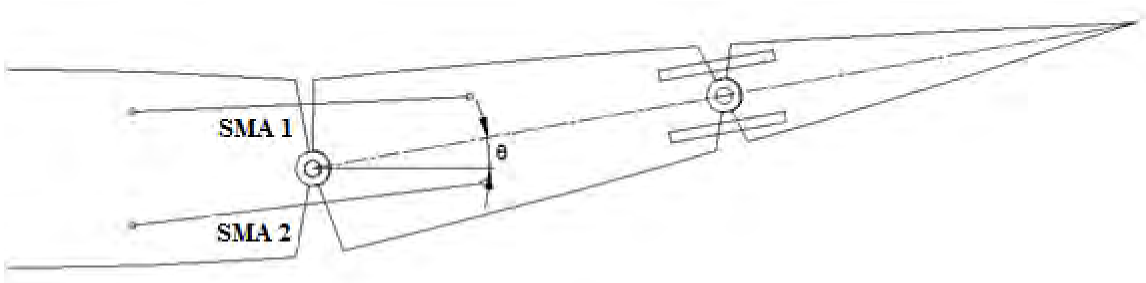


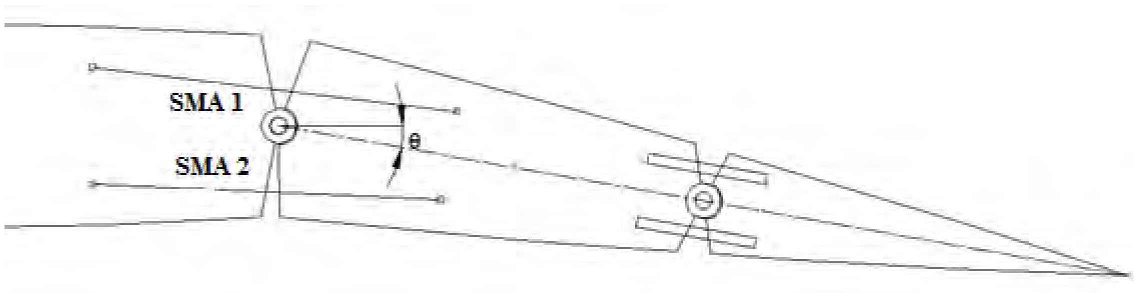
Figure 1: Schematic of the prototype airfoil used.

For greater versatility of the prototype, three articulation points have been inserted, resulting in an airfoil made of four moving parts (P1, P2, P3 and P4). For simplification, the parts P1, P2, and P4 were fixed and the part P3 is mobile (Figure 1). Two SMA wire were used as actuators (SMA 1 and SMA 2) to rotate P3 at an angle (see Figures 2a and 2b) in the counterclockwise (positive angle) or clockwise (negative angle).



(a)

ISSN 2176-5480



(b)

Figure 2: Control angle of the airfoil: (a) SMA 1 activated and SMA 2 free; (b) SMA 1 free and SMA 2 activated.

In the proposed model (see Figure 2), we want to establish a way for the aerodynamic profile of the determination of an angle (θ) between the sections of the airfoil. This angle is achieved by the effect of shape memory alloy (SMA1 or SMA 2) through the passage of an electric current. The function of the electric current is to change the temperature of the actuators via the Joule effect, modifying the shape of SMA.

The different sections were designed to fit together by means of pins. This profile was machined on an acrylic plate of 15 mm thickness, using the machining center ROMI Discovery 560, which is available in the laboratory of machining at Faculty of Engineering of Ilha Solteira-SP in Brazil. To facilitate machining of the piece, two holes were inserted into each section, which in turn were utilized for positioning the stringers of the wing profile.

In this paper, two joints (P3 and P4) were fixed to achieve the experimental trials. Only the middle joint (P3) was triggered by SMA wires. The position of each wire SMA was chosen such that drilling was not too close to the edges or too close to the line of bending profile while also maximizing the length of the wire.

The prototype airfoil was proposed by Faria (2010) and it is shown in figure 3.

