Wind tunnel testing of the control system for a new morphing wing application with a full-scaled portion of a real wing

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ABSTRACT

The paper presents the implementation and the experimental testing of a control system for a morphing wing model developed with a full-scaled portion of a real aircraft wing. The morphing wing experimental model was designed, manufactured and tested during an international research project involving industrial partners, research entities and academia from Canada and Italy. Based on the dimensions of a full scale wing tip structure, the model contained two morphable parts: the wing and the attached aileron. The wing has been equipped with a flexible upper surface made from composite materials and morphed by using four miniature electrical actuators. To evaluate the aerodynamic performance of the morphing system during the wind tunnel tests, the air flow behavior over the upper surface has been analyzed based on the information provided by an array of 32 Kulite pressure sensors. Also, in the wind tunnel tests an infrared camera has been used to provide a second opinion related to the aerodynamic performance of the system.

KEYWORDS: *Morphing wing, Control system, Experimental model, Wind tunnel testing, Infra-red analysis*

NOMENCLATURE

dY_{opt} = desired vertical displacements of the optimized airfoil at the actuation points
dY_{real} = real vertical displacements at the actuation points
M = Mach number
α = angle of attack

δ = aileron deflection angle
FFT = Fast Fourier transform
GUI = Graphic User Interface
LVDT = Linear Variable Differential Transformer
SMA = Shape Memory Alloy
STD = Standard Deviation

1 INTRODUCTION

A main need in today and future aircraft is the reduction of the fuel consumption. This need is seen in green technology development that has the aim to improve the aircraft performance while reducing fuel consumption. A lot of research studies are being carried out to reduce fuel consumption by reducing drag, which is directly related to the airflow type around the aerodynamic aircraft body design. The drag reduction concept is connected to the laminar flow and to the displacement of the transition point between laminar and turbulent flows towards the trailing edge [1].
In the last years was developed a strong research trend in this area having as target the study of the possibilities to modify the shapes of the wings airfoils in order to promote large laminar regions on the wing surface, over an operating range of flow conditions characterized by Mach numbers, airspeeds, and incidence angles; the generated concept was called *morphing wing*. The research studies were developed around the world, being performed both at industry and university levels. A short review of the literature shows a lot of morphing architectures conceived for this kind of studies, developed at low scale or at high scale, with different actuation and control principles, and optimized by using different cost parameters and functions.
Researchers at Universidade da Beira Interior, Portugal optimized a wing for a small experimental unmanned aerial vehicle based on coupled aerodynamic and structural constraints ([2]). With the aim to have a minimum drag at different flight speeds a set of optimal wing shapes were obtained.
In order to increase range or endurance for a given fuel load through improved lift-to-drag ratio for small-sized and medium-sized unmanned air vehicles, a morphing wing project was developed at RMIT University, Melbourne, Australia ([3]); the wind tunnel testing of the experimental model investigated the project gains.
In the same trend, to vary the geometry of a wing to adapt to different flight conditions, the specialists from Ryerson University, Toronto, Canada designed a novel underactuated parallel mechanism ([4]); the main feature of the design was the usage of active and passive linearly adjustable members to replace the structure of a conventional wing box.
At University of Southampton, UK, the design of spinal structures for the control of morphing airfoils was realized during a research grant ([5]); the aim was to find structures that, when suitably loaded, can alter the aerodynamic shape of a cladding that forms the airfoil.
Another morphing wing project was developed at Texas A&M University, where the aerodynamic models were validated using wind tunnel tests ([6]).
A collaborative research between the specialists from Beijing Institute of Technology, China, and from Cranfield University, UK, realized and tested a morphing wing integrated with a trailing edge control actuation system ([7]); the research results demonstrated that the morphing wing integrated with the flexible trailing edge control surface can improve aerodynamic characteristics.
An approach for optimal airfoil-morphing design based on a compact approach to describe the airfoil geometry coupled to a two-level optimization procedure was developed at Politecnico di Milano ([8]).
In Germany, at the Aerodynamics Institute, RWTH Aachen, an experimental model of an adaptive wing with an adjustable upper side over the entire chord was used in wind tunnel tests to show the possible improvement of the aerodynamic performance of wings at transonic speeds ([9]).
In trend with the morphing wing projects proposed and realized around the world, our research team from Research Laboratory in Active Controls, Avionics and Aeroservoelasticity (LARCASE) - École de Technologie Supérieure in Montreal, Canada developed a major research project called CRIAQ 7.1, in collaboration with Bombardier Aerospace, Thales Canada, École de Polytechnique and the Institute for Aerospace Research at the National Research Council Canada. The project main aim was to extend the laminarity of an airfoil by delaying the transition point. The experimental wing model was a rectangular one (0.5 m x 0.9 m), having two parts: 1) a metal fixed one, designed to sustain the wing loads; and 2) a morphing part, consisting of a flexible skin installed on the upper surface of the wing. The morphing part was actuated by two shape memory alloys actuators (SMA) to realize the

desired optimized airfoil shapes obtained in a preliminary aerodynamic study for thirty-five airflow conditions as combinations of seven angles of attack (between -1° and 2°) and five Mach numbers (between 0.2 and 0.3). Three control methods were designed to obtain and maintain the optimized airfoils during the experimental tests performed in the wind tunnel. For all experimentally tested control strategies and control algorithms bench tests and wind tunnel tests have shown that the morphing wing controller worked very well in real time. The proposed and tested control algorithms were based on various control techniques, classical or unconventional ([10]-[24]).
The work presented here exposes the implementation and the testing of the control system designed for a new morphing wing application developed by using an actuation mechanism based on some miniature electrical actuators.

