Morphing Wing, UAV and Aircraft Multidisciplinary Studies at the Laboratory of Applied Research in Active Controls, Avionics and AeroServoElasticity LARCASE

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Several large-scale projects were carried out at the LARCASE at ÉTS in numerical studies and experimental tests for morphing aircraft using three equipments. In this article, these projects are explained. First, two projects have been carried out at LARCASE on morphing wing studies in collaboration with industrial and research institutes teams. The first project was carried out in collaboration with aerospace companies, such as Bombardier Aerospace, Thales Canada, the Institute of Aerospace Research – National Research Council of Canada IAR-NRC, and École Polytechnique. The second project was carried out internationally as it took place with the same Canadian partners as those involved in the first project, but it also took place in collaboration with Italian partners of Alenia, CIRA and University of Naples – Frederico II. In these two projects, two morphing wings were designed, and then manufactured and equipped with several actuators and pressure sensors. These morphing wings designed to improve their aerodynamic performance were then tested in the IAR-NRC wind tunnel. The LARCASE Price-Païdoussis wind tunnel was used for the design and experimental testing of the ATR-42 model aircraft morphing wing models. Numerical results have been obtained following morphing studies of autonomous aerial systems UAS-S4 or S-45. Other morphing type concepts were also applied to the wings and horizontal tail of the Cessna Citation X business aircraft in order to reduce fuel consumption and flight distance.

Introduction

Research programs have been launched, and continue to be conducted in Europe (such as Clean Sky, CleanSky2, Smart Intelligent Aircraft Structures SARISTU [1] - [7]), Canada (the Green Aviation Research and Development Business-Led Network of Centres of Excellence (GARDN BL-NCE), Japan, USA with the aim to achieve the most efficient green aircraft technologies possible in terms of minimum fuel or bio-fuel consumption, lower emissions, reduced noise, etc.

The LARCASE at the ETS is equipped with the following three major research equipments shown in Figure 1: 1. the Price-Païdoussis subsonic blown wind tunnel from McGill University (on the upper left hand side of Figure 1), 2. the Research Aircraft Flight Simulator (RAFS) for the Cessna Citation X business aircraft from CAE Inc. (on the upper right hand side of Figure 1), and 3. the Research Aerial System (RAS) from Hydra Technologies (on the bottom side of Figure 1). These equipments were and continue to be used in the morphing aircraft numerical and experimental research. The LARCASE website can be consulted at https://en.etsmtl.ca/Unites-de-recherche/LARCASE/Accueil?lang=en-CA.

The Price-Païdoussis subsonic blow down wind tunnel is powered by a 40 HP, 67 Amps electrical engine, from North Western Electric Co. and is fitted with a double impeller centrifugal fan. The test chambers

Figure 1 – Illustration of the LARCASE equipment

are manufactured from wood, with Plexiglas removable doors on each side, for greater accessibility to the models installed inside. The biggest test chamber has dimensions of 0.62 x 0.91 x 1.83 m (H x W x L), and the maximum speed that can be obtained is of 40 m/s, equivalent to a Mach number of 0.12, with a maximum Reynolds number of 2.4 million. The smallest of the two test chambers has the dimensions of 0.31 x 0.61 x 1.22 m (H x W x L), and the maximum speed is of 61 m/s. equivalent to a Mach number of 0.18 at a Reynolds number of 3.5 million. Reynolds numbers were calculated using a chord of 0.8 m, which is the maximum chord that a model can have, in order to be tested in either of these two test chambers. The wind tunnel's turbulence level is approximately 0.3, that corresponds to a critical amplification factor of 5.5 for the XFoil solver analysis.

The second equipment is the Research Aircraft Flight Simulator (RAFS) that was designed and manufactured by the well-known aircraft modeling and simulation company CAE Inc. for the research needs of the LARCASE. The RAFS is equipped with the highest level of certification D flight dynamics toolbox for the Cessna Citation X business aircraft. The RAFS and the third equipment UAS-S4 were both acquired with research funds from the MDEIE and NSERC.

The third equipment is called the Research Aerial System (RAS), and is composed of an Unmanned Aerial Vehicle (UAV) aircraft, an UAV airframe/trainer aircraft, a fully portable ground control station, autopilot hardware and software and a replacement parts kit. The RAS is in fact a modified version of an existing manufactured UAS-S4 called God of Winds. The RAS has an approximate fuselage length of 9.84 ft and a wingspan of 14.76 ft. It may fly at a maximum speed of 90 knots at an altitude of 15,000 ft, and has a maximum take-off weight of 132 lbs. Hydra Technologies, a private Mexican company specialized in the development of unmanned aerial systems for military, police and civil applications, has built the RAS accordingly to the research needs of the LARCASE.

Different major projects took place at the LARCASE in the area of morphing aircraft numerical and experimental studies by use of the three equipments above mentioned. In this paper, these projects will be explained. Firstly, two major projects took place at the LARCASE at the ETS on morphing wing studies in collaboration with industrial and research institutes partners since 2016. The first project took place in collaboration with teams from major Aerospace companies: Bombardier Aerospace, Thales Canada, the Institute of Aerospace Research – National Research Council of Canada IAR-NRC, École Polytechnique. The second project was international as it took place with same partners as the ones mentioned in the first project, but in addition, took place in collaboration with Italian partners from Alenia, CIRA and Federico II – University of Naples. In both projects, two different morphing wings were equipped with various actuators and pressure sensors. These wings were designed, manufactured, and further they were tested using experimental wind tunnel tests at the IAR-NRC with the aim to improve their aerodynamic performances.

In the frame of the Canada Research Chair in Aircraft Modeling and Simulation Technologies, other projects took place. For example, the Price-Païdoussis subsonic blow down wind tunnel was used for design, manufacturing and testing of reduced scale morphing wing models, such as the ATR-42 model. At this time, numerical results were obtained for other reduced wing scale models of the UAS-S4 or S-45. In addition, morphing concepts were applied also on the Cessna Citation X business aircraft wing and horizontal stabilizer with the aim to reduce fuel consumption and the distance.

Explanation of projects at the LARCASE

As mentioned in the Introduction, the LARCASE is equipped with 3 infrastructures shown in Figure 1 and explained above. All these equipments are used for the morphing wing technologies development projects explained next.

Project 1. CRIAQ 7.1 – Laminar flow improvement on an aeroelastic research wing (Morphing Wing equipped with Smart Material Actuators and Pressure Sensors)

In this project, presented in [8], the analyzed wing had its dimensions of 0.5 m x 0.9 m, and its reference airfoil was chosen to be that of a laminar Wing Trailing Edge Airfoil (WTEA). The aerodynamic characteristics and performance were analyzed in transonic regime in a previous project and published (Khalid 1993; Khalid and Jones 1993). Three different teams worked on this project in the areas of aerodynamics, structures and controls. The project took place during a period of three years: 1. design, 2. manufacturing, 3. wind tunnel testing.