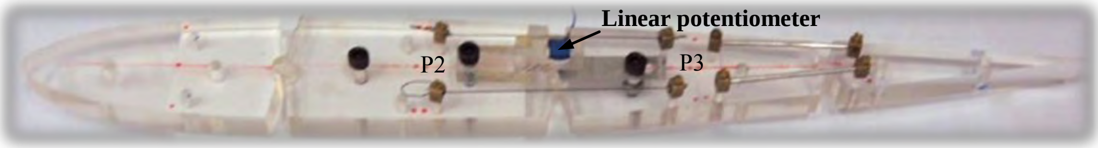
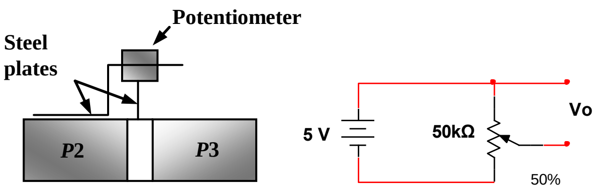


Figure 3: Prototype built an airfoil

A linear potentiometer (model TRIMPOT 3386-F) was used as a sensor to measure the angle θ and positioned between the parts P2 and P3 (Figure 3). Figure 4 illustrates the installation of the sensor (a) and the equivalent electric circuit (b).



(a) (b)

Figure 4: (a) Installation of the sensor and (b) equivalent circuit.

The value of the output voltage (Vo) as a function of the angle (θ) of the sensor is given by:

$$Vo = a\theta + b \quad (1)$$

where $a = -0.012$ e $b = 2.6$.

ISSN 2176-5480

3. EXPERIMENTAL APPARATUS

The experimental setup, built in the laboratory, can be seen in Figure 5 and consists of a prototype of the airfoil actuated by a pair of shape memory alloys wires.

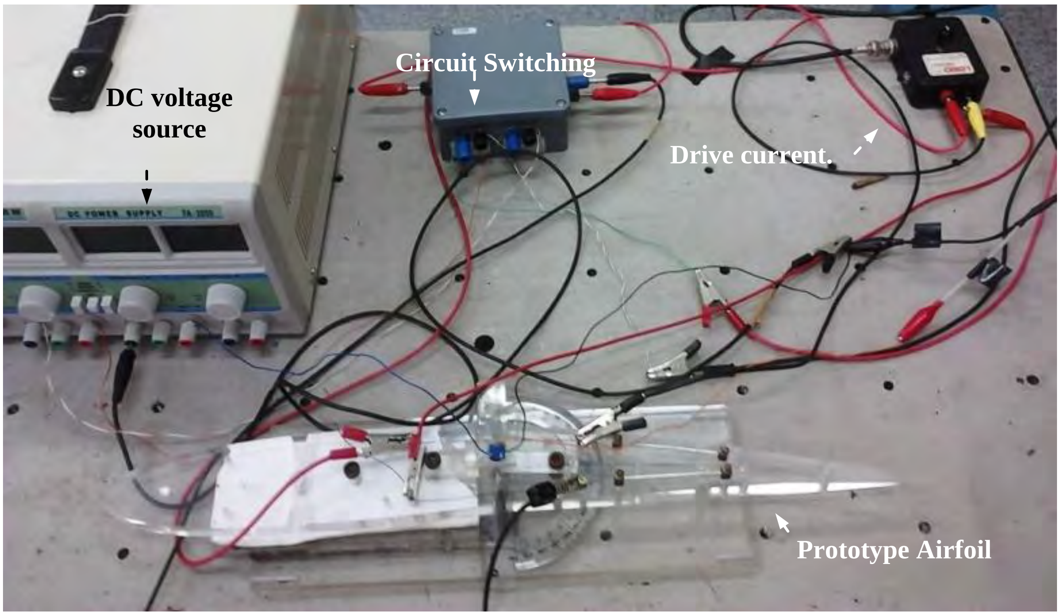


Figure 5: The experimental setup.

The experimental setup basically consists of a DC voltage source for feeding the potentiometer that detects the change in the angle between the parts P3 and P4. This angle is achieved by the effect of shape memory alloy by passing an electric current generated by a current driver manufactured by Lord (Model RD-3002-1) whose input is a voltage to be applied by the fuzzy controller. This controller implemented in dSPACE ® environment (model DS1103) makes the interface between the SMA and the current driver in a sampling time of 1 ms. The environment dSPACE ® is an integrated interface with Matlab Simulink ® that brings together tools analysis and design of control systems with a software implementation in real time.

A switching circuit was designed to switch the controller action in SMA 1 or SMA 2. The schematic diagram of this circuit is shown in Figure 6.

