Aircraft energy consumption limitation through drag reduction based on morphing wing technology: a new multidisciplinary experimental model

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AIRCRAFT ENERGY CONSUMPTION LIMITATION THROUGH DRAG REDUCTION BASED ON MORPHING WING TECHNOLOGY - A NEW MULTIDISCIPLINARY EXPERIMENTAL MODEL

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Abstract

The research presented in this present paper was done within the framework of the international CRIAQ MDO505 Morphing Wing project, developed as a collaborative research project between academia, research centres and industry partners. The work exposed in the paper is related to the development of an experimental morphing wing model and its performance evaluation by using some wind tunnel tests. The model designed, fabricated and tested during the project is based on the dimensions of a full scale wing tip structure, equipped with a morphable flexible upper surface made from composite materials and deformed by using four miniature electrical actuators, with an array of 32 Kulite pressure sensors to monitor the air flow behaviour over the upper surface, and with an aileron also electrical actuated. After a short introduction a project description is made, followed by the presentation of the morphing wing model instrumentation and of the mechanisms used to control it. Finally, a wind tunnel aerodynamic results analysis is performed.

Keywords

Energy save, Drag reduction, Morphing wing, Experimental testing.

1 Introduction

Regarded as one of the promising technologies in terms of saving fuel and limit emissions in the aerospace industry, the morphing technology has undergone various ways of implementation, among which highlights the morphing wing. The advantages of this technology have been proven by developing and testing numerous experimental models both in Industrial laboratories and in the laboratories of universities and research institutes. The researches were carried out both by local projects involving a single institution, and through collaborative projects with large industrial impact, involving entities from all sectors of aerospace field, and integrating human resources and expertise from academia, research and testing, and industry. The mechanism that has been identified morphing wing technology impact on fuel consumption was to improve the aerodynamic performance of the vehicle by reducing the drag. Therefore, technical solutions were sought to change the wing shape as a function of the flight conditions so as to obtain an extension of the laminar flow on its surface, extension equivalent with a decrease in drag force ([1]-[20]).

In order to develop such green aircraft technologies, our research team from Research Laboratory in Active Controls, Avionics and AeroServoElasticity (LARCASE) at École de Technologie Supérieure in Montréal, Canada, developed some morphing wing projects. In a first project, called CRIAQ 7.1 (Consortium for Research and Innovation in Aerospace in Quebec), a morphing wing experimental model was realized at LARCASE laboratory (Fig. 1). During this project, new methodologies to morph a wing by using smart actuators and various control techniques, starting from open loop control architectures to closed loop real time optimization of the morphing wing controller, were developed and experimentally validated ([21]-[40]). In the open loop architecture, the research team proposed and validated few control techniques for the morphing wing actuation system, based on classical or intelligent methodologies. On the other way, simulations and experimental methods pertinent to transition location detection has been presented ([35], [36], [40]).

Figure 1: Wind tunnel experimental model for CRIAQ 7.1 project

In another morphing wing project developed by our team, a wing prototype with an integrated actuation mechanism was fabricated and tested at Ecole de Technologie Superieure in Montreal (Fig. 2). In this project instead of using adaptive materials such as SMA and piezoceramic actuators, a new approach using electrical actuators coupled to two actuation lines was tested. A control system was designed for the actuation system to obtain the optimized profile for each considered flight case. The actuator position was controlled using a cascade control algorithm. The aerodynamic results obtained in our Price-Paidoussis wind tunnel were compared with the numerical results predicted by XFoil software in the optimization phase ([41]-[44]).

Figure 2: Morphing wing model in Price- Païdoussis subsonic wind tunnel

The here exposed work refers to the morphing wing studies of the LARCASE team related to a new CRIAQ project, Multi-Disciplinary Optimization 505 (MDO 505), aiming at fuel consumption optimization by applying morphing wing technology to a real aircraft wing. The project, realized at École de Technologie Supérieure in Montréal, Canada, is the result of a collaborative multidisciplinary research team, integrating human resource coming from partners in Canada and Europe. The industrial partners in Canada are Bombardier Aerospace and Thales, while in Europe is Alenia Aerospace. The universities and research institutes participating in Canada are École de Technologie Supérieure (ETS), École Polytechnique and Institute of Aerospace research at National Research Council of Canada (IAR-NRC). Universities and research centres participating from Europe are Frederico II Naples University and Italian Aerospace Research Center (CIRA) ([45]-[46]).