2 RESEARCH PROJECT SHORT DESCRIPTION

The morphing wing application was actually related to an international multidisciplinary research project, implying specialists from Canada and Italy, with background in aerodynamics, aeroservoelasticity, mechanics, control and electrical engineering. Called "Multi-Disciplinary Optimization" 505 (MDO 505), this project aimed at fuel consumption optimization by applying morphing wing technology to a real aircraft wing equipped with an aileron ([25], [26]). In this research project, realized at Ecole de Technologie Supérieure in Montréal, Canada in collaboration with Thales, Bombardier Aerospace, École Polytechnique, IAR-CNRC, and also with italian researchers from Frederico II Naples University, CIRA and Alenia, a wing-aileron prototype (Fig. 1 [26], [27]) was designed, tested and validated using win tunnel tests at IAR-NRC.

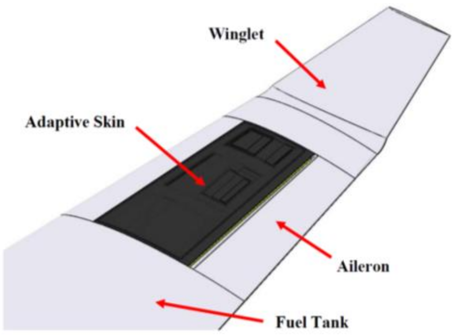


Figure 1: Structure of the wing

The structural stiffness of the morphing structure was determined via a specific numerical optimization routine. The aerodynamic team computed the optimized airfoils for different flight cases. The experimental model is based on a full-scaled portion of the wing of a real aircraft, having a maximum chord of 1.5 m, and a minimum one of 1.08 m. To morph the adaptive skin on the upper side of the wing four miniature electromechanical actuators were used (Fig. 2 [26], [27]); the four morphing actuators were in-house designed and manufactured. The design of the actuator started after having fixed the structural constraints of the flexible skin and the particular flight cases.

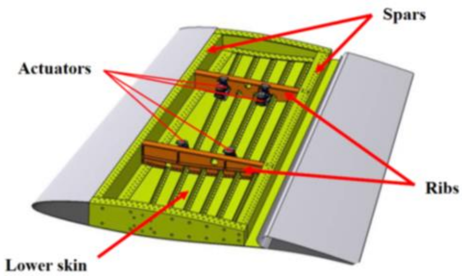


Figure 2: Structural elements of the developed model

To achieve the project purposes, two particular objectives were fixed for our research team (Research Laboratory in Active Controls, Avionics and Aeroservoelasticity (LARCASE) of the Ecole de Technologie Supérieure in Montréal, Canada): 1) to detect and visualize airflow characteristics using pressure sensors installed on the upper surface of the morphing wing; and 2) to develop a system for active

control of the morphing wing during flight to move the transition point from laminar to turbulent flow closer to the trailing edge, thereby promoting large laminar regions on the wing surface, and thus reducing drag over an operating range of flow conditions characterized by Mach number (M), angle of attack (α) and aileron deflection angle (δ) ([25], [26]).
The four designed actuators modify the flexible upper surface of the wing so that the upper flow is modified and consequently the transition point from laminar to turbulence is delayed. The flexible upper wing surface is closed to the wing tip, while the skin is made of composite materials. The first actuation line is located at 32% and the second actuation line is at 48% of the chord. The actuators are fixed on the wing ribs and the top is attached to the flexible skin with screws. A database that relates the actuator displacements and the optimized airfoils was tailored for different flight conditions ([25], [26]).
The actuator principle is similar to that of a conventional electromechanical actuator. It consists of a brushless direct current motor whose shaft is coupled to a gearing system. The other end of the gearing system is attached and linked to a nut. To maintain the optimized shape, the corresponding desired displacement has to be achieved by the actuator, even under the influence of external perturbations such as structural and aerodynamic loads. External perturbation rejection is accomplished with the help of a robust control logic based on the position control. According to aerodynamic principles, by using an aileron, there is an increase or decrease of the lift depending on the direction of the aileron deflection. To solidify the entire structure, the lower structure is made of aluminum and is designed to have the space for the actuation system, the strain gauge transducer, a Linear Variable Differential Transformer (LDVT) and its cabling system (Fig. 3).

