A MORPHING WING USED SHAPE MEMORY ALLOY ACTUATORS NEW CONTROL TECHNIQUE WITH BI-POSITIONAL AND PI LAWS OPTIMUM COMBINATION
Part 2: Experimental Validation

Teodor Lucian Grigorie, Andrei Vladimir Popov, Ruxandra Mihaela Botez
École de Technologie Supérieure, Montréal, Québec H3C 1K3, Canada

Mahmoud Mamou, Youssef Mébarki
National Research Council, Ottawa, Ontario K1A 0R6, Canada

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Abstract: The paper represents the second part of a study related to the development of an actuators control system for a morphing wing application, and describes the experimental validation of the control designed in the first part. After a short presentation of the finally adopted control architecture, the physical implementation of the control is done. To implement the controller on the physical model two Programmable Switching Power Supplies AMREL SPS100-33 and a Quanser Q8 data acquisition card, were used. The inputs of the data acquisition were two signals from Linear Variable Differential Transformer potentiometers, indicating the positions of the actuators, and six signals from thermocouples installed on the SMA wires. The acquisition board outputs channels were used to control power supplies in order to obtain the desired skin deflections. The control validation was made in two experimental ways: bench test and wind tunnel test. All 35 optimized airfoil cases, used in the design phase, were converted into actuators vertical displacements which were used as inputs reference for the controller. In the wind tunnel tests a comparative study was realized around of the transition point position for the reference airfoil and for each optimized airfoil.

1 INTRODUCTION

The spectacular and continuous evolution of the aerospace engineering domain was highlighted in the last years especially through the boarded equipments and systems technology development, mainly those of avionics. But, in the same time, the two related sub-domains, propulsion systems and aircraft structures, in parallel registered very important discoveries, sometimes notified to the general public too little. Thus, the concept of green aircraft launched major trends in the aerospace field research, of which can be mentioned reduction of noise and chemical pollution of the atmosphere, reduction of fuel consumption and increase of aircraft flight autonomy. This concept is a consequence of the predictions for future according with that the air traffic is seen to more than double in the next 20 years. Therefore, both environmental and economic pressures will strongly increase and significant progress will need to be achieved in both improving the efficiency and minimizing the environmental impact of aircraft. In order to provide these required changes, aircrafts in new concepts are designed and will be developed. These suppose the validation and after that the integration of new technologies and solutions at the level of all major aircraft components: cabin, wing, power plant system, and fuselage; multidisciplinary investigations already explore the different associated aspects of aero-dynamics, acoustics, materials, structure, engines and systems. The aims of these investigations are to ensure an improved quality and affordability, whilst meeting the tightening environmental constraints (emission and noise), with a vision of global efficiency of the air

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transport system.

Within this context are developed our research related to the morphing aircraft new challenge field, precisely to the morphing wing concept in this field (Chang, 2009, Smith, 2007, Hinshaw, 2009, Gonzalez, 2005, Namgoong, 2006, Majji, 2007, and Ruotsalainen, 2009). The presented work objective is to develop an actuation control concept for a new morphing mechanism using smart materials, like Shape Memory Alloy (SMA), as actuators. These smart actuators modify the upper surface of a wing made of a flexible skin so the laminar to turbulent transition point moves close to the wing airfoil trailing edge. The final purpose of the research project is to obtain a drag reduction as a function of flow condition, by changing the wing shape.

The chosen wing model was a rectangular one, with a reference airfoil WTEA-TE1, a chord of 0.5 m and a span of 0.9 m. The model was equipped with a flexible skin made of composite materials morphed by two actuation lines. Each actuation line uses shape memory alloys wires as actuators.

In the first part of this paper a control for the actuation lines of the morphing wing system was designed. In this way, 35 optimized airfoils available for 35 different flow conditions (five Mach numbers (0.2 to 0.3) and seven angles of attack (-1˚ to 2˚) combinations) were used.

From the developed actuation mechanism results that each actuation line uses three SMA wires (1.8 m in length) as actuators, and contains a cam, which moves in translation relative to the structure (on the *x*-axis in Fig. 1). The cam causes the movement of a rod related on the roller and on the skin (on the *z*-axis). The recall used is a gas spring. The horizontal displacement of each actuator is converted into a vertical displacement at a rate 3:1, which makes that the horizontal stroke of x mm to be converted into a vertical stroke $z=x/3$; results a cam factor $c_f=1/3$, therefore, for the approximately 8 mm maximum vertical displacement, obtained from the optimized airfoils numerical data, a 24 mm maximum horizontal displacement must be actuated.