During the first year period, the aerodynamics and structures teams worked together to find the optimized shapes of the wing airfoil for aerodynamic performance improvement, thus for flow transition towards the airfoil trailing edge. The reference airfoil modified its shape for different flow cases in two specific points of actuation located at 25.3% and 47.6% of the chord with respect to the leading edge of the airfoil. These flow cases were expressed by 7 angles of attack between -1°and 2°, and five Mach numbers, between 0.2 and 0.3, thus 35 optimized airfoils were defined [9]. As shown in Figure 2, the morphing wing consisted of two main parts: 1. one fixed part and 2. one morphing part. The morphing part was manufactured from a flexible skin that was installed on the wing upper surface, and was equipped with two lines of nickel-titanium shape memory alloys actuators (SMA) that were located at the positions mentioned above, at 25.3% and 47.6% of the chord. The flexible skin had a thickness of 1.3 mm, a Young modulus of

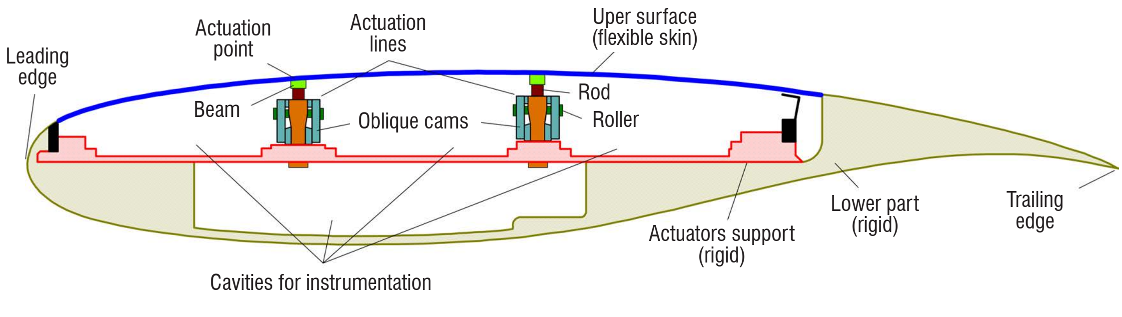

Figure 2 – Morphing wing model – cross section

60 GPa and the Poisson's ratios of 0.12 for the carbon/Kevlar® hybrid and 0.25 for the unidirectional carbon [10].

The horizontal motion that took place along the wing span was converted by the actuation system into vertical motion that was perpendicular to the chord. Therefore, as shown in Figure 3, the actuation system comprised two oblique cams with sliding rods, span-wise positioned.

Each actuator could move up or down with a certain distance smaller than 8 mm with respect to its original position in order to obtain each one of the 35 optimized airfoils. This actuation distance for each airfoil (obtained in two points) was given by the mechanical equilibrium between the SMA wires and the gas springs; the SMAs pulled the sliding rod in one direction, while the gas pulled the springs in the opposite direction. Three parallel SMA wires were connected to a power supply, and thus used to actuate each sliding rod.

The morphing wing control system has an open loop, and a closed loop architecture. In the open loop, the SMA system of actuation was controlled, while in the closed loop, the open loop architecture was included as an internal loop, and the transition region was controlled based on the 32 pressure sensors measurements. These 32 pressure sensors were actually of two types: optical and kulite sensors, and they were of course installed on the upper surface morphing wing skin with the aim to measure the pressures on the morphing wing. In fact, the flow transition was detected at frequencies between 3 kHz and 5 kHz by kulite sensors while the optical sensors were unable to detect it [10]. The Root Mean Square (RMS) method was used to visualize the transition from the laminar to turbulent flow because of the fact that is based on the pressure fluctuation increase in turbulent flow, while in the laminar flow they are of the order of 5e-4 Pa. The occurrence of a spike in the RMS plot in the array of sensors indicates the occurrence of the turbulence in that sensor location, and thus in the location of the transition between that sensor and the previous one in the array.

A second method to measure the flow transition used infrared measurements instead of pressure sensors measurements. An example of transition flow measurement is shown for one optimized airfoil with respect to the reference airfoil for one of the 35 flow cases, and is expressed in change of colours as seen on Figures 4.a, and 4.b. While the flow transition was found at the location of 26% of the chord (x/c = 26%) for the reference airfoil (Figure 4.a), the flow transition was found for the optimized airfoil at the x/c = 58%; thus, the transition was moved by up to 32% of the chord over the reference case for the optimized airfoil (Figure 4.b).

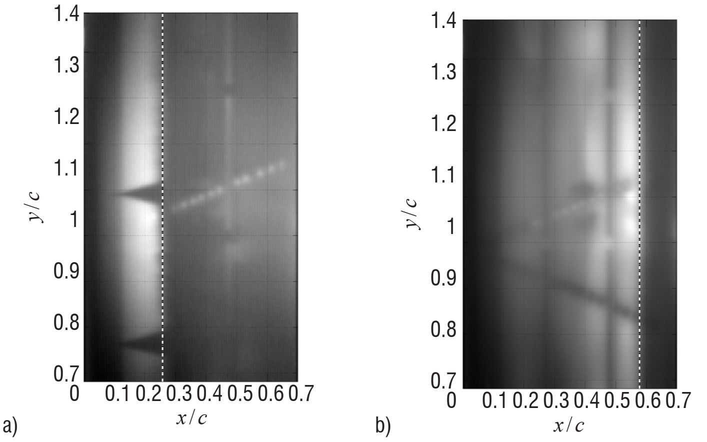

Figure 4 – Infrared results obtained at $M = 0.25$ and $\alpha = 0.5$ deg in a) reference, and b) after optimization

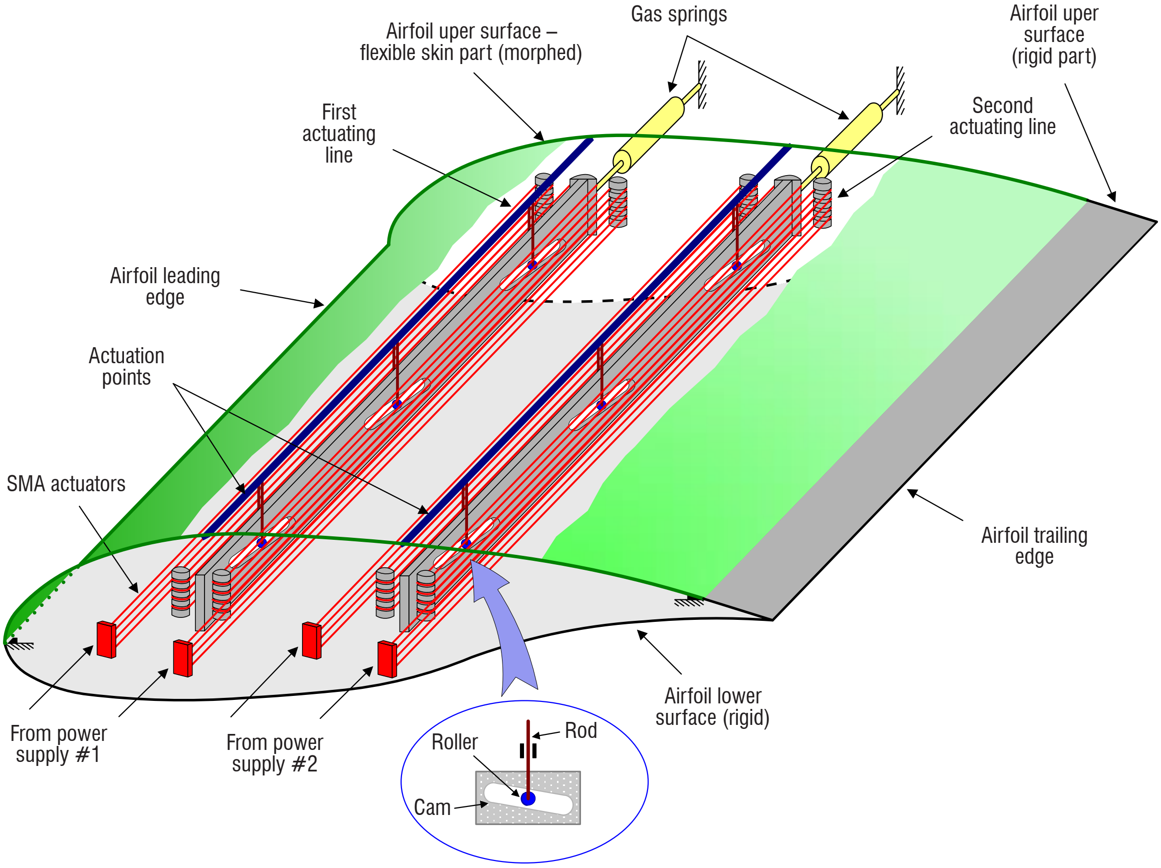

Figure 3 – Actuation system of the morphing wing

The same types of results were obtained for all the other 34 cases corresponding to optimized airfoils in terms of transition location moving closer to the airfoil trailing edge by a maximum of 40% of the chord. This transition delay will result evidently in drag, and thus, in fuel consumption reduction ([9], [11]-[14]).