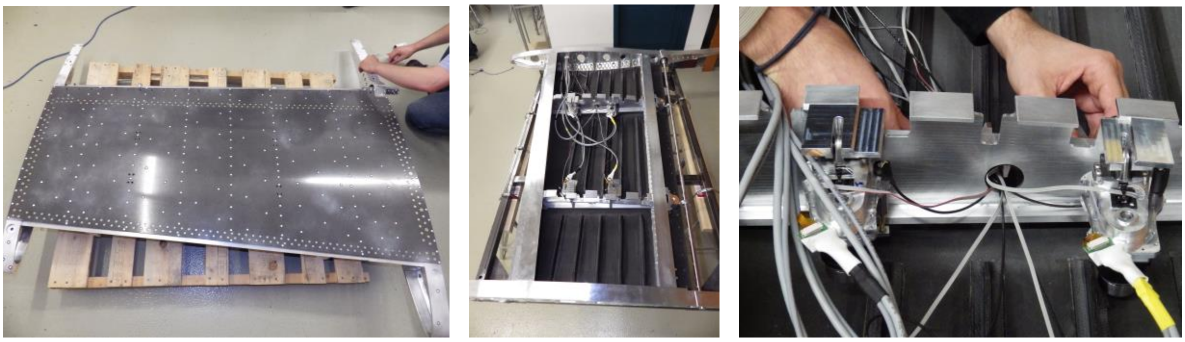


Figure 3: Experimental model of the morphing wing

3 CONTROL SISTEM IMPLEMENTATION

The control system purpose is to control the wing morphing system, and the aileron deflection angle. The actuation system was equipped with four identical actuators, requiring in this way the same position controllers. The control system was experimentally tested in two situations: 1) on the bench, with no aerodynamic load, and 2) in the wind tunnel, with aerodynamic load corresponding to each optimized flight case ([25], [26], [28], [29]).
The inputs of the control loop are the vertical displacements of the actuators associated to the optimized airfoil which corresponds to the airflow conditions. This optimized airfoil is requested by the operator to be reproduced by the flexible skin, being selected from the computer database through the graphic interface listbox and charged into the software. The software sends to the control loop the vertical coordinates, at the actuators lines level, required to reproduce the optimized airfoil. Therefore, for each flight case the control system asks to the actuators to morph the skin until the real vertical displacements dY_{real} in the actuation points equal the vertical deflections dY_{opt} characterizing the differences between the optimized airfoil and the reference airfoil; the real vertical deflections (the control feedback) is measured by using the four LVDT sensors associated with each of the four actuators. The testing of the control system in the wind tunnel allows also the validation of the numerically obtained optimized airfoils through the real time visualization of the transition point position based on the pressure sensors data ([25], [26], [28], [29]).
Beside the evaluation of the control loop performance, the bench testing of the control system given also the opportunity to evaluate of the level of reproducibility of the numerically optimized shape of the upper surface of the wing with the experimental obtained one. To verify this reproducibility, the morphed wing was laser-scanned for each optimized airfoil in the database (for all optimized flight

cases), and software results were compared with the numerical results in terms of skin shapes ([25], [28]).
The wind tunnel test, allowed, on the other way, the validation of the aerodynamic optimization of the system through the visualization of the transition point position for each optimized airfoil in the database (for all optimized flight cases). These visualizations are based on the information provided by 32 the pressure sensors installed on the flexible skin. As a supplementary evaluation method for the transition point position in wind tunnel tests, an infrared visualization of the flow was performed by using the IAR-NRC experimental facility ([25], [26], [28], [29]).
The bench testing of the experimental model was performed in the LARCASE laboratory at the ETS in Montréal, Canada; the scheme of the experimental bench test used to validate the implemented controller in the open loop is presented in Fig. 4 ([25], [28]).