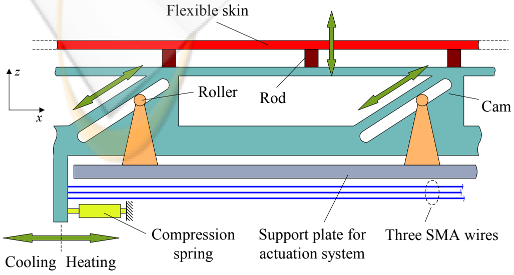

Figure 1: The actuation mechanism concept.

The designed controller controls the SMA actuators in terms of supply electrical current so that to cancel the deviation between the required values for vertical displacements (corresponding to the optimized airfoils) and the real values, obtained from two position transducers (Fig. 2).

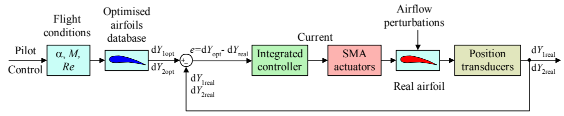

Figure 2: Operating schema of the SMA actuators control.

The finally numerical validated configuration (in the first part of the paper) of the integrated controller was a combination of a bi-positional controller (particularly an on-off one) and a PI (proportional-integral) controller, due to the two phases (heating and cooling) of the SMA wires interconnection. The resulted controller must behave like a switch between cooling phase and heating phase, situations where the output current is 0 A, or is controlled by a law of PI type

$$i(t)=\begin{cases}0, \text{ if } e\le 0,\\ 1792.8\cdot e(t)+787.0061\cdot\int e(t)\cdot \mathrm{d}t, \text{ if } e>0.\end{cases} \quad (1)$$

e is the operating error (see Fig. 2).

2 PHYSICAL MORPHING WING CONTROL IMPLEMENTATION

Starting from the theoretical and numerical simulation resulted considerations to implement the controller on the physical model two Programmable Switching Power Supplies AMREL SPS100-33, controlled by Matlab through a Quanser Q8 data acquisition card, were used (Fig. 3) (Kirianaki, 2002, Park, 2003, and Austerlitz, 2003).

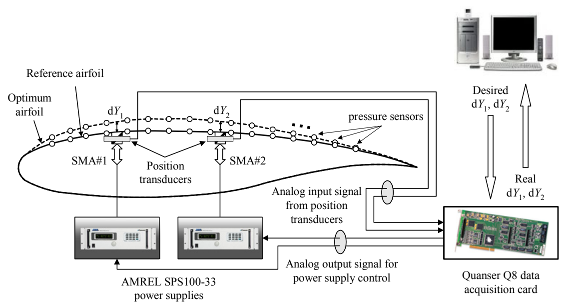

Figure 3: Physical model operating schema.

The power supplies have RS-232 and GPIB IEEE-488 as standard features and the technical characteristics: Power 3.3kW, Voltage (dc) 0÷100 V, Current (dc) 0÷33 A. The Q8 data acquisition card has 8 single-ended analog inputs with 14-bit resolution. All 8 channels can be sampled simultaneously at 100 kHz, with A/D conversion times of 2.4 µs/channel, simultaneous sampling and sampling frequencies of up to 350 kHz for 2 channels. Also, the Q8 card is equipped with 8 analog outputs, with software programmable voltage ranges and simultaneous update capability with an 8 µs settling time over full scale (20V).

The acquisition board was connected to a PC and programmed through Matlab/Simulink R2006b and WinCon 5.2 (Fig. 4).

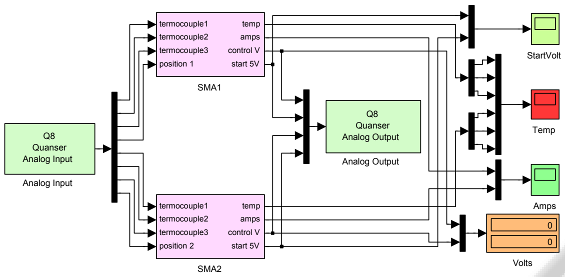

Figure 4: Simulink actuators control.