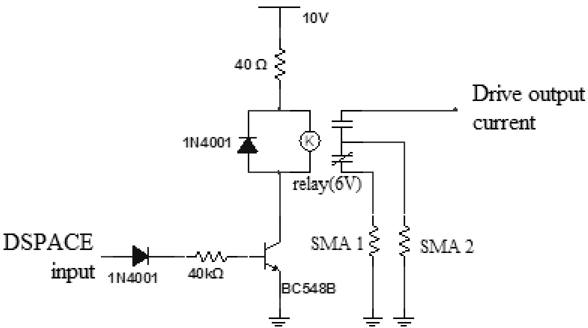


Figure 6: The switching circuit.

Because of the noise, it was used a digital filter Butterworth low-pass fifth order with cutoff frequency of 10Hz at the output of the sensor (potentiometer) in order to minimize the effect of unwanted noise in the proposed control circuit.

The goal is to ensure that the angle of the airfoil (θ) reaches a pre-established reference angle (r). So, we want to design a fuzzy controller that ensures the minimization in a shortest time. The signal error is defined by:

$$E = r - \theta \tag{2}$$

ISSN 2176-5480

4. EXPERIMENTAL APPARATUS

The fuzzy control was introduced in 1965 (Zadeh, 1965) as an emerging technology originally focused on industrial applications, added a dimension to the promising field of modern control engineering.

An important feature in the design of fuzzy control theory is the possibility of using a set of natural rules, intuitive and own common sense, which seeks to approximate the behavior of the driver of human behavior in the real world. Therefore, the fuzzy controllers are aware of the nonlinearities present in the plant, however, incorporate them into their design methodology. This methodology is based on the theory of fuzzy systems involving among others, some striking features, which are: the construction of fuzzy rules, the use of logical operators, the use of membership functions for mapping the input variables and output plant (Driankov et al., 1996).

The fuzzy control methodology is based on the theory of fuzzy systems (Zadeh, 1965) and involves overcoming five well-defined steps, which are: a) definition of the input variables and output b) characterization of the range of values of the variables input and output c) definition of the set of membership functions, d) definition of the rule base e) definition of the fuzzy inference engine. For the problem at hand, the construction stages of the fuzzy controller are described below.

a) Definition of Input and Output Variables

In this work were adopted as input variables of the process, the error (E) and the variation angular error (dE/dt). As for the output variable, picked up the electric voltage (v) applied to the current driver.

b) Characterization of Interval Values of Variables Input and Output

The intervals of values that the input and output variables can assume ([$x_{\inf}, x_{\sup}$]) are defined as: i) for the angular error (E): range of $[0,5]$ degrees to SMA1 and $[-5,0]$ to SMA2 ii) variation of the angular error ($[-5,5]$) in the range of degrees / s iii) the output variable is defined interval ($[0.6,5]$) volts.

c) Definition the set of Membership Functions

The labels or membership functions try to translate verbally the meaning of the variable region of the universe to some variation of it (universe of discourse). For input variable dE/dt, the universe of discourse is divided into triangular membership functions that describe the system variables through labels or linguistic variables, namely: "Big Negative" (*BN*), "Negative Medium" (*NM*), "Low Negative" (*LN*), "Zero" (*Z*), "Low Positive" (*LP*), "Positive Medium" (*PM*) e "Big Positive" (*BP*). For the input variables E and output v, the corresponding universe of discourse were divided by 7 equally spaced membership functions, which are: *Z*, *E*1, *E*2, *E*3, *E*4, *E*5 e *E*6 (to SMA 1); *E6*, *E*5, *E*4, *E*3, *E*2, *E*1 e *Z* (to SMA 2) e *Z*, *V*1, *V*2, *V*3, *V*4, *V*5 e *V*6 (to the voltage *v*).

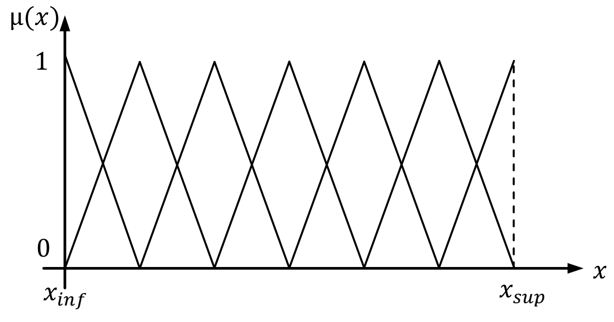


Figure 7: A set of membership functions used for input and output variables of the fuzzy controller.