Numerical simulations, bench tests and wind tunnel tests were performed to design, improve and validate experimentally the morphing wing control system ([11]-[19]). A high number of control methodologies were developed and applied in this project for the open loop and closed loop, based on Adaptive Neuro-Fuzzy Inference System ANFIS ([19]), Hybrid Fuzzy Logic Proportional Integral Derivative and Conventional On-Off Controller ([17],[18]), On-Off and Proportional-Integral Controller ([15],[16]), and Real Time Optimization ([9]). The aeroelastic analysis of the flexible wing upper skin was performed using MSC/Nastran software. This analysis showed that flutter has occurred at the Mach number of 0.55 higher than the Mach number of 0.3, the maximum Mach number allowed in the IAR-NRC wind tunnel. For this reason, the wind tunnel tests were performed safely [20].

The smart material actuators had low frequencies and high operating temperatures which make them difficult to be considered for their implementation on an aircraft ([15]-[19], ([21],[22]). For this reason, the Canadian industrial teams from Bombardier and Thales have launched a second major project at the LARCASE in which electrical actuators were considered instead of smart material actuators; the electrical actuators can be implemented on aircraft as they do not present the disadvantages of the smart material actuators.

Project 2. CRIAQ MDO 505 - Morphing architectures and related technologies for wing efficiency improvement

While in project 1, a morphing wing box concept was developed, in project 2, an existing aircraft wing-tip was developed with the aim to increase the Technical Readiness Level (TRL) of such type of device. Both multidisciplinary projects 1 and 2 required interactions between aerodynamic, structural and controls teams. The full-size wing-tip structure was formed by a morphing wing and two types of ailerons: a conventional rigid aileron and a morphing aileron.

The full-scale morphing wing model had a span of 1.5 m and a root chord of 1.5 m, a taper ratio of 0.72, and leading and trailing edges sweep angles of 8°. The chord distribution of the wing model followed the distribution of the wing-tip section, while the sweep angle and the span-wise twist distribution were modified in order to reduce the 3D flow effects. The wing box and its internal structure (spars, ribs, and lower skin) were manufactured from aluminum alloy, while the adaptive upper surface, which was located between 20% and 65% of the wing chord, was manufactured from carbon fibre composite materials.

The upper skin shape morphing, driven by actuators placed inside the wing box structure was a function of the flight condition (defined in terms of Mach number, Reynolds number and angle of attack). These actuators were specifically designed and manufactured in-house to meet the project requirements. Four electrical actuators were installed on two actuation lines; two actuators each, placed at 37% and 75% of the wing span, were fixed to the ribs and to the composite skin. Each actuator has the ability to operate independently from the others, and has a displacement range between ± 3.5 mm. On each actuation line, the actuators were positioned at 32% and 48% of the local wing chord.

The aileron hinge articulation was located at 72% of the chord. As mentioned above, two ailerons were designed and manufactured. One aileron was structurally rigid, while the other one represented a new morphing aileron concept. Both ailerons were designed to be attached to the same hinge axis of the wing box, and both were able to undergo a controlled deflection between -7° and +7°. This interval was more restricted than the normal deflection range of an aileron, but it was considered sufficient to demonstrate the proof of concept for the morphing aileron. This restriction was determined by the available space inside the NRC wind tunnel and by the load limits of the wind tunnel balance.

The aerodynamic objectives of the optimized shapes of the upper surface of the morphing wing and the rigid aileron assembly were to delay the onset of the flow transition region, and to reduce the drag coefficients. The objectives of the optimized shapes of the upper surface of the morphing wing and the morphing aileron had the aim to improve the lift coefficient, and thus the behavior of the boundary layer.

The optimized shapes were found through a 2D (airfoil) aerodynamic analysis because of the fact that in the beginning of the project bi-dimensional characteristics of the flow were expected to occur in the morphing upper surface skin of the wing located between the central ribs. The skin was clamped on all sides of the wing, and had the dimensions of 60 cm along the span and 55 cm along the chord; the first actuation line was installed at 56 cm from the wing root, while the second actuation line was installed at approximately 117 cm from the root.

An in-house Genetic Algorithm GA was developed as function of morphing wing structure and aileron (rigid and morphing) constraints or requirements with the aim to obtain the optimized airfoils. Following the comparison of the results obtained with the GA with the results obtained with both the Artificial Bee Colony (ABC) algorithms and the Gradient Method, the GA was selected due to the fact that results were better. Then, a coupling of the GA with a cubic spline reconstruction routine and the 2D XFoil solver was done in order to evaluate the model aerodynamic performances. Thus, optimized airfoils were obtained for a high number of different airspeeds (Mach numbers), angles of attack and aileron deflection angles. The results showed a flow transition onset improved by up to 10% of the chord, a lift improvement by up to 50% on average, and a maximum of 70% by using a morphing aileron ([23],[24]).

In addition to the 2D analysis, a 3D analysis was performed using ANSYS Fluent after establishing the wind tunnel matrix cases with the aim to compare the 2D with the 3D results. The analysis used the numerical wing for the first analyses, and after the first set of wind tunnel tests, its scanned shapes were used, and so on. Following the comparison of the 2D with 3D results, it was found that the transition region was over-estimated by XFoil (2D) solver with 2-3% of the chord [25].

A delay of the flow transition from the laminar to the turbulent state of up to 5% of the chord was found experimentally during wind tunnel tests, which resulted in drag reduction by up to 2%. In addition, drag reduction was found also where transition was not observed.

An example is the over-estimation of the transition region by the numerical optimization for almost all cases (146 cases for all three sets of wind tunnel tests).

The experimental pressures measured by kulite sensors had the same values as the numerically-calculated pressures by XFoil or ANSYS solvers, and the aerodynamic performances were therefore improved.

The design and manufacturing of the composite upper surface of the morphing wing, of the rigid and morphing ailerons was one of the structural work objectives. This composite skin had specific elastic properties on its both chord and span directions, which ensured the flexibility needed by the morphing upper surface, while respecting the design, manufacturing and structural requirements demanded by the industrial partners. Another achieved objective was closely related to the design, manufacturing and testing of the internal morphing system. This system included actuators and sensors needed for the structural bench testing, and for the wind tunnel tests ([26], [27], [31]).

The structural and the aerodynamic teams needed to interact closely during the project for the design, and mainly for the optimization of the morphing skin. The optimization gave the number, thickness and distribution of plies/fibres that were chosen for the composite morphing skin modeling. The main result of this optimization was quantified in terms of the composite skin flexibility that was tested through morphing by both structural and controls teams. Therefore, control bench testing was performed at the LARCASE in the absence of the wing to ensure obtaining the morphed required shapes.