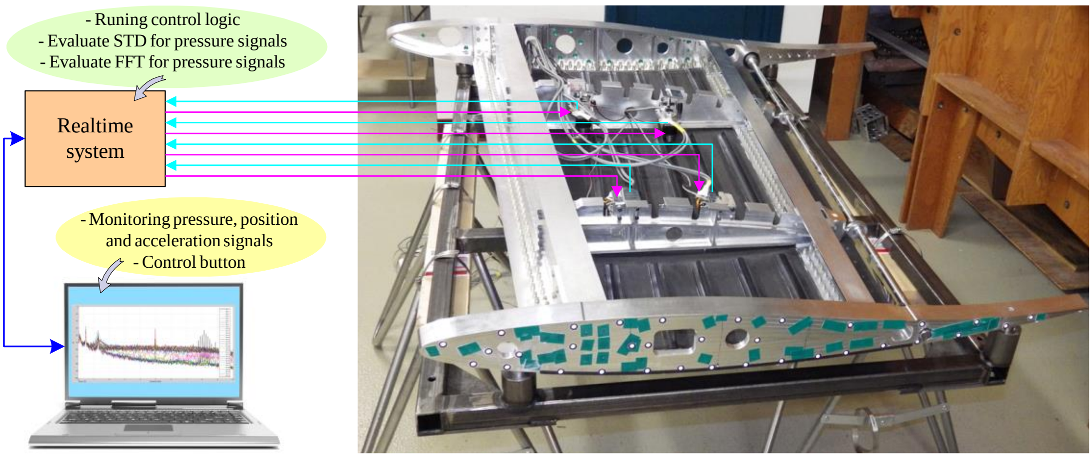


Figure 4: Control architecture in bench tests

In this control mechanism, the real-time system converts the desired vertical positions in motor rotation units and asks to the actuators to go to this positions (commands represented by the lines in magenta in Fig. 4), and obtains in the same time the feedback signals related to the real linear positions of the actuators by using the LVDT sensors data (signals represented by the cyan lines in Fig. 4) ([25], [28]).
The system interfacing the remote computer and the morphing wing experimental model was based on the architecture presented in Fig. 5; it was designed by using a National Instruments Real Time (RT) Target. The feedback for the control system of the morphing actuators was provided by four Linear Variable Differential Transformers (LVDT) used as position sensors and having axes parallel to the actuators axes ([26], [29]). The experimental instrumentation included ([26], [29]): 1) a NI PXIe-1078, 9-Slot 3U PXI Express Chassis; 2) a NI PXIe-8135 embedded controller; 3) four NI PXIe-4330 Data Acquisition Cards; 4) a NI PXI-8531, 1-Port CANopen Interface for PXI; 5) a NI PXIe-6356 Simultaneous X Series Data Acquisition Card; 6) a SCXI-1000 rugged, low-noise chassis that can hold up to four SCXI modules; 7) a NI SCXI-1540 8-Channel LVDT Input Module; 8) a NI SCXI-1315; 9) two Programmable power supplies Aim-TTi CPX400DP.

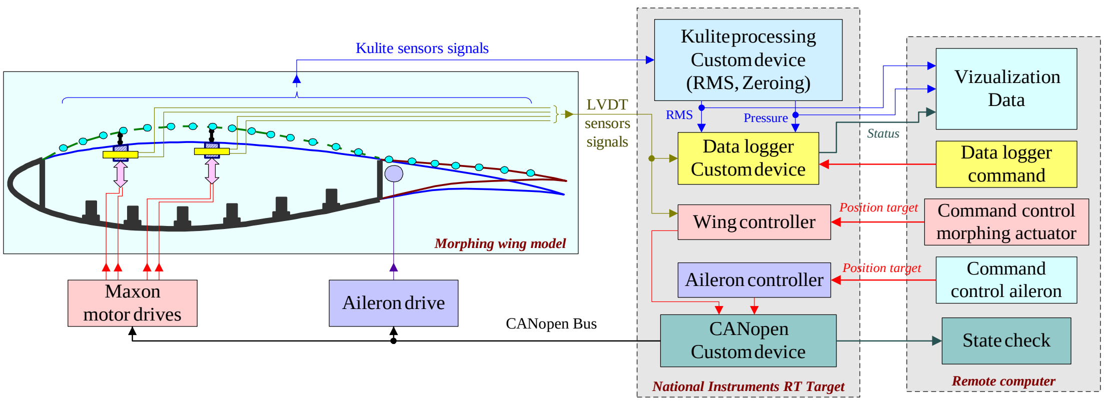


Figure 5: National Instruments RT target and remote computer configurations

The GUI used for the control system and data acquisition system in the wind tunnel tests is shown in Fig. 6 ([25]).

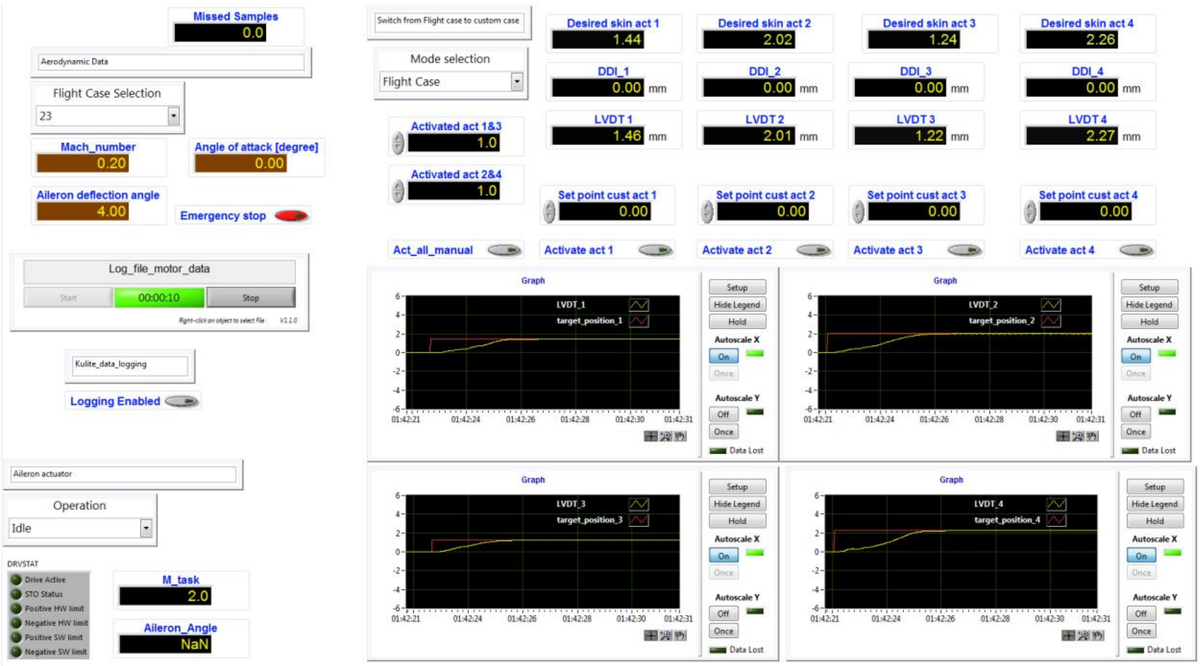


Figure 6: The Graphic User Interface (GUI) developed for wind tunnel tests

To develop the control system of the morphing wing actuators, among others tested architectures, a proportional fuzzy feedforward architecture was chosen for each of the four controllers; its architecture is shown in Fig. 7, wherein each actuator is coupled to a controller ([25], [28]).