The choice of the shape of the membership function most appropriate is not always obvious, and it may even be beyond the reach of knowledge for a particular application (Driankov et al., 1996). However, fuzzy systems whose parameters are functions of pertinence can be completely defined by experts. In those cases, the choice of triangular functions is more common, because the idea of defining regions of pertinence total average void and is more intuitive than the specification of the average value and dispersion of these concepts related to Gaussian functions.

d) Defining the Rule Base

In fuzzy logic, the inputs and output of the controller are related by a set of well established rules such as "if…then". The rule base has the function of representing a structured the policy to an experienced operator control of the process and/or a control engineer. In this paper, the rule base was built from the intuitive knowledge of the dynamic behavior of the airfoil on the application of electric current in SMA 1 and SMA 2. Tables 1 and 2 show, respectively, the rule base constructed for SMA 1 and SMA2.

Table 1. Base rules for SMA 1.

$\frac{dE}{dt}$ \ E	Z	E1	E2	E3	E4	E5	E6
BN	Z	V1	V3	V3	V4	V5	V5
NM	Z	V2	V3	V4	V5	V5	V5
LN	Z	V3	V4	V4	V5	V6	V6
Z	Z	V3	V4	V5	V6	V6	V6
BP	Z	Z	Z	Z	Z	Z	Z
PM	Z	Z	Z	Z	Z	Z	Z
LP	Z	Z	Z	Z	Z	Z	Z

Table 2 –Base rules for SMA 2.

$\frac{dE}{dt}$ \ E	E6	E5	E4	E3	E2	E1	Z
BN	Z	Z	Z	Z	Z	Z	Z
NM	Z	Z	Z	Z	Z	Z	Z
LN	Z	Z	Z	Z	Z	Z	Z
Z	V6	V6	V5	V5	V4	V3	Z
LP	V6	V5	V5	V4	V4	V3	Z
PM	V5	V5	V4	V4	V3	V2	Z
BP	V5	V5	V4	V3	V3	V1	Z

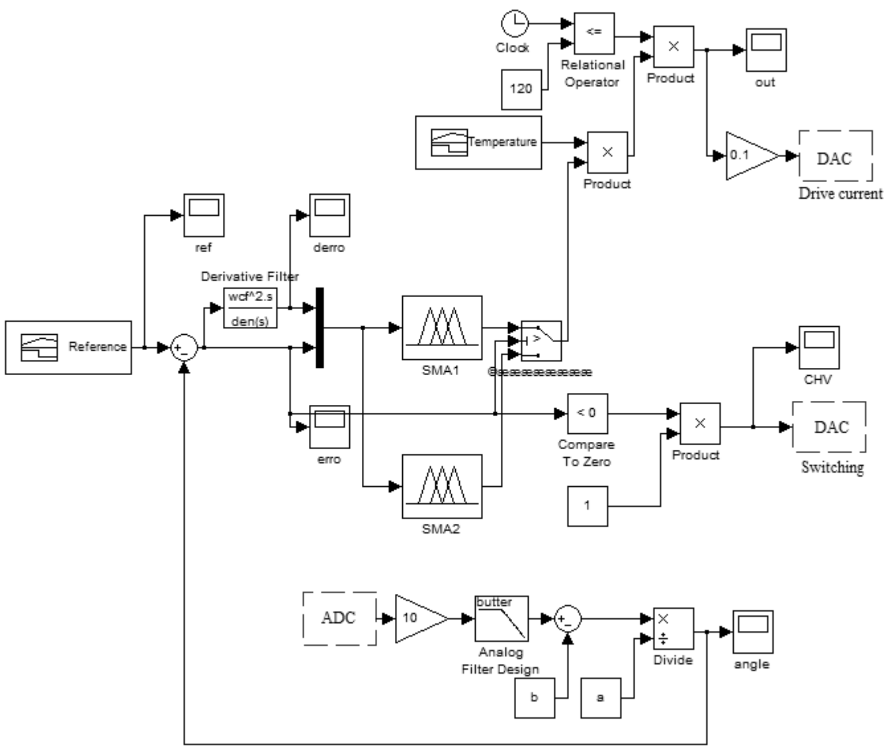
e) Fuzzy Inference System

Once defined the rules derived from the symbolic language built into the control System, is set to stage the mathematical translation of this language. This is conducted by using logical operators defined by the treory of fuzzy sets (Driankov et al., 1996). This task is devided into three subteps (Fuzzification, Inference Engine, Desfuzzification). In this work, was used as inference engine fuzzy implication minimum (Mamdani type) held by connective **E**. For the transformation of fuzzy set output on a numerical control action, the strategy adopted to desfuzzication was centroid of area (Driankov et al., 1996).