In addition, 1 g loads tests were performed to test the behavior of the wing under static conditions. These 1 g loads corresponded to in-flight loadings that a wing structure would encounter, and allowed the observation of the static behaviour of the actively morphing wing under loading; the 1 g load tests were successful, as the wing tip structure passed these tests under both morphed and un-morphed conditions. The scans performed during the tests have shown that no bending deformations were detected beyond the ones considered as expected and safe.

The wing-tip internal and external structure were slightly modified to accommodate the actuation and pressure sensors systems, and to correspond to the wind tunnel dimensions. The maximum dimensions of the wing model were determined also as function of the length, width and height of the wind tunnel. Since the wind tunnel chamber dimensions were fixed, if there were any inconsistencies between the wind tunnel and the model, then the model was designed to fit within the wind tunnel dimensions. Any modification of the geometry was slight, not something radical or necessary visible in any way. The wing tip was manufactured at the IAR-NRC in Ottawa. For the wing manufacturing, the requirements regarding the precision of manufacturing techniques were provided by Bombardier.

Furthermore, the optimization of the upper surface composite skin led to a gain of approximately 2 kg on the total wing tip weight (without the actuation system installed). Overall, the wing tip equipped with the composite upper surface, internal actuation system and aileron had its weight similar to the original base aluminium wing tip. The fully equipped morphing wing without aileron weighted approximately 60 kg, while the aileron weighted approximately 18 kg.

In addition, due to the displacements and forces requirements, the actuation system was developed (design and manufacturing) from the beginning of the project. In the beginning of the project, the actuators displacements were set at +/- 10 mm. After performance of preliminary analyses, the displacements were lowered to 5 mm in order to reduce the forces needed to displace the skin. Finally, the requirements for the actuators were: to have a displacement of +/- 5 mm (a total of 10 mm), to develop forces of up to 2,000 N and to have dimensions that would allow them to fit inside the wing box. In project 1, the actuators have the maximum displacements of +/- 8 mm. An analysis of the "off-the-shelf" actuator market has shown that this type of actuator was not on the market ([28],[29]).

Therefore, four electrical actuators were designed and manufactured in-house at the ETS, and they have met the constraints of size, displacements, forces and safety as required by the project team. The displacement targets resulted from the aerodynamic optimization, and the associated force magnitudes resulted from the structural analysis of the wing with its upper surface morphed with the maximum allowed displacements.

The maximum values of the actuators displacements were chosen in the beginning of the project (the 10 mm values) following aerodynamic optimization, and the subsequent values (smaller than 10 mm) were established by structural analysis and manufactured wing capabilities. Therefore, since the actuators had to respect security requirements, the values determined by the structural analysis were considered as the maximum allowed displacements.

A rigid aileron was also designed and manufactured by the NRC team. The aileron met the constraints set by Bombardier, and was activated by using an external actuation system. The external actuator was mounted on the wing's mounting block. This actuator was constrained to perform limited deflections, between 7 degrees down and 7 degrees up with a step of 1 degree, because of the limited available space inside the wind tunnel testing chamber.

From control systems point of view, the objectives were the design and implementation of an integrated control system that connected the wing tip pressure sensors, electrical actuators and aileron external actuator. The control system was developed using the data calculated from the aerodynamic optimization. The control system developed during this project respected all the constraints for safety and certification requirements demanded by the Thales Canada team.

The control system implemented four (4) interchangeable controllers for the actuator displacements control. The four controllers were based on Proportional Integral Derivative (PID), Fuzzy-Logic and Neural Network control algorithms. All these controllers used both external and internal data from the skin and the actuators to calibrate the system to the desired precision of 0.2 mm. Scans performed at the NRC and LARCASE wind tunnel facilities after each wind tunnel test showed that the controllers achieved the desired actuators displacements and their precisions for each studied flight case.

The main controller (part of the integrated communication and control system) was developed as a PID controller, as per Thales Canada recommendations. The integration of controllers on the whole National Instruments (NI) system was a step forward to an embedded system for morphing wing as required by Thales. Therefore, the control and communication systems were developed following Thales requirements, and in collaboration with NI, that pushed the high morphing technology to a high TRL. In addition, different other linear and nonlinear algorithms were developed (as mentioned at the ETS previously) to analyze the obtained results – for comparison purposes, and they were integrated also on the NI system.

It is also important to understand that the controller has to operate in wind tunnel conditions so it needed to be robust, easy, automatic and safe to manipulate. The controller had to solve (minimize or eliminate) the uncertainties of all other disciplines. The controllers were tested in wind tunnel, and on a wing model based on a real aircraft wing tip. The results obtained by different methodologies, and their performance were compared with those obtained by the PID controller.

The controllers and the full control system were bench tested using an aluminium skin in the design phase, and a composite skin (identical to the one installed on the wing tip demonstrator) in the final phases of the design and development of the morphing wing. For the development of the control system, "off-the-shelf" and "user-defined" designed parts were used, as well as commercial and "in-house" software.

The control system was validated using the wind tunnel tests results, which showed that it was fast, reliable and robust. The precision of the controllers was validated with static high precision scans of the upper-surface composite skin after each of the three sets of wind tunnel tests. Figure 5 and Figure 6 show the morphing upper surface and ailerons integration that can achieve the desired shapes obtained during numerical optimization. No winglet is considered in this project.

From the point of view of the morphing aileron system, the objective was the design, manufacture and testing of an aileron capable of changing its shape while deflecting with certain angles in order to improve the lift performances of the wing. The morphing aileron had to respect geometrical and deflection requirements. The deflection angles were provided by the Canadian team along with the aileron shapes to the Italian team. The Italian team developed an aileron that respected the geometrical and wing box installation requirements, and this aileron was capable of morphing during tests ([30], [32]).

Figure 7 presents the morphing wing model concept as it was mounted and tested in the NRC subsonic wind tunnel. Figure 8 presents an overview of the morphing wing control system. The wing was equipped with 32 kulite pressure sensors installed on two parallel staggered lines at 60 cm from the root of the wing. Three accelerometers were installed on the wing: on the wing box, aileron and balance shaft, for safety purposes, by monitoring the vibration behaviour of

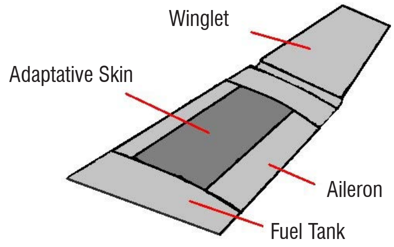

Figure 5 – The layout of the morphing skin on the aircraft wing

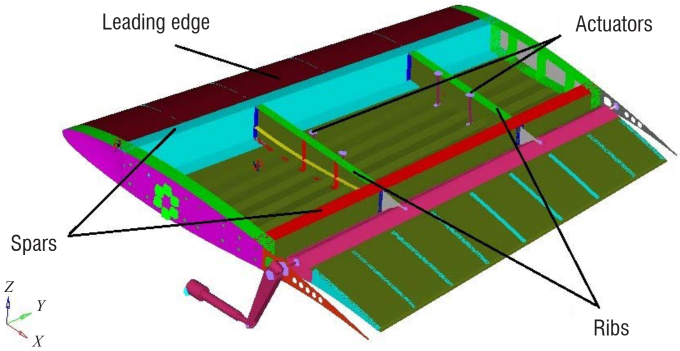

Figure 6 – The structural elements of the CRIAQ MDO 505 morphing wing box (the morphing skin is not shown in the figure)