2 Morphing wing project

In this research project, a wing-aileron prototype was designed, tested and validated using win tunnel tests at National Research Council Canada (IAR-NRC). The multidisciplinary research team of the project was divided into three sub-teams covering aerodynamic, structural, and control fields. The main aims of the project were to reduce the operating costs for the new generation of aircraft through in-flight fuel economy, and also to improve aircraft performances, expand its flight envelope, replace conventional control surfaces, reduce drag to improve range and reduce vibrations and flutter risk ([47]).

The first specific objective for our research team in this project was to develop a new morphing mechanism using miniature electrical actuators for a full-scaled portion of the wing of a real aircraft equipped with an aileron. The actuators deform the upper wing surface, made of a flexible skin, so that the laminar-to-turbulent transition point moves closer to the wing trailing edge reducing in this way the drag force as a function of flow condition by changing the wing shape. The flow conditions were univocally defined by mean of Mach numbers, airspeeds, angles of attack and aileron deflection angles. The second specific objective was to develop a control system for the morphing actuators to obtain the desired morphed shape of the wing for each studied flow case, while the third specific objective was to develop a monitoring system able to detect and visualize the airflow characteristics using pressure sensors installed on the upper surface of the morphing wing.

The used experimental wing segment was with a maximum chord of 1.5 m, and a minimum one of 1.08 m, and has three distinct parts: 1) a metal part, which has the structure as in the original aircraft wing; 2) a morphing part, consisting of a flexible skin installed on the upper surface of the wing; and 3) an actuated aileron (Fig. 3 [47], [48]). The first part structure includes four ribs, two at the ends (Rib 1 and Rib 4), and two inside (Rib 2 and Rib 3) having also the role to support the actuators. The morphing skin, made from composite materials, allowing the wing shape changing, was positioned on the upper side of the wing between 20% and 65% of the wing chord (Fig. 4). To morph the flexible skin were used four similar actuators disposed on two actuation lines positioned at 37% and 75% of the wing's span. The actuators were positioned at 32% and 48% of the local wing chord on each of the two actuation lines. The actuators were fixed on the wing ribs and the top were attached to the flexible skin with screws.

The actuation mechanism architecture supposed the direct actuation of the flexible skin by the four actuators. This architecture, with estimated forces of over 1300 N per actuator, correlated with the small space inside the morphed wing (the wing thickness varies between 10 cm and 20 cm), and with small maximum displacement (maximum 5 mm) imposed serious size/power constraints to the actuators. Because on the market was no suitable actuator, it was designed in-house by using some components acquired on the market such as the miniature brushless direct current (BLDC) motor ([47]).

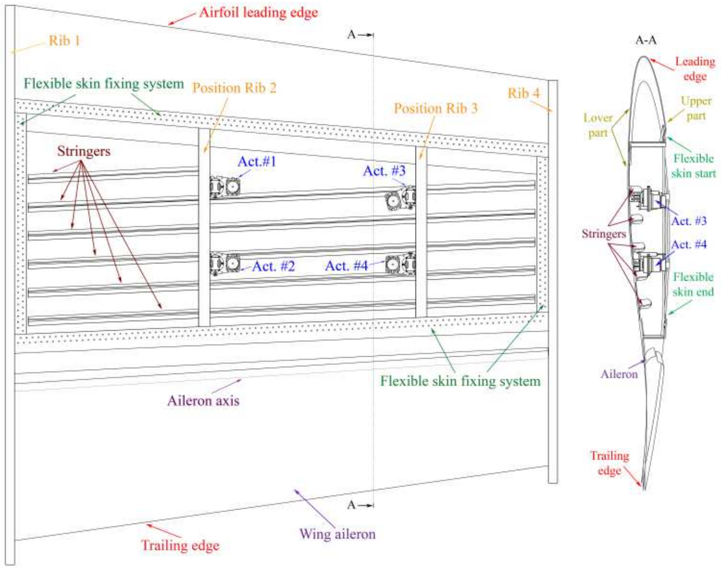

Figure 3: Wing structure and actuations lines positions

To establish the optimum shape of the wing for a specific flow condition an optimization phase was performed by the aerodynamic team of the project. The optimization procedure was applied for several combinations of Mach numbers (M), angles of attack (α) and aileron deflection angles (δ). An in-house developed genetic algorithm was used in the iterative optimization process, with the objective to search the optimum shapes for an airfoil through local thickness changes to improve the upper surface flow. The optimization started from a reference airfoil shape, and was a complex one, needing several interactions between the genetic algorithm parameters, objective function, aerodynamic solver and shape reconstruction using spline interpolation ([48]).