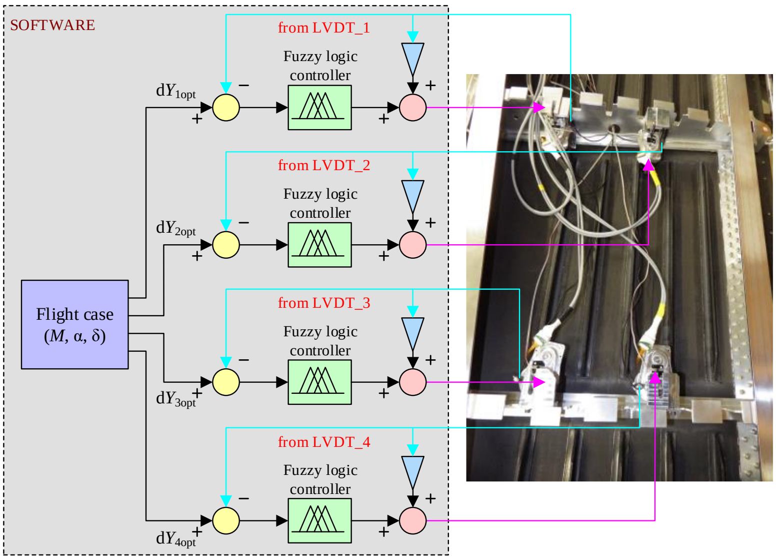


Figure 7: Control architecture of the morphing wing model

The controller’s input is the position error, and its output is the number of pulses required to reach the desired vertical position in millimetres. The controller’s output is sent directly to the motor integrated in the actuator. The developed control system includes four similar controllers, each one associated to an actuator. The designed controllers were tuned based on knowledge obtained from the system behaviour ([25], [28]).

In the bench tests the actuators were controlled simultaneous or independently to cover a large spectrum of interactions between them, the flexible skin and the rigid structure of the experimental model. All tests were performed in the laboratory conditions, in the absence of the aerodynamic forces ([25], [28]).

4 WIND TUNNEL TESTING OF THE MORPHING WING MODEL

The last test of the controlled experimental model was in the wind tunnel, the pressure signals being logged in parallel while the shape of the airfoil changed. Wind tunnel testing was performed at IAR-NRC wind tunnel facility in Ottawa. 32 pressure sensors were installed on the wing upper surface to sense the static pressure on the wing. They are located between 28% of the chord and 68% of the chord. Simultaneously with the control system characteristics monitoring by using the GUI in Fig. 6, the user visualized on a parallel screen the real time Fast Fourier Transforms (FFT) associated to the 32 Kulite pressure sensors equipping the upper surface flexible skin (Fig. 8). As a secondary method to evaluate the transition point position over the entire wing model surface for each tested flow case the infra-red (IR) thermography was used. In this way, visualizations with a Jenoptik Variocam camera were performed to measure the surface temperatures ([25], [26], [28], [29]).