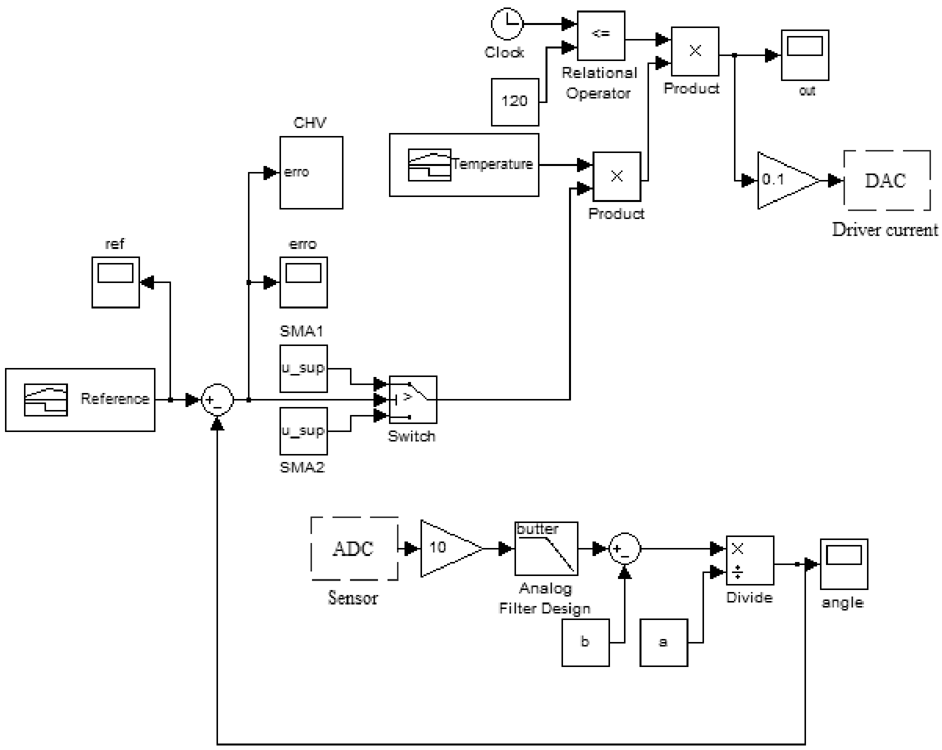
5. EXPERIMENTAL APPARATUS

In this section we present a set of tests that seek to evaluate the performance characteristics of the closed loop system by comparing two types of controllers: fuzzy and on-off. The block diagrams of the proposed control systems were built in Matlab Simulink ® and implemented in DSpace ®. These diagrams are shown in Figure 8a and 8b.

ISSN 2176-5480



(a)



(b)

Figure 8: Block diagrams of the control system fuzzy (a) and on-off (b).

According to the diagram shown above, from the error signal (E) and the variation of the angular error (dE/dt), the controller (on-off or fuzzy) produces an electrical voltage signal (v) which feeds the current driver and turn excites the actuator SMA1 or SMA2, depending on the error signal.

ISSN 2176-5480

The angular motions of the airfoil generated by the actuator, are obtained by linear potentiometer. Thus, the output signals of the potentiometer is acquired, filtered, and according to Equation 1 are transformed into values in degrees. These values are then compared with the reference generating the error signal E once derivative resulted in its time variation (dE/dt). The error signals (E) and variation of the angular error (dE/dt) are again fed by the controller and a new output generated is fed back to the control loop. Note that in both diagrams is a waiting time required to cool the shape memory alloy (this work 3s) before the other shape memory alloy acts, this is done in the diagram by the block temperature. According to Figure 9a, the signal of the fuzzy controller can take two values as the error is positive or negative. In other words, we have:

$$v(t) = V_{SMA\,1}(t) \text{ if } E(t) > 0 \qquad (3)$$

or

$$v(t) = V_{SMA\,2}(t) \text{ if } E(t) < 0 \qquad (4)$$

where $V_{SMA\,1}(t)$ and $V_{SMA\,2}(t)$ are the voltages applied by the fuzzy controllers in SMA1 and SMA2, respectively. In relation to the on-off controller, it was assumed voltage constant $3.25V$ (v_{max}) applied to both for SMA1 and SMA2. Thus, by signal voltage (10V or 0 in the output dSPACE ®) to the input of the switching circuit (see Figs. 6 and 9), the relay physical (Fig. 6), switches the action of the fuzzy controller SMA1 or SMA2, depending on the error signal E generated. Assuming initially positioned near the airfoil zero angle, Figs. 9-12 show the transient responses for: r, θ, E, v and the voltage applied to the circuit switching.