The input signals were two signals from Linear Variable Differential Transformer potentiometers that indicate the positions of the SMA actuators, and six signals from thermocouples installed on all the SMA wires components. The acquisition sampling time was set to 0.01 second. The outputs channels of the acquisition board were used to control each power supply through analog/external control by use of a DB-15 I/O connector. The current supplied to the actuator was set to be limited at 10 A, and the control signal was set to be 0÷0.6061V (maximum voltage for the power supply is 2 V for 33 A current supply).

The operation principle of the physically implemented controller is relative simple. The initial input, which is the optimized airfoil for any flow condition, is chosen manually by the operator from the computer database through a user interface. Then the displacements (dY_1, dY_2) that are required to be reproduced by the two control points on the flexible skin are sent to the controller. This controller sends an analog signal 0 – 2 V to the power supply that provides a current to the SMA. The SMA will respond accordingly and change its length according to the temperature of the wire. This will result in a change of the actuators positions, which are sensed by the linear variable differential transducer (LVDT). The signal position received from the LVDT is compared to the desired position and the error obtained is fed back to the controller. If the realized position is greater than the desired position the controller will disconnect the control current letting the SMA wire to cool down. During the cooling down process the SMA will maintain its length due to the hysteretic behavior. This effect is taken into account for actuators displacement. Also the controller uses three thermocouples signals from each SMA wire to monitor the temperature of the wires and maintain it below 130˚C, as an upper limit.

3 SMA ACTUATORS CONTROL BENCH TEST VALIDATION

The morphing wing system in the bench test runs is shown in Fig. 5.

The gas springs that maintain the SMA wires in tension had a preloaded value of 225 lbs (1000 N) since in the laboratory condition there is no aerodynamic force.

After an initial calibration test the calibration gains and constants were established for the two LVDT potentiometers and for the six thermocouples. The calibration test for LVDT potentiometers consisted of several scans of airfoil using a laser beam. On the calibration, the SMA actuators were in "zero setting position" with no power supplied and the skin coordinates were measured using the laser beam that scanned the center line of the wing model. The laser was set to scan the chord of the model on a 370 mm length with a speed of 5 mm per second.

In the bench test, the 35 optimized airfoil cases were converted into SMA actuator #1 and #2 vertical displacements which were used as inputs reference for the controller. A typical test run history is shown in Fig. 6 for α=1°, Mach=0.3 flight condition (dY_1=5.22 mm, dY_2=7.54 mm – vertical displacements of the skin in the actuation points).

On observe that the controllers, in the two actuation lines, work even in zero values of the desired signal because of the gas springs pretension. Also, small oscillations of the obtained deflection are observed around the desired values of the deflections. The amplitude of the oscillations in this phase is due to the LVDT potentiometers mechanical link and to the inertia of the SMA wires, being smallest than 0.05 mm. The heating phase is approximately 9 times more rapidly than the cooling phase; heating time equals 8 s while the cooling time

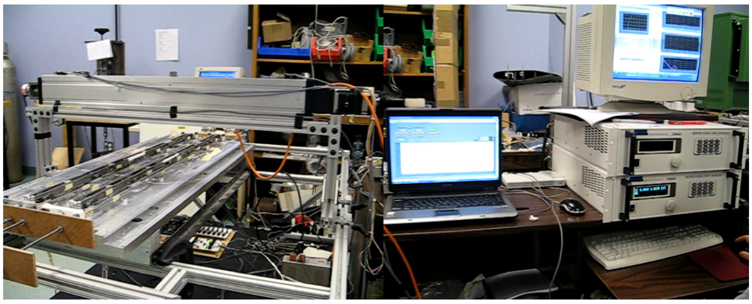

Figure 5: Morphing wing system in the bench test runs.

equals 70 s. There can be observed the differences between the numerical model of the SMA actuators and the physical model.