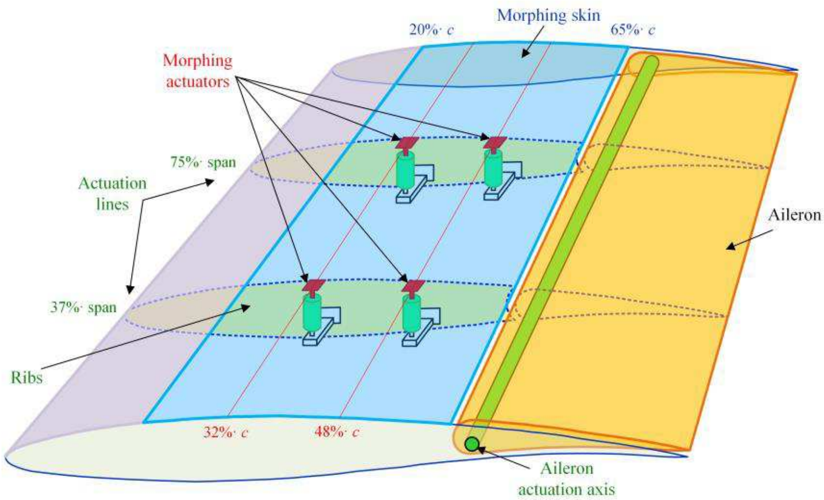

Figure 4: 3D view of the morphing wing structure

For each optimized airfoil resulted four vertical displacements corresponding to the positions of the four actuators. Actually, the optimization gave the displacement values for one pair of actuators situated at 37% of the wing span, while the displacements for the second pair of actuators were calculated as a linear dependence ([48]). All optimization results were stored in a database in order to be used as reference vertical displacements for the control system.

The aerodynamic performance of the morphing wing model was tested in wind tunnel at Institute for Aerospace Research at the National Research Council Canada (IAR-NRC) in Ottawa for ninety seven flow cases. The tested flow cases were obtained as combinations of nineteen values for the angle of attack (varied from -3 degree to +3 degree), three values for the Mach number (0.15, 0.2, 0.25) and thirteen values for the aileron deflection angle (varied between -6 degrees an +6 degrees). For each case, the flexible upper surface of the wing was actuated in order to obtain the four optimized values of the vertical displacements corresponding to the four actuation points and stored in the aerodynamic database. The evaluation of the laminar-to-turbulent transition location was performed by using the pressure data obtained from 32 high precision Kulite piezoelectric-type sensors placed on the flexible skin on two closes chord lines ([46]-[48]).

3 Instrumentation of the experimental model

For the four morphing actuators was developed a control system able to control theirs linear positions. Actually, the control system included four similar controllers software implemented, able to modify the actuators linear positions until the real displacements of the morphing skin in the four actuation points equalled the desired displacements of the optimized airfoil resulted for a flow case. The feedback signals containing the actuators positions are provided by four Linear Variable Differential Transformers (LVDT). From the point of view of the control system were developed and tested various controllers, based on classical or intelligent techniques. The controllers were preliminary tested in the lab conditions, in the absence of the airflow, together with the associated software and hardware components included in the experimental model (Fig. 5) ([47]).