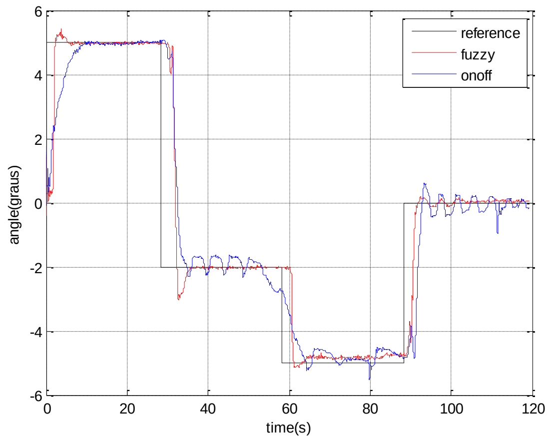


Figure 9: Transient behavior of the angle θ.

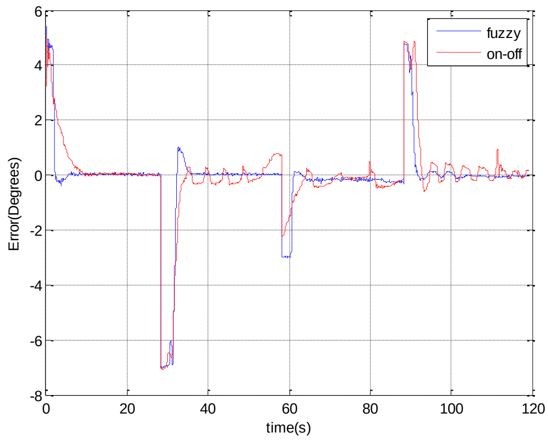


Figure 10: Transient behavior of the angular error E .

ISSN 2176-5480

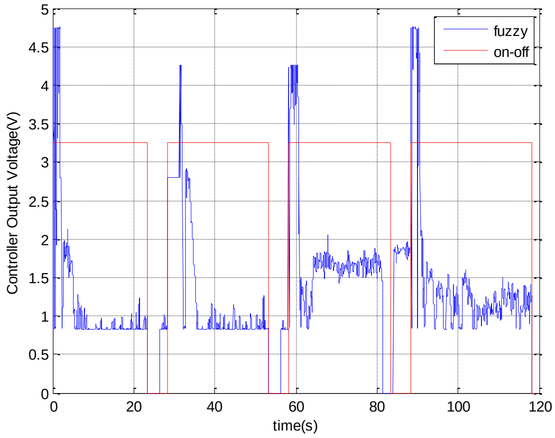


Figure 11: Transient behavior of the voltage v.

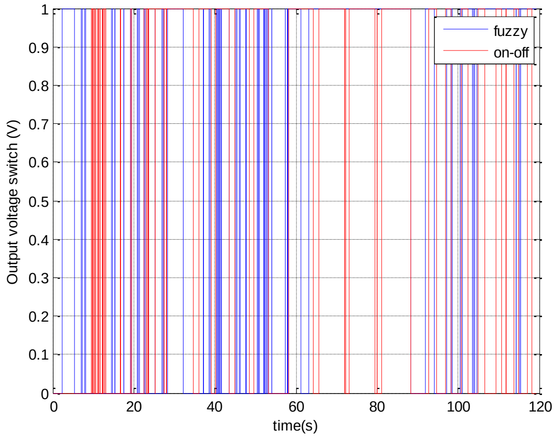


Figure 12: the voltage applied to the circuit switching.

From the analysis of the graph shown in Figure 9, it clearly appears that the fuzzy controller showed results quite optimistic about minimizing the angular error (E), giving the system a low settling time for SMA (around 2 seconds) and an enhanced damping compared with on-off controller. For the latter, there is little damped characteristic of the airfoil, particularly in smaller angles, which remains after expiry of the oscillating transient. Such behavior can also be seen in Figs. 10.