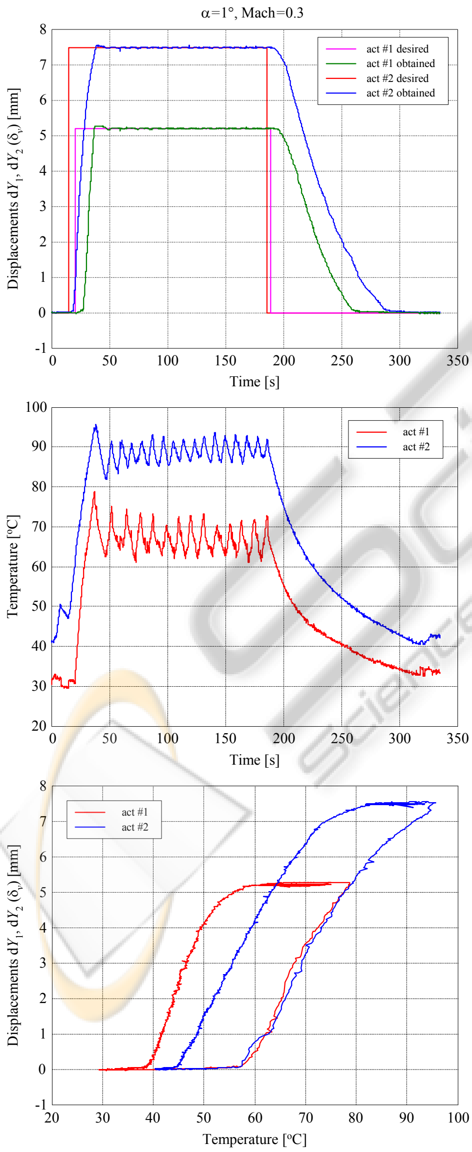

Figure 6: Bench test for α=1°, *M*=0.3 flight condition.

The bench test results confirmed that the experimental version of the designed integrated controller woks well even in the lab conditions, where no aerodynamic forces are loaded and the preloaded gas springs force is 1000N.

4 SMA ACTUATORS CONTROL VALIDATION IN WIND TUNNEL TESTS

Once confirmed the well working of the designed integrated controller through bench test, the next step in our morphing wing project was to validate the controller in a wind tunnel test simultaneously with the transition point real time detection and visualization for all 35 optimized airfoils. The model was tested for all 35 theoretical studied flight conditions, a comparative study being realized around of the transition point position for the reference airfoil and for each optimized airfoil. So, simultaneously with the controller testing, a validation study for the aerodynamic part of the project was realized.

The morphing wing system in the wind tunnel runs is shown in Fig. 7.

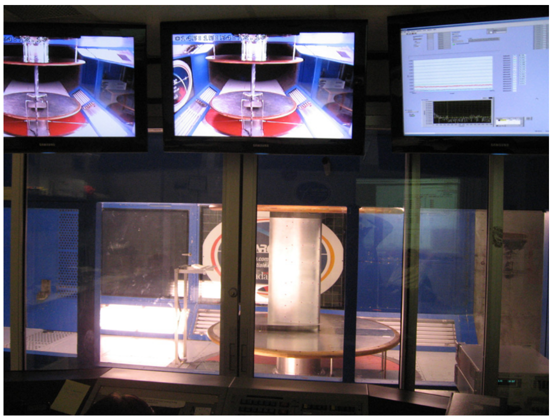

Figure 7: Wind tunnel morphing wing model.

The transition detection was made real time using the pressure data obtained from the 32 Kulite and optical pressure sensors. The pressure data acquisition was performed using the IAR-NRC analog data acquisition system which was connected to the 32 sensors. The sampling rate of each channel was 15 kS/s, which allowed a boundary layer pressure fluctuations FFT spectral decomposition up to 7.5 kHz for all channels. The signal was processed by use of Simulink and visualized in real time on the computer screen in dedicated windows.

The pressure signals were analyzed through Fast Fourier Transforms (FFT) decomposition in order to detect the magnitude of the noise in the surface air flow. Subsequently, the data is filtered by means of high-pass filters and processed by calculating the Root Mean Square (RMS) of the signal in order to obtain a plot diagram of the noise in the air flow. This signal processing is necessary to disparate the inherent electronically induced noise, by the Tollmien-Schlichting that are responsible for triggering transition from laminar flow to turbulent flow. The measurements showed that in processed data the transition appeared at frequencies between 3kHz - 5kHz and the magnitude of pressure variations in the laminar flow boundary layer are of the order 5e-4 Pa (7.25e-8 psi). The transition between laminar flow and turbulent flow was shown by an increase of the pressure variations, reflected also by a strong variation of the pressure signal RMS.

For the wind tunnel test the preloaded forces of the gas springs were reconsidered to the 1500 N because of the presence of the aerodynamic forces on the flexible skin of the wing. In Fig. 8 are presented the control results for test run α=2°, Mach=0.225 (dY_1=5.56 mm, dY_2=7.91 mm).