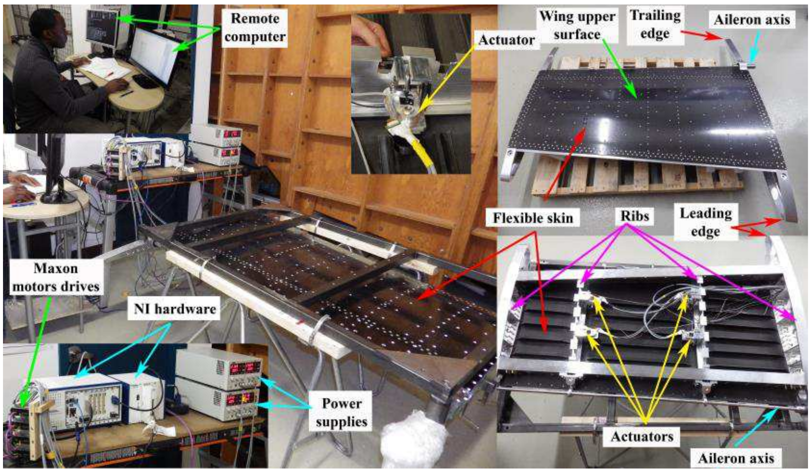

Figure 5: Bench test at École de Technologie Supérieure in Montréal

The experimental model instrumentation was developed around a National Instrument equipment and included a NI PXIe-1078, 9-Slot 3U PXI Express Chassis, a NI PXIe-8135 embedded controller, four NI PXIe-4330 Data Acquisition Cards with Integrated Signal Conditioning for Bridge-Based Measurements, a NI PXI-8531, 1-Port CANopen Interface, a NI PXIe-6356 Simultaneous X Series Data Acquisition Card, a SCXI-1000 rugged, low-noise chassis that can hold up to four SCXI modules, a NI SCXI-1540 8-Channel LVDT Input Module, a NI SCXI-1315, and two Programmable power supplies Aim-TTi CPX400DP.

The next test of the experimental model was in the wind tunnel (Fig. 6), the pressure signals being logged in parallel while the shape of the airfoil changed. A Graphical User Interface (GUI) was developed for the control system and for the data acquisition system. Simultaneously with the control system characteristics monitoring, 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. 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 ([49]).

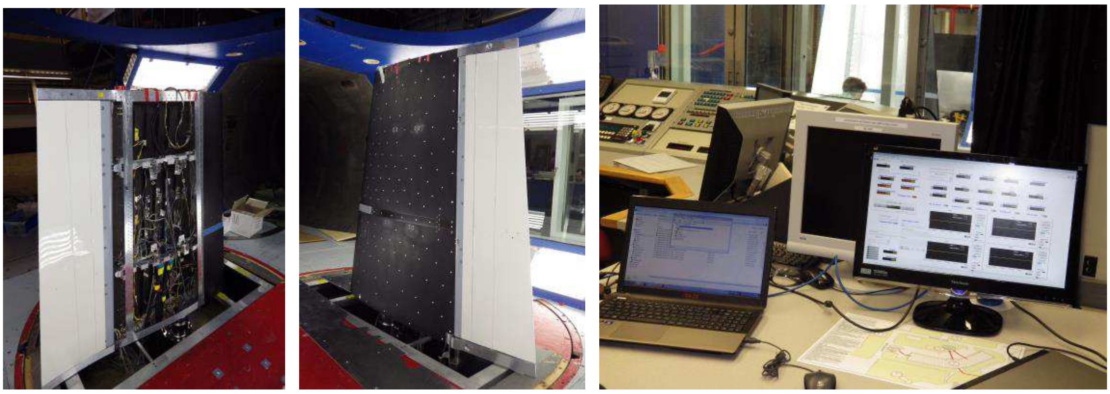

Figure 6: Wind tunnel testing of the experimental model

4 Wind tunnel experimental results

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.

For the flow case associated to Mach=0.15, α=-2˚, δ=-2˚, Fig. 7 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. 8. 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.

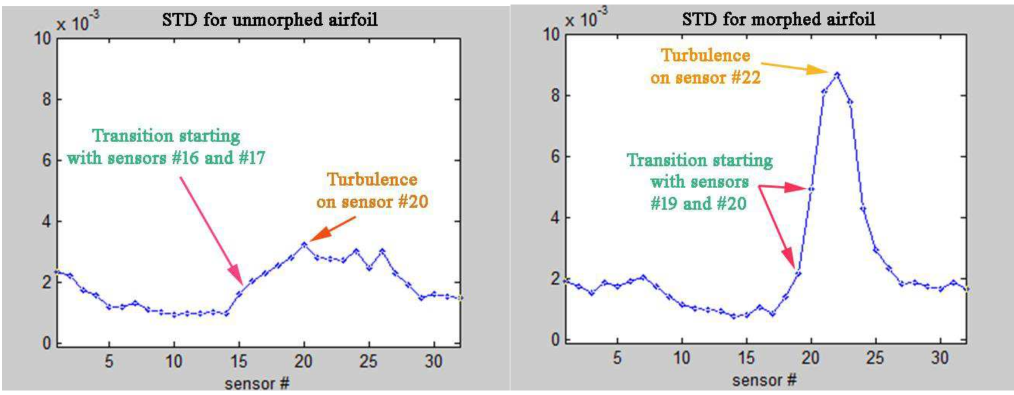

Figure 7: STD of the pressure data acquired for Mach=0.15, α=-2˚, δ=-2˚ flow case