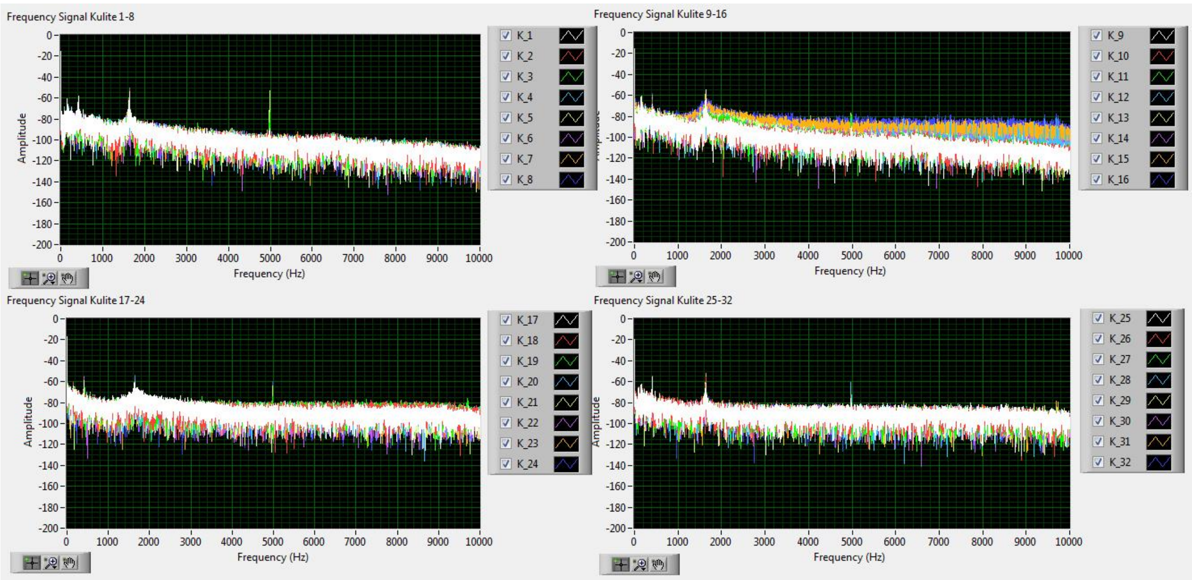


Figure 8: Fast Fourier Transforms (FFT) of pressure data for an acquisition sequence

For the flight case characterized by Mach=0.25, α=0.5° and δ=-1° resulted the actuation characteristics shown in Fig. 9. For all actuated cases it was found that the controller performed well, the static error being less than 0.1 millimetres. The measured positions for the four actuators were sensed by the LVDTs while the desired positions were loaded from the database made from the data predicted by the aerodynamic team.

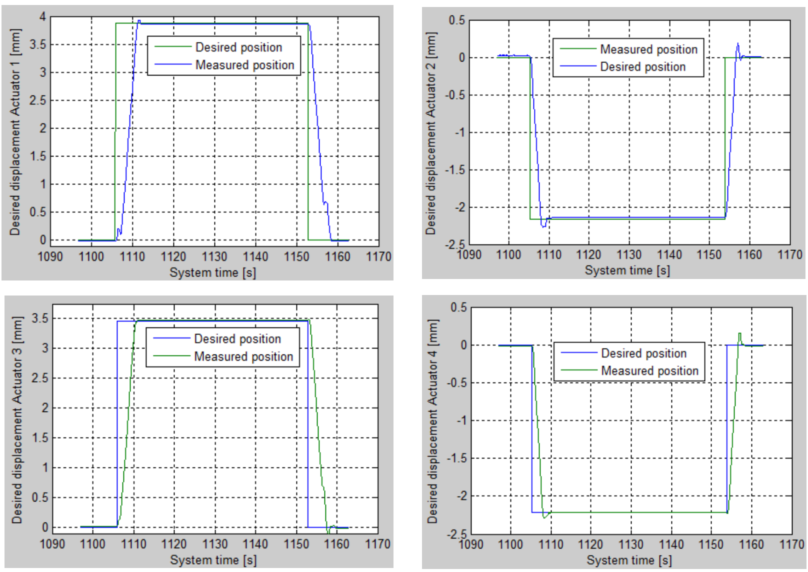


Figure 9: Wind tunnel controller results for flight case 38 (Mach=0.25, α=0.5°, δ=-1°)

To evaluate the aerodynamic gain of the morphing wing technology on the experimental model, the recorded pressure data during the wind tunnel tests were post processed in order to obtain the pressure coefficient distribution curve and the spectral repartition of the pressure. The transition region determined by the flow separation and characterized by the amplification of the Tollmien-Schlichting waves was captured by the Kulite pressure sensors. The same aerodynamic gain was also evaluated by using the infra-red thermography technique. The pressure data were recorded at 20 kHz rate, for both un-morphed and morphed airfoils in ninety-seven flow cases, and were analysed using Fast Fourier Transforms (FFT) decomposition to detect the magnitude of the noise in the surface air flow. Subsequently, the data were high pass filtered at 1 kHz and processed by calculating the standard deviation (STD) of the signal to obtain a plot diagram of the pressure fluctuations in the flow boundary layer ([25], [26], [28], [29]).

For the flow case associated to Mach=0.15, α=-2°, δ=-2°, Fig. 10 presents the STDs of the acquired pressure data both for un-morphed and morphed airfoils. It results that the transition for un-morphed airfoil begins on the pressure sensor #16 (placed at 50.79% of the wing chord), while for morphed airfoil it begins on the sensor #19 (placed at 53.45% of the chord). On the other way, the maximum value of the STD for un-morphed airfoil was associated with the sensor #20 (placed at 54.60% of the chord), while for morphed airfoil was associated with the sensor #22 (placed at 56.87% of the chord). In the same flow case, the FFT plots for the two airfoils (un-morphed and morphed) are shown in Fig. 11. The FFT associated to the un-morphed airfoil shows that the curve corresponding to the sensor #17 is easiest detached indicating the transition beginning. A more visible detachment appears at the level of the sensors #18 and #19, producing the transition to the upper FFT curves package. For the morphed airfoil, the FFT characteristics show that the transition begin on the sensor #20, the maximum influenced FFT curves corresponding to the sensors #21 to #23. As a consequence, the FFT and STD based conclusions are similar for this flow case, the laminar region being extended with over 3% of the chord in the Kulite sensors section.