The experimental results show a decrease of the SMA wires work temperatures vis-à-vis of numerically simulated and bench tested cases. An explanation can be the appearing of the aerodynamic forces with particular values for each flight condition. The decrease of these temperatures is a beneficial one taking into account the negative impact of a strong thermal field on the other component of the system, especially on the flexible skin and on the pressure sensors. Also, from the experimental results a high frequency noise influencing the LVDT sensors and the thermocouples instrumentation amplifiers can be observed. The noise sources are the wind tunnel vibrations and instrumentation electrical fields. With this noise, the amplitude of the actuation error (difference between the realized deflections and desired deflections) is under 0.07 mm, but this don't affecting the transition, which is stable on a sensor with a high RMS spike; Fig. 9 presents the results obtained on the transition monitoring for the run test in Fig. 8.

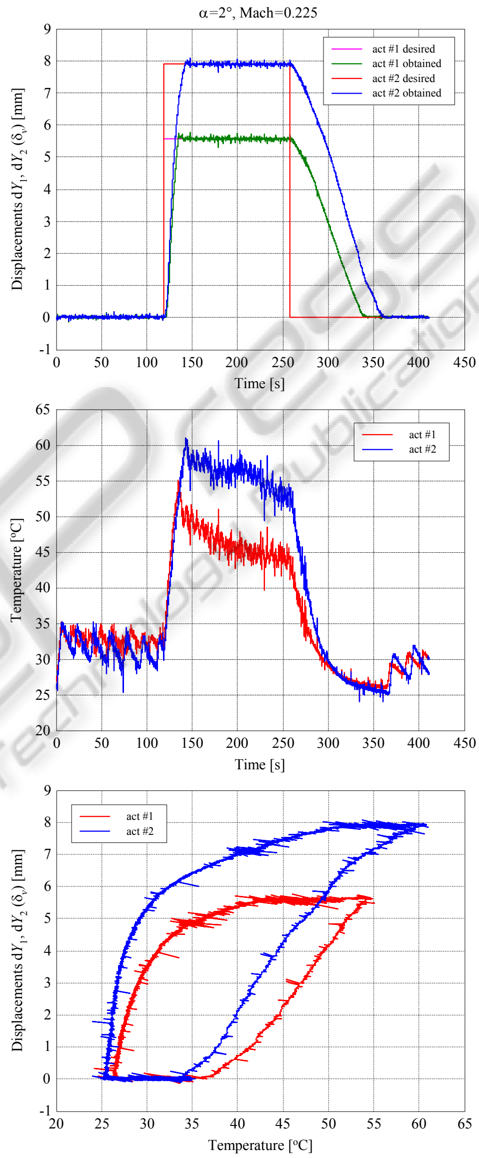

Figure 8: Wind tunnel test for α=2°, M=0.25 flight condition.

The actuation line control obtained precision can have some influence in the transition point position detection only if the density of the chord disposed pressure sensors becomes bigger; from the experimental data evaluation one concluded that, even the value of the error is 1 mm around the optimized values, the transition point position on the airfoil surface is not significantly changed.