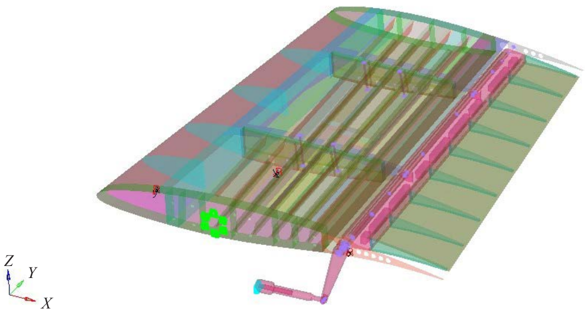

Figure 7 – CRIAQ MDO 505 morphing wing model

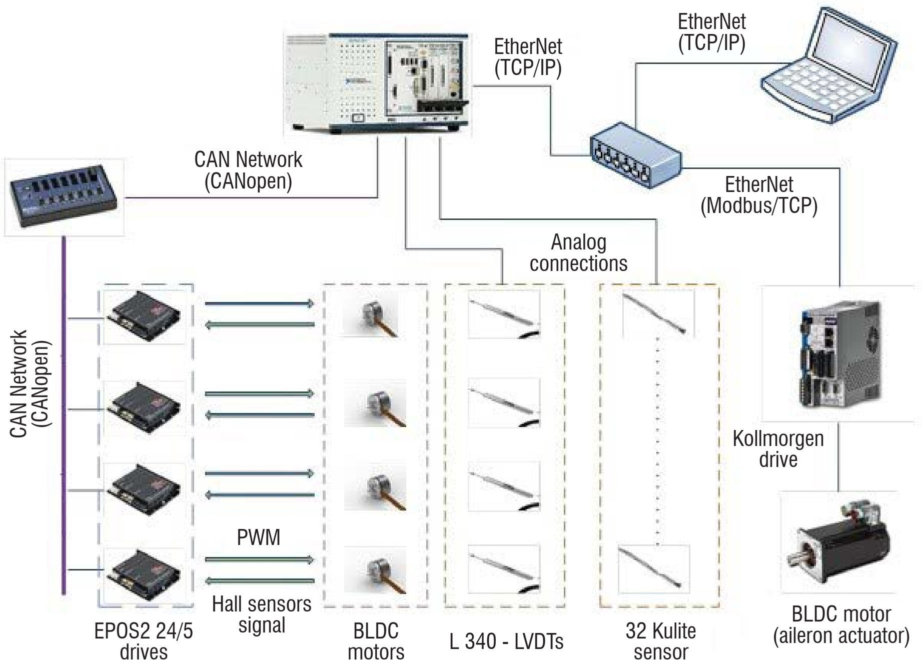

Figure 8 – Overview of the morphing wing control system

the wing during wind tunnel tests. The wing tip was manufactured, and complied with the technological requirements demanded by the industrial partners. Aeroelastic studies were performed in [27]. In this reference, two finite element models are analyzed; the first model corresponds to a traditional aluminium upper surface skin of constant thickness and the second model corresponds to a composite optimized upper surface skin for morphing capabilities. The two models were analyzed for flutter occurrence, and effects on the aeroelastic behaviour of the wing were studied by replacing the aluminium upper surface skin of the wing with a specially developed composite version. The morphing wing model with composite upper surface was manufactured and fitted with three accelerometers to record the amplitudes and frequencies during tests at the subsonic wind tunnel facility at the National Research Council. The results presented showed that no aeroelastic phenomenon occurred at the speeds, angles of attack and aileron deflections studied in the wind tunnel and confirmed the prediction of the flutter analysis on the frequencies and modal displacements.

Project 3. ATR-42 Optimized Wing Geometry for Laminar Flow Improvement Validation using the Price-Païdoussis Subsonic Wind Tunnel

This project took place at the LARCASE in the time frame between projects 1 and 2. An experimental validation of optimized wing geometry in the Price-Païdoussis subsonic wind tunnel was presented in [33].

In this project, two reduced scale wing models based on the ATR-42 aircraft airfoil were designed. The first model was based on the original airfoil shape while the second model was based on the optimized airfoil shape for one flight condition expressed by the Mach number of 0.1 and the angle of attack of 0°. Then, these models were manufactured using optimized glass fiber composite, and were further tested in the wind tunnel at three wind speeds and various angles of attack at which the model was optimized. Figure 9 shows the installation of the model in the test chamber of the Price-Païdoussis subsonic wind tunnel.

An "in-house" genetic algorithm was coupled with a cubic spline reconstruction routine to design the optimized airfoils. Then, the XFoil aerodynamic solver was used to obtain the pressure coefficients for the optimized airfoils in 14 points on the upper surface of the wing, and these numerically calculated data were compared with the experimental pressure data obtained experimentally in the wind tunnel. The transition region was calculated with a second derivative methodology from the experimental pressure data obtained in the wind tunnel, and was validated with the transition region predicted by XFoil code. This methodology was also used in the project 1 [34].

Two DC motors were used to rotate two eccentric shafts which morphed the flexible skin located between 10% and 70% of the chord along two parallel actuation lines. A Proportional-Derivative control algorithm was used to control and validate the morphing wing model using Matlab/Simulink in-house codes [35].

The transition region moved from 2% to 18% of the chord, thus giving an improvement of the laminar flow, and a drag coefficient reduction from 3% to 10.5% of its initial value. LabView software was used for controlling the reduced models in the wind tunnel, which were simulated using Matlab/Simulink program.

Project 4. UAS-S4 and UAS-S5 Morphing Studies

Within the Canada Research Chair in Aircraft Modeling and Simulation Technologies (website: http://www.chairs-chaires.gc.ca/chairholders-titulaires/profile-eng.aspx?profileId=2744), various projects were performed by the LARCASE team by using a reduced scale UAS-S4 or UAS-S45 morphing wing model to be tested in the Price-Païdousssis subsonic wind tunnel at the ÉTS. Most of these morphing configurations were already aerodynamically and structurally designed and analysed, as explained in this section.

Figure 9 – Installation of the model in the wind tunnel

In [36], an in-house optimization methodology was developed with the aim to reduce drag coefficients on the **UAS-S4** morphing wing. This methodology was based on the Artificial Bee Colony (ABC), and the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithms, and was applied for various flight conditions given in terms of Reynolds numbers, airspeeds and angles of attack; the optimized airfoils were obtained for their displacements of 2.5 mm, and for various flight cases. Then, reductions of drag coefficients up to 14% were obtained using a 2D linear panel method, coupled with an incompressible boundary layer model and a transition estimation criterion.

In [37], the ABC and BFGS algorithms were coupled as explained in [36] and [38] with the aim to delay the boundary layer separation and to increase the maximum lift coefficient. Validation of the coupling of these algorithm results were validated with an advanced commercially optimized tool. The 2D linear panel method was coupled with an incompressible boundary layer model and a transition estimation criterion, and was used to calculate the lift and drag coefficients. Lift coefficients increased by up to 18%, drag coefficients decreased, and boundary layer separated at high angles of attack for airfoil displacements smaller than 2.5 mm, as the ones in [36].

In [38], the ABC and BFGS algorithms used in [36] were applied with Non-Uniform Rational B-Splines in the optimization methodology with the aim to increase the lift-to-drag ratio, and to reduce the drag. The lift-to-drag ratios and the drag coefficients were calculated for four flight cases expressed by angles of attack between -40 and 80, by using a rapid, nonlinear lifting line method, coupled with a two-dimensional viscous flow solver, as well as a Navier-Stokes 3D solver. The comparison of aerodynamic coefficients obtained in the 2D flow with those obtained in the 3D flow conducted to the conclusion that the 2D new nonlinear lifting line method could be successfully used, as it gave close results to the 3D Navier-Stokes solver, and was also faster. It was found that the lift-to-drag ratio increased with a maximum of 4%.