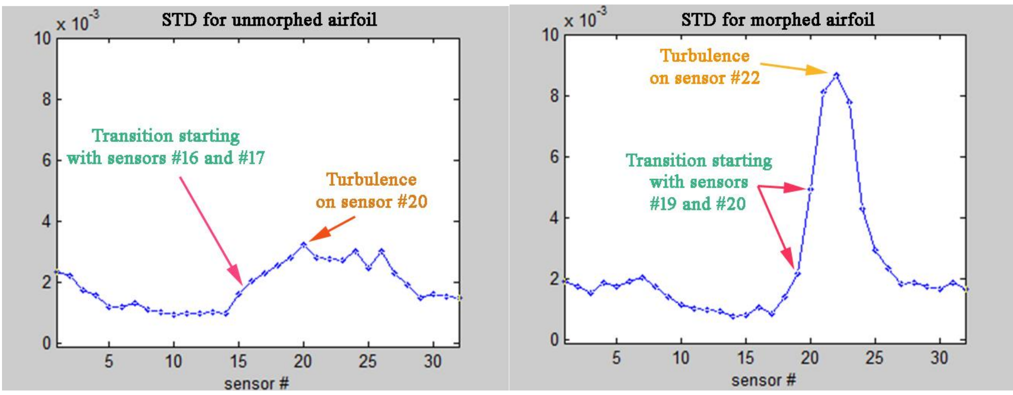
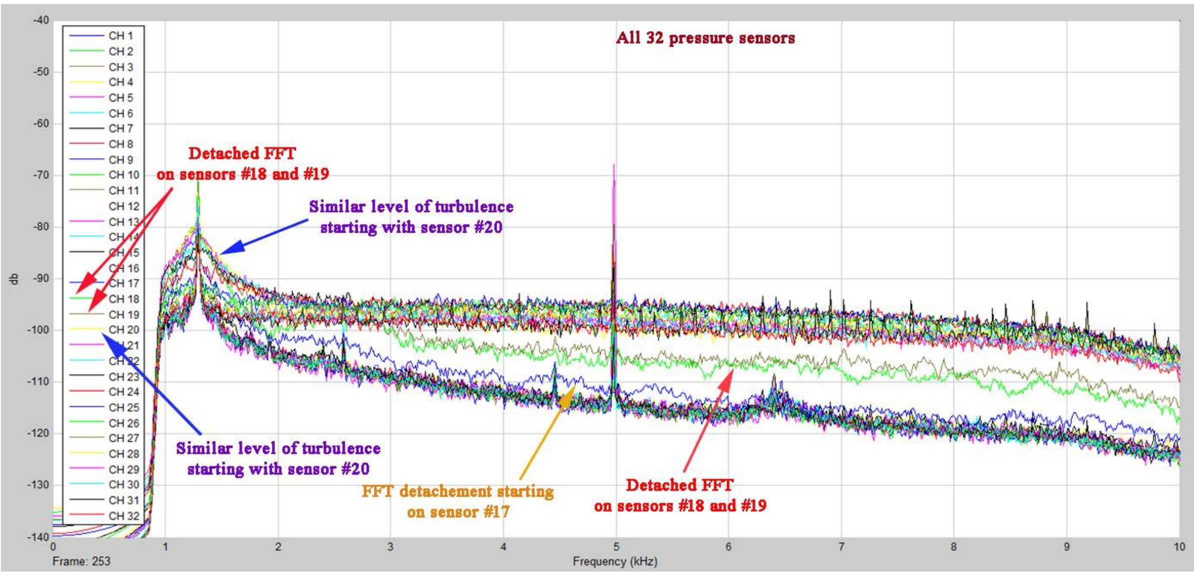


Figure 10: STD of the pressure data acquired for Mach=0.15, α=-2°, δ=-2° flow case



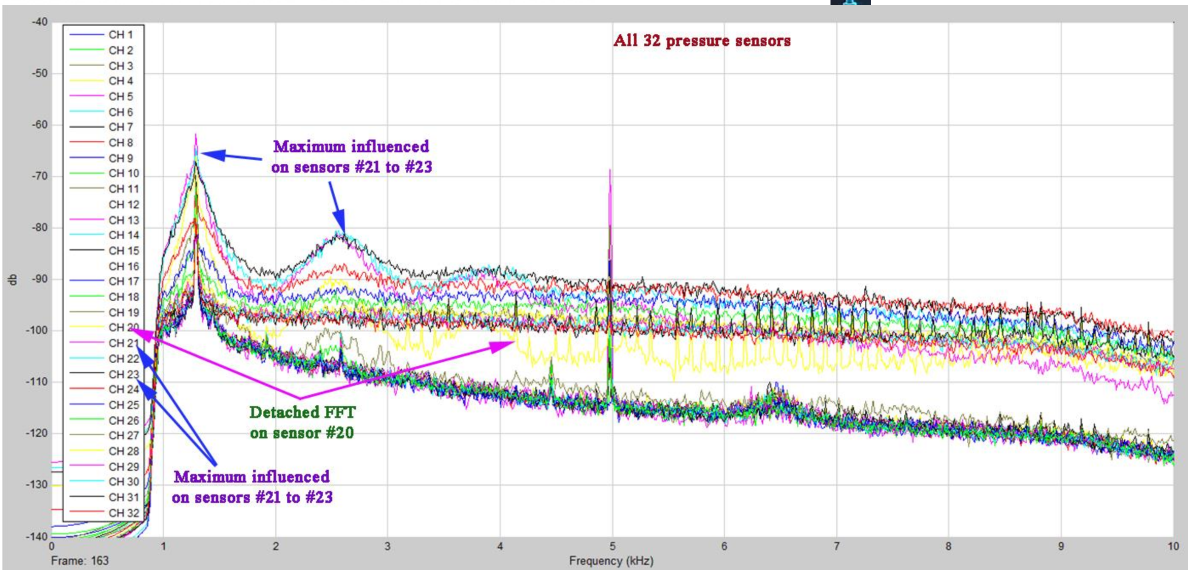


Figure 11: FFT of the pressure data acquired for Mach=0.15, α=-2˚, δ=-2˚ flow case