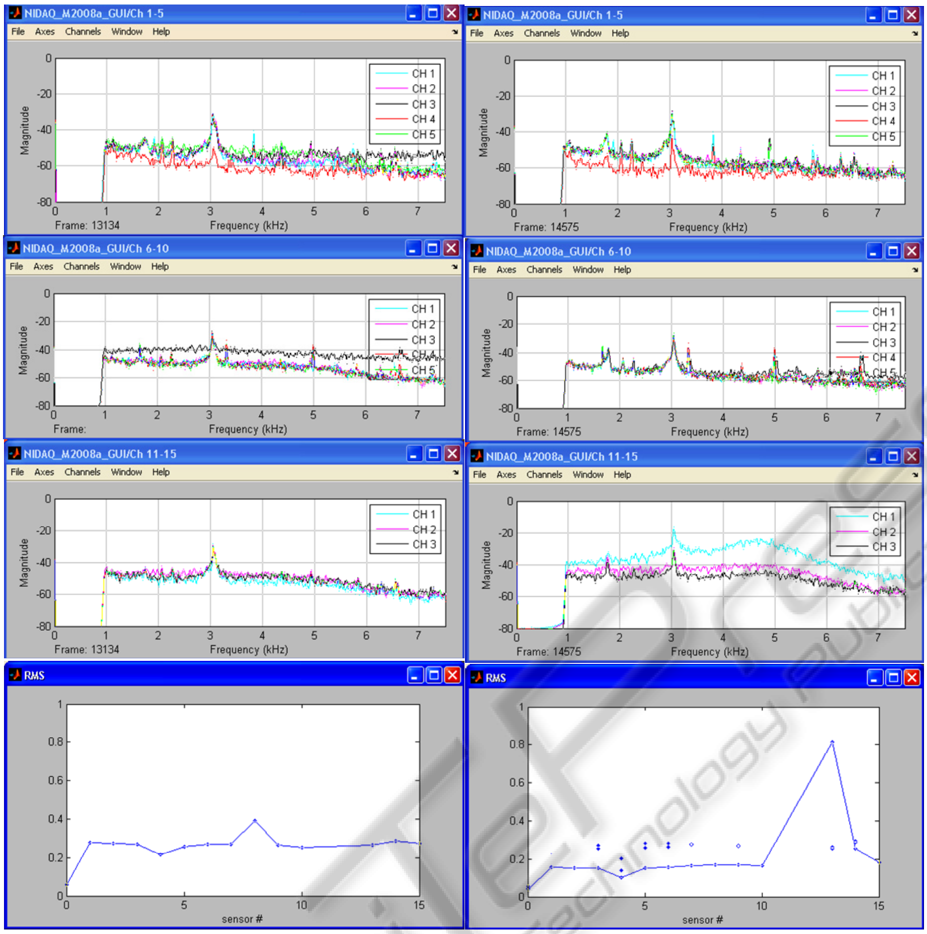

Figure 9: Results obtained on the transition monitoring for the run test in Figure 8.

In Fig. 9 are presented the outputs of the Kulite pressure sensors in leading edge – trailing edge sense of positioning (3 sensors are broken and was not considered in the monitoring phase) and the real time pressure signals RMS for each of these sensors. The left hand column presents the results for reference airfoil, and the right hand column the results for optimized airfoil. The spike of the RMS suggests that we have turbulence on the sensor no. 13, near the trailing edge.

So, the results obtained for the actuators control are very good, the controller fully satisfying the requirements imposed for the project purpose achievement.

The future work on the project supposes the development of the closed loop control, based on the pressure information received from the sensors and on the transition point position estimation. Evidently, the closed loop control will include, as an internal loop, the actuation lines here presented controller.

5 CONCLUSIONS

The paper represents the second part of a study related to the development of an actuators control system for a morphing wing application, and describes the experimental validation of the control designed in the first part. The control validation was made in two experimental ways: bench test and wind tunnel test.

In the bench test phase, the 35 optimized airfoil cases were converted into SMA actuator #1 and #2 vertical displacements which were used as inputs reference for the controller. The characteristics in Fig. 6 (α=1°, Mach=0.3 flight condition) show that the controllers, in the two actuation lines, work even in zero values of the desired signal because of the gas springs pretension. Also, small oscillations of the obtained deflection are observed around the desired values of the deflections. The amplitude of the oscillations in this phase is due to the LVDT potentiometers mechanical link and to the inertia of the SMA wires, being smallest than 0.05 mm. The heating phase is approximately 9 times more rapidly than the cooling phase; heating time equals 8 s while the cooling time equals 70 s.

For the final experimental validation test (wind tunnel test), with real aerodynamic forces load, the 1500 N preloaded forces of the gas springs was reconsidered. From Fig. 8 (α=2°, Mach=0.225) a decrease of the SMA wires work temperatures vis-à-vis of numerically simulated and bench tested cases is observed. The decrease of these temperatures is a beneficial one taking into account the negative impact of a strong thermal field on the other component of the system, especially on the flexible skin and on the pressure sensors. Also, a high frequency noise influencing the LVDT sensors and the thermocouples instrumentation amplifiers can be observed. The noise sources are the wind tunnel vibrations and instrumentation electrical fields. With this noise, the amplitude of the actuation error (difference between the realized deflections and desired deflections) is under 0.07 mm, but this doesn't affecting the transition, which is stable on a sensor with a high RMS spike like in Fig. 9.

So, the results obtained for the actuators control are very good, the controller fully satisfying the requirements imposed for the project purpose achievement.

The designed controller is used for the open loop development stage of a morphing wing project, but the closed loop of the morphing wing system, based on the pressure information received from the sensors and on the transition point position estimation, will include, as an internal loop, the actuation lines here presented controller.

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