The UAS-S4 wing design was modified by decreasing its sweep and increasing of its aspect ratio. Shape optimization was added to this redesign, and resulted in reductions of drag coefficients of up to 5% in the cruise regime [39].

An adaptive leading edge system was designed numerically for the **UAS-S45**, for which aero-structural studies were already performed. At this time, the structural analysis of the model aims to validate the structural integrity of the adaptive leading edge wing model proposed. Figure 10 shows the wing equipped with leading edge system designed using ANSYS / Fluent code. Structural studies were also performed using the Hypermesh code.

A new morphing wing system was designed and manufactured at the LARCASE, and had the aim to reduce the drag, and therefore the fuel consumption. The morphing wing allowed the change of its trailing edge shape, and it was found that the aileron could be replaced on the wing by the morphing trailing edge in order to reduce the drag following experimental tests in the Price-Païdoussis subsonic blow down wind tunnel.

Project 5. Cessna Citation X Business Aircraft Morphing Studies through its Performance Optimization

The LARCASE is equipped with the Research Aircraft Flight Simulator (RAFS) that has the flight dynamics tests data of the Cessna Citation X business aircraft validated, and therefore certified to their highest level D by the FAA. Thus, it is possible to use the flight test data of the RAFS to validate the research proposed in this project; the RAFS is presented in Figure 1, as one of the LARCASE equipments, and is further used in this project for morphing wing and horizontal tail design of the Cessna Citation X.

Although the LARCASE team has several accurate performance models of the Cessna Citation X that can predict its behavior during a flight, this project requires designing and validating a new model specially composed of an aerodynamic model of the Cessna Citation X horizontal stabilizer made from geometrical data. To design this model, the horizontal stabilizer airfoil of the aircraft was found from a Genetic Algorithm (GA) coupled to a level D flight simulator data and a Bezier-Parsec parameterization curve.

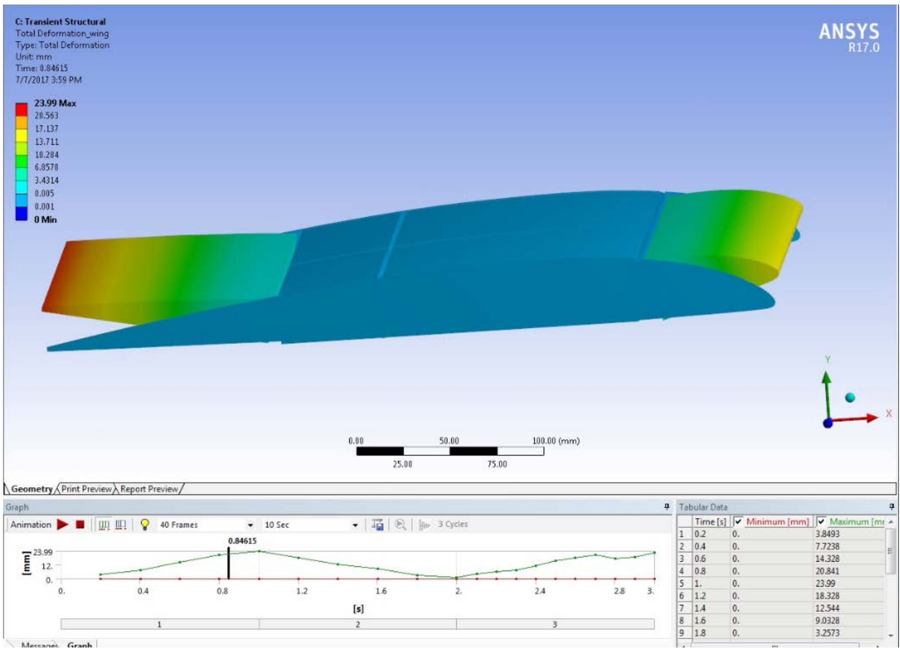

Figure 10 – Wing equipped with leading edge system design with ANSYS / Fluent code

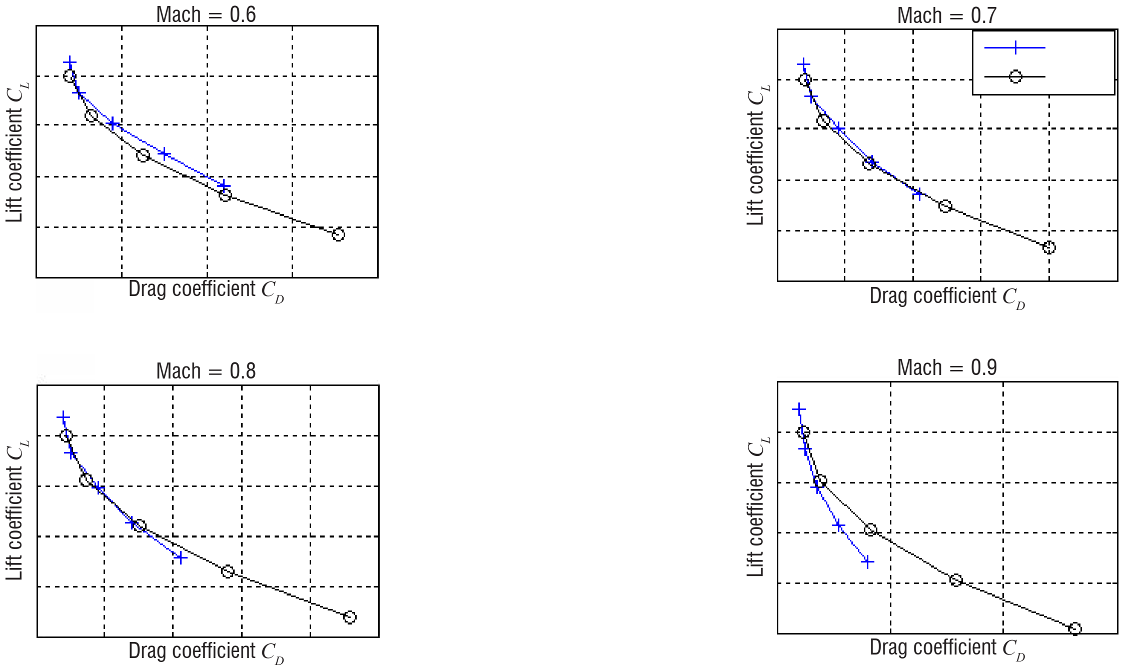

Figure 11 – Horizontal Tail aerodynamic polar comparison between results obtained by the modeled wing equipped with the average airfoil (Model) and experimental reference data obtained from the Flight Simulator (RAFS)

Figure 11 shows a comparison between aerodynamic polar of the wing equipped with the average airfoil founded and aerodynamic polar given by the Research Aircraft Flight Simulator (RAFS) that is constitute a relevant reference. For Mach numbers of 0.6, 0.7 and 0.8, aerodynamic coefficients, for angle of attack between 0 to -6 degrees, are very well estimated with a maximum difference of 0.15 on the lift coefficient and 0.006 on the drag coefficient (for angle of attack equal to -6 degrees and Mach = 0.8). For Mach number 0.9, coefficients seem to be well estimates only for angle of attack close between 0 to -4 degrees. From results obtained in Figure 11, the horizontal tail model geometry is validated [40].