The infra-red thermography visualizations (from 0% to 70% of the chord) of the extrados for this flow case with and without any morphing applied are shown in Fig. 12. The wind blows from the left to the right, the blue region indicates the low-temperature area associated with the laminar flow, while the yellow region indicates the high temperature area associated with the turbulent flow. The transition area of the 3D-wing was averagely represented by the black line and delimited by the two white lines along the wing span. The IR average transition in this flow case was 53.18% of the chord for the un-morphed airfoil and 56.89% of the chord for the morphed airfoil. Therefore, according to the IR analysis, for this flow case the laminar region was extended with an average value of 3.71% of the chord by using the morphing wing technology.

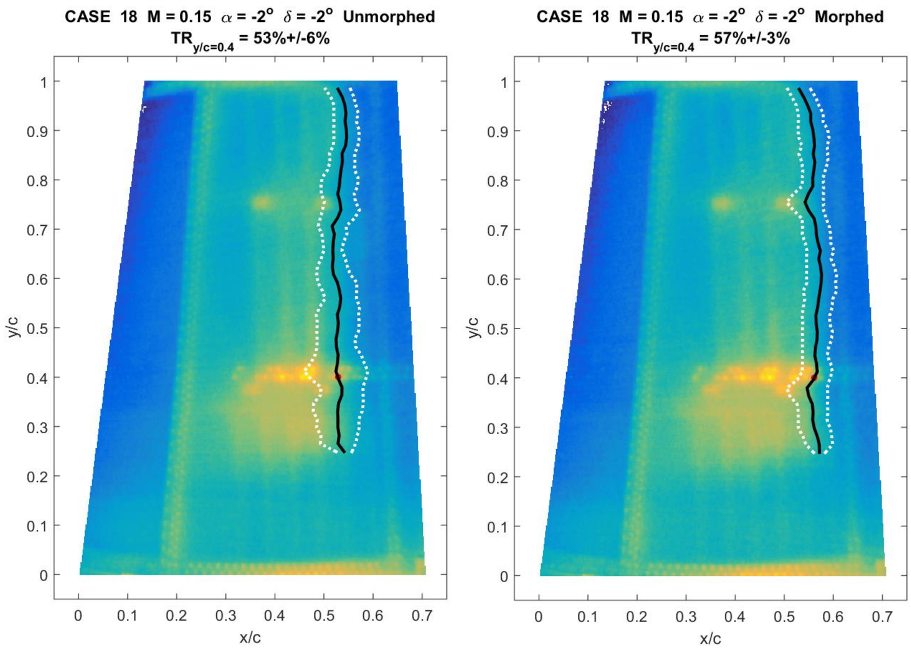


Figure 12: IR visualisation for Mach=0.15, α=-2˚, δ=-2˚ flow case

CONCLUSIONS

The paper exposed the implementation and testing results of a control system for a morphing wing application. The application was developed with a full-scaled portion of a real wing by a multidisciplinary team with experts from Canada and Italy. The controlled actuation system was based on four miniaturized electrical actuators designed, manufactured and integrated in the wing by the project team. In the development phase of the control system of the morphing wing actuators many variants have been tested. The current paper presented a proportional fuzzy feedforward architecture which was chosen for each of the four controllers used in the control mechanism. The system interfacing the remote computer and the morphing wing experimental model was designed by using a National Instruments Real Time (RT) Target. The feedback for the control system of the morphing actuators was provided by four Linear Variable Differential Transformers (LVDT) used as position sensors and having axes parallel to the actuators axes. The testing of this control architecture provided very good results both during the bench tests, with no aerodynamic load, and during the wind tunnel test. For all tested flight cases the static error was less than 0.1 mm and the overshoot less than 5% of the static values. The wind tunnel tests evaluated also the aerodynamic gain of the controlled morphing wing by using two techniques to detect the laminar to turbulent transition region over the wing upper surface: processing pressure data collected from Kulite pressure sensors mounted on the flexible skin of the wing and the infra-red thermography technique. For the wind tunnel test exposed here, the FFT and STD methods based on pressure data shown that the laminar region has been extended with over 3% of the chord in the Kulite sensors section. On the other way, the IR analysis shown that the laminar region was extended with an average value of 3.71% of the chord by using the morphing wing technology. The experimentally obtained results confirmed the feasibility of the morphing wing technology, and, having in mind that our project used a real wing structure, create the premises for a future application of this technology on real aircrafts.

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