With respect to the voltage applied to the current driver (see Figure 11), is observed with the application of fuzzy control, there was a reduction of approximately the 50% RMS value v in relation to the control system switches off under application the voltage constant $3.25V$. Note, the intervals where the voltage is zero for the cooling time of the shape memory alloy.

In Figure 12, there is the transient behavior of the voltage applied to the switching circuit shows the action of the controller in SMA1 with voltage to 0V, under the condition $E(\mathrm{t}) > 0$ (see Fig 8) and SMA2 when applied a voltage of 10V (to $E(\mathrm{t}) < 0$).

It is worthy to note that numerous experimental tests were performed, considering other types of references, and in all cases studied, the results were very satisfactory and the fuzzy controller proved to be robust and stable. Worthwhile to emphasize that the fuzzy controller was built intuitively, there is therefore the need for detailed knowledge of the dynamic model of the system to be controlled.

6. CONCLUSION

This paper presented a methodology for the control problem of angular positioning in adaptive wings using shape memory alloys and controllers based on fuzzy logic. These controllers are designed to reduce the complexity of experimental design and implementation, making it the solution for complex control problems, difficultly treatable by classical techniques.

To perform the experimental trials was considered a model airfoil proposed and built by Faria (2010) containing a pair of shape memory alloys coupled. Experimental tests were conducted to evaluate the action of the proposed fuzzy controller. This was assessed a fuzzy controller designed intuitively that proved attractive to the problem in question. The fuzzy compensator presented simplicity of construction and ease of experimental implementation. The fuzzy controller showed to be efficient for the problem. The performance characteristics were quite satisfactory in comparison with the control system turns off. A fact that worth mentioning, was the reduction of approximately 50% in the amount of energy used to power the current driver by the fuzzy controller in relation to the control system on-off. From the practical point of view, the design methodology of fuzzy controller proved right and promising to solve the control problem of angular positioning of adaptive wings using shape memory alloys.

7. ACKNOWLEDGEMENTS

At the National Institute of Science and Technology (INCT) for the financial support which enabled the execution of this work dedicate exclusively.
At the CNPq and FAPEMIG for partial funding of this work through INCT-LES.

8. REFERENCES

Bilgen, O., De Marqui Jr., C., Kochersberger, K. B. e Inman, D. J., 2011, "Macro-Fiber Composite Actuators for Flow Control of a Variable Camber Airfoil". *Journal of Intelligent Material Systems and Structure*, Vol. 22, pp. 81-91.

Driankov, D., Hellendoorn, H. e Reinfrank, M., 1996, "An Introduction to Fuzzy Control", *Springer-Verlag*, 2ª Edição.

Faria, C. T., 2010, "Controle da Variação do Arqueamento de um Aerofólio utilizando Atuadores de Memória de Forma", *Dissertação de Mestrado*, Faculdade de Engenharia de Ilha Solteira, Universidade Estadual Paulista - UNESP, Ilha Solteira-SP.

Feng, Y., Rabbath, C. A., Hong, H., Janaideh, M. A. e Su, C. Y., 2010, "Robust Control for Shape Memory Alloy Micro-Actuators Based Flap Positioning System", *2010 American Control Conference*, Baltimore-MD, pp. 4181-4186.

Léchevin, N. e Rabbath, C. A., 2005, "Quasipassivity-based Robust Nonlinear Control Synthesis for Flap Positioning Using Shape Memory Alloy Micro-Actuators", *2005 American Control Conference*, Portland-OR, pp. 3019-3024.

Paiva, A. e Savi, M.A., 2006, "An Overview of Constitutive Models for Shape Memory Alloys", *Mathematical Problems in Engineering*, Article ID56876, pp.1-30.

Seigler, T. M., Neal, D. A., Bae, J. S. e Inman, D. J., 2007, "Modeling and Flight Control of Large-Scale Morphing Aircraft", *Journal of Aircraft*, Vol. 44, No. 4, pp. 1077–1087.

Viana, F. A. C., Maciel, B. C. O., Brasil Neto, N. S., Oliveira, M. F., Steffen Jr., V. e Góes, L. C. S., 2009, "Aircraft Longitudinal Stability and Control Derivatives Identification by using Life Cycle and Levenberg-Marquardt Optimization Algorithms". *Inverse Problems in Science & Engineering*, Vol. 17, pp. 17-34.

Zadeh, L. A., 1965, "Fuzzy Sets, Information and Control", Vol. 8, No. 3, pp. 338-353.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.