In this project, the Cessna Citation X Business Aircraft performances (fuel consumption, distance) were optimized due to morphing technologies. The two surfaces of the aircraft: stabilizer and wing were morphed, one at a time, with the aim to reduce the fuel consumption in cruise. Thus, the morphing stabilizer benefits were studied separately of the morphing wing benefits. However, the horizontal stabilizer of the Cessna Citation X turns around the span axis of horizontal tail with an angle between -8 to 2 degrees. With this range of angle, the horizontal stabilizer generates for sure some unwanted drag. To cancel this drag, the LARCASE proposes to balance the aircraft by a horizontal stabilizer equipped by a morphing wing that can generate enough lift on the tail to balance the aircraft.

It can be concluded that all the five above projects are interesting and that the LARCASE team continues to work on these projects related to morphing technologies in the aeronautical field, and produce interesting results ■

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Acronyms

ABC	(Artificial Bee Colony)
ANFIS	(Adaptive Neuro-Fuzzy Inference System)
BFGS	(Broyden-Fletcher-Goldfarb-Shanno)
GA	(Genetic Algorithm)
GARDN BL-NCE	(Green Aviation Research and Development Business-Led Network of Centres of Excellence)
LARCASE	(Research Laboratory in Active Controls, Avionics and Aeroservoelasticity)

NI	(National Instruments)
PID	(Proportional Integral Derivative)
RAFS	(Research Aircraft Flight Simulator)
RAS	(Research Aerial System)
RMS	(Root Mean Square)
SARISTU	(Smart Intelligent Aircraft Structures)
SMA	(Smart Material Alloys)
TRL	(Technical Readiness Level)
UAV	(Unmanned Aerial Vehicle)
WTEA	(Wing Trailing Edge Airfoil)

References

[1] G. M. CAROSSA, S. RICCI, A. DE GASPARI, C. LIAUZUN, A. DUMONT, M. STEINBUCH - *Adaptive Trailing Edge: Specifications, Aerodynamics and Exploitation.* Chapter in the book: Smart Intelligent Aircraft Structures (SARISTU), Edition: 1, Publisher: Springer International Publishing, Editors: Piet Christof Wölcken, Michael Papadopoulos, pp.143-158, 2015.

[2] M. ARENA, R. PECORA, F. AMOROSO, M. C. NOVIELLO, F. REA, A. CONCILIO - *Aeroelastic Analysis of an Adaptive Trailing Edge with a Smart Elastic Skin*. The 2nd International Conference on Energy Engineering and Smart Materials: ICEESM 2017, AIP Conference Proceedings 1884(1):040002, DOI 10.1063/1.5002521, 2017.

[3] F. REA, R. PECORA, F. AMOROSO, M. REA, M. C. NOVIELLO, G. AMENDOLA - *Aeroelastic Stability Analysis of a Wind Tunnel Wing Model Equipped with a True Scale Morphing Aileron*. International Journal of Mechanical Engineering and Robotics Research, Vol. 6, No. 6, November 2017.

[4] G. AMENDOLA, I. DIMINO, A. CONCILIO, R. PECORA, F. AMOROSO, M. ARENA - *Morphing Aileron*. DOI: 10.1016/B978-0-08-100964-2.00018-6, Morphing Wing Technologies, 2018.

[5] A. CONCILIO, I. DIMINO, M. CIMINELLO, R. PECORA, F. AMOROSO, M. MAGNIFICO - *An Adaptive Trailing Edge.* DOI: 10.1016/B978-0-08-100964-2.00017-4, Morphing Wing Technologies, 2018.

[6] I. DIMINO, M. CIMINELLO, A. CONCILIO, A. GRATIAS, M. SCHUELLER, R. PECORA - *Control System Design for a Morphing Wing Trailing Edge*. DOI: 10.1007/978-3-319-44507-6_9, Smart Structures and Materials, 2017.

[7] I. DIMINO, M. CIMINELLO, A. CONCILIO, R. PECORA, F. AMOROSO, M. MAGNIFICO, M. SCHUELLER, A. GRATIAS, A. VOLOVICK, L. ZIVAN - *Distributed Actuation and Control of a Morphing Wing Trailing Edge*. DOI: 10.1007/978-3-319-22413-8_9, Smart Intelligent Aircraft Structures (SARISTU), 2016.

[8] R. M. BOTEZ, P. MOLARET, E. LAURENDEAU - *Laminar Flow Control on a Research Wing Project Presentation Covering a Three Years Period*. Canadian Aeronautics and Space Institute Annual General Meeting, Toronto, Ont., Canada, May 16-18, 2007.

[9] A. V. POPOV, T. L. GRIGORIE, R. M. BOTEZ, M. MAMOU, Y. MEBARKI - *Real Time Morphing Wing Optimization Validation Using Wind-Tunnel Tests*. Journal of Aircraft, Vol. 47, no 4, pp. 1346-1355, 2010.

[10] C. SAINMONT, I., PARASCHIVOIU, D. COUTU - *Multidisciplinary Approach for the Optimization of a Laminar Airfoil Equipped with a Morphing Upper Surface*. NATO VT-168 Symposium on Morphing Vehicles, Evora, Portugal, 2009.

[11] A. V. POPOV, R. M. BOTEZ, M. MAMOU, T. L. GRIGORIE - *Variations in Optical Sensor Pressure Measurements Due to Temperature in Wind-Tunnel Testing*. Journal of Aircraft, Vol. 46, no 4, pp. 1314-1318, 2009.

[12] A. V. POPOV, T. L. GRIGORIE, R. M. BOTEZ, M. MAMOU, Y. MEBARKI - *Controller Optimization in Real Time for a Morphing Wing in a Wind Tunnel*. 15th IEEE Mediterranean Electro-technical Conference (MELECON 2010), Malta, pp. 107-112, 2010.

[13] A. V. POPOV, T. L. GRIGORIE, R. M. BOTEZ, M. MAMOU, Y. MEBARKI - *Modeling and Testing of a Morphing Wing in Open-Loop Architecture*. Journal of Aircraft, Vol. 47, no 3, pp. 917-923, 2010.

[14] A. V. POPOV, T. L. GRIGORIE, R. M. BOTEZ, M. MAMOU, Y. MEBARKI - *Closed-Loop Control Validation of a Morphing Wing Using Wind Tunnel Tests*. Journal of Aircraft, Vol. 47, no 4, pp. 1309-1317, 2010.

[15] T. L. GRIGORIE, A. V. POPOV, R. M. BOTEZ, M. MAMOU, Y. MEBARKI - *On-Off and Proportional-Integral Controller for a Morphing Wing. Part 1: Actuation Mechanism and Control Design*. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Vol. 226, no 2, pp. 131-145, 2012.

[16] T. L. GRIGORIE, A. V. POPOV, R. M. BOTEZ, M. MAMOU, Y. MEBARKI - *On-Off and Proportional-Integral Controller for a Morphing Wing. Part 2: Control Validation - Numerical Simulations and Experimental Tests*. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Vol. 226, no 2, pp. 146-162, 2012.

[17] T. L. GRIGORIE, A. V. POPOV, R. M. BOTEZ, M. MAMOU, Y. MEBARKI - *A Hybrid Fuzzy Logic Proportional-Integral-Derivative and Conventional On-Off Controller for Morphing Wing Actuation Using Shape Memory Alloy Part 1: Morphing System Mechanisms and Controller Architecture Design*. The Aeronautical Journal, Vol. 116, pp. 433-449, 2012.

[18] T. L. GRIGORIE, A. V. POPOV, R. M. BOTEZ, M. MAMOU, Y. MEBARKI - *A Hybrid Fuzzy Logic Proportional-Integral-Derivative and Conventional On-Off Controller for Morphing Wing Actuation Using Shape Memory Alloy Part 2: Controller Implementation and Validation*. The Aeronautical Journal, Vol. 116, pp. 451-465, 2012.

[19] T. L. GRIGORIE, R. M. BOTEZ - *Adaptive Neuro-Fuzzy Inference System-Based Controllers for Smart Material Actuator Modeling*. Proceedings of the Institution of Mechanical Engineers Part G: Journal of Aerospace Engineering, Vol. 223, no 6, pp. 655-668, 2009.

[20] S. COURCHESNE, A. V. POPOV, R. M. BOTEZ - *New Aeroelastic Studies for a Morphing Wing*. INCAS Bulletin, Vol. 4, no 2, pp. 19-28, 2012.

[21] T. L. GRIGORIE, R. M. BOTEZ, A. V. POPOV - *Adaptive Neuro-Fuzzy Controllers for an Open-Loop Morphing Wing System*. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Vol. 223, no 7, pp. 965-975, 2009.

[22] T. L. GRIGORIE, R. M. BOTEZ - *New Adaptive Controller Method for SMA Hysteresis Modelling of a Morphing Wing*. The Aeronautical Journal, Vol. 114, pp. 1-13, 2010.

[23] A. KOREANSCHI, O. SUGAR GABOR, J. ACOTTO, G. BRIANCHON, G. PORTIER, R. M. BOTEZ, M. MAMOU, Y. MEBARKI - *Optimization of a Morphing Wing Tip Aircraft Demonstrator for Drag Reduction at Low Speeds, Part I - Numerical Analysis Using 3 Algorithms: Genetic, Artificial Bee Colony and Gradient Descent*. Chinese Journal of Aeronautics, Vol. 30, no 1, pp. 149-163, 2017.

[24] A. KOREANSCHI, O. SUGAR GABOR, J. ACOTTO, G. BRIANCHON, G. PORTIER, R. M. BOTEZ, M. MAMOU, Y. MEBARKI - *Optimization of a Morphing Wing Tip Aircraft Demonstrator for Drag Reduction at Low Speeds, Part II - Experimental Validation Using Infra-Red Transition Measurements During Wind Tunnel Tests*. Chinese Journal of Aeronautics, Vol. 30, no 1, pp. 164-174, 2017.

[25] O. SUGAR GABOR, A. KOREANSCHI, R. M. BOTEZ, M. MAMOU, Y. MEBARKI - *Numerical Simulation and Wind Tunnel Tests Investigation and Validation of a Morphing Wing-Tip Demonstrator Aerodynamic Performance*. Aerospace Science and Technology, Vol. 53, pp. 136-153, 2016.

[26] F. MICHAUD, S. JONCAS, R. M. BOTEZ - *Design, Manufacturing and Testing of a Small-Scale Composite Morphing Wing*. Proceedings of the 19th International Conference on Composite Materials ICCM19, Montréal, Québec, Canada, July 28-Aug. 2, 2013.

[27] A. KOREANSCHI, M. B. HENIA, O. GUILLEMETTE, F. MICHAUD, Y. TONDJI, O. SUGAR-GABOR, M. FLORES-SALINAS - *Flutter Analysis of a Morphing Wing Technology Demonstrator: Numerical Simulation and Wind Tunnel Testing*. INCAS Bulletin, Vol. 8, no 1, pp. 99-124, 2016.

[28] M. J. TCHATCHUENG KAMMEGNE, D. H. NGUYEN, R. M. BOTEZ, T. L. GRIGORIE - *Control Validation of a Morphing Wing in an Open Loop Architecture*. AIAA Modeling and Simulation Technologies Conference, Dallas, TX, USA, June 22-25, 2015.

[29] M. J. TCHATCHUENG KAMMEGNE, H. BELHADJ, D. H. NGUYEN, R. M. BOTEZ - *Nonlinear Control Logic for an Actuator to Morph a Wing: Design and Experimental Validation*. The 34th IASTED International Conference on Modelling, Identification and Control MIC, February 16-18, 2015.

[30] R. M. BOTEZ, A. KOREANSCHI, O. SUGAR GABOR, Y. MEBARKI, M. MAMOU, Y. TONDJI, G. BRIANCHON, F. AMOROSO, R. PECORA, L. LECCE, G. AMENDOLA, I. DIMINO, A. CONCILIO - *Innovative Wing Tip Equipped with Morphing Upper Surface and Morphing Aileron for Greener Aviation*. Greener Aviation Conference, Brussels, Belgium, June 11-13, 2016.

[31] F. MICHAUD - *Design and Optimization of a Composite Skin for an Adaptive Wing*. Master of Science Thesis, ÉTS, Montreal, Canada, 2014.

[32] R. M. BOTEZ, A. KOREANSCHI, O. SUGAR GABOR, Y. MEBARKI, M. MAMOU, Y. TONDJI, F. AMOROSO, R. PECORA, L. LECCE, G. AMENDOLA, I. DIMINO, A. CONCILIO - *Numerical and Experimental Testing of a Morphing Upper Surface Wing Equipped with Conventional and Morphing Ailerons*. AIAA SciTech Forum – 55th AIAA Aerospace Sciences Meeting, Grapevine, USA, AIAA Paper nr. 2017-1425, 2017.

[33] A. KOREANSCHI, O. SUGAR-GABOR, R. M. BOTEZ - *Numerical and Experimental Validation of a Morphed Wing Geometry Using Price-Païdoussis Wind Tunnel Testing*. The Aeronautical Journal, Vol. 120, no 1227, pp. 757-795, 2016.

[34] A. V. POPOV, R. M. BOTEZ, M. LABIB - *Transition Point Detection from the Surface Pressure Distribution for Controller Design*. Journal of Aircraft 45 (1), pp. 23-28, 2008.

[35] M. J. TCHATCHUENG KAMMEGNE, T. L. GRIGORIE, R. M. BOTEZ, A. KOREANSCHI - *Design and Wind Tunnel Experimental Validation of a Controlled New Rotary Actuation System for A Morphing Wing Application*. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Vol. 230, no 1, pp. 132-145, 2015.

[36] O. SUGAR GABOR, A. SIMON, A. KOREANSCHI, R. M. BOTEZ - *Aerodynamic Performance Improvement of the UAS-S4 Éhecatl Morphing Airfoil Using Novel Optimization Techniques*. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Vol. 230, no 7, 2015.

[37] O. SUGAR GABOR, A. SIMON, A. KOREANSCHI, R. M. BOTEZ - *Improving the UAS-S4 Éhecatl Airfoil High Angles-of-Attack Performance Characteristics Using a Morphing Wing Approach*. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Vol 230, no 1, pp. 118-131, 2016.

[38] O. SUGAR GABOR, A. KOREANSCHI, R. M. BOTEZ - *Analysis of UAS-S4 Éhecatl Aerodynamic Performance Improvement Using Several Configurations of a Morphing Wing Technology*. The Aeronautical Journal, Vol. 120, no 1231, pp. 1337-1364, 2016.

[39] O. SUGAR GABOR, A. KOREANSCHI, R. M. BOTEZ - *A New Non-Linear Vortex Lattice Method: Applications to Wing Aerodynamic Optimizations*. Chinese Journal of Aeronautics, Vol. 29, no 5, pp. 1178-1195, 2016.

[40] M. SEGUI, M. MANTILLA, R. M. BOTEZ - *Conception and Validation of an Aerodynamic Model of the Cessna Citation X Horizontal Stabilizer Using OpenVSP and Digital Datcom Software*. 20th International Conference on Engineering Education and Research ICEER-2018, Innsbruck, Austria, 2018.

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