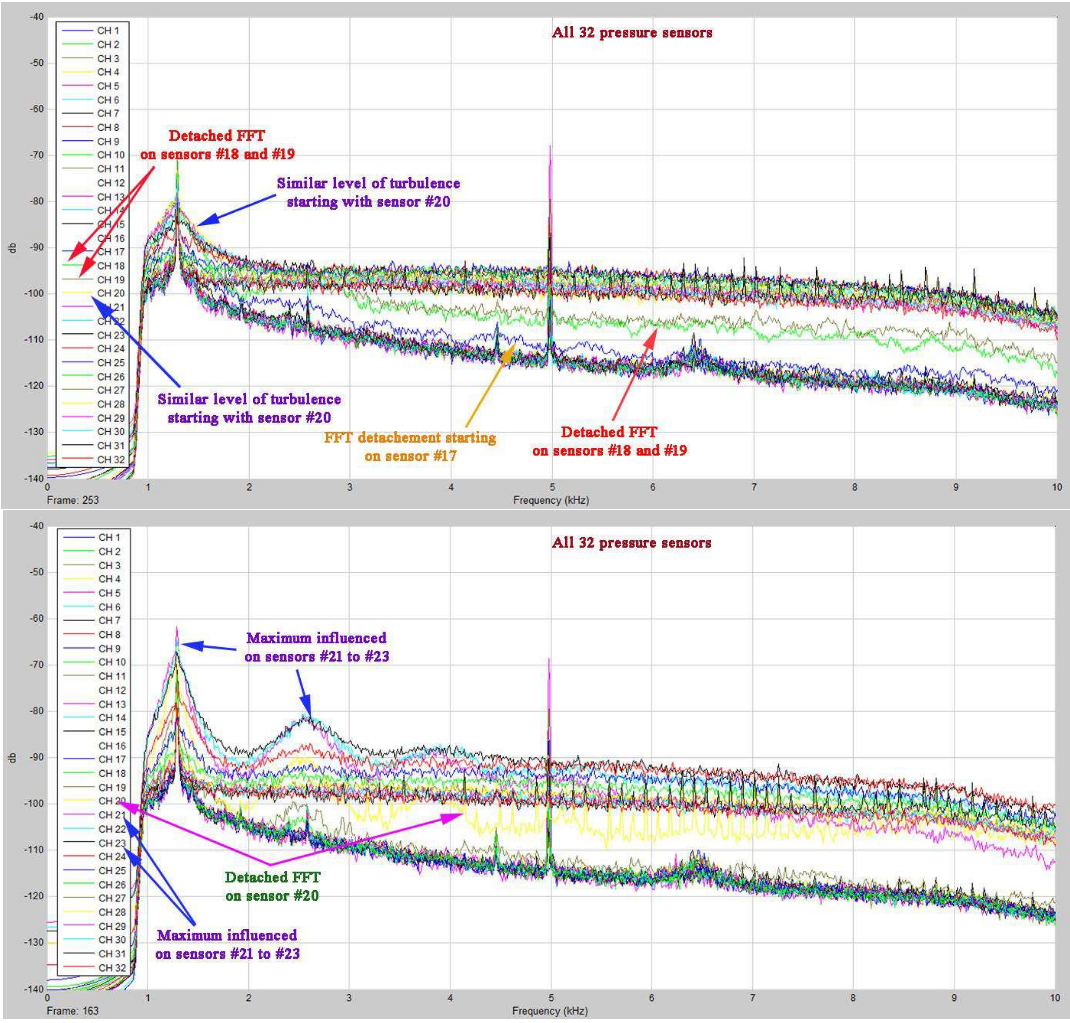

Figure 8: FFT of the pressure data acquired for Mach=0.15, α=-2˚, δ=-2˚ flow case

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. 9. The wind blow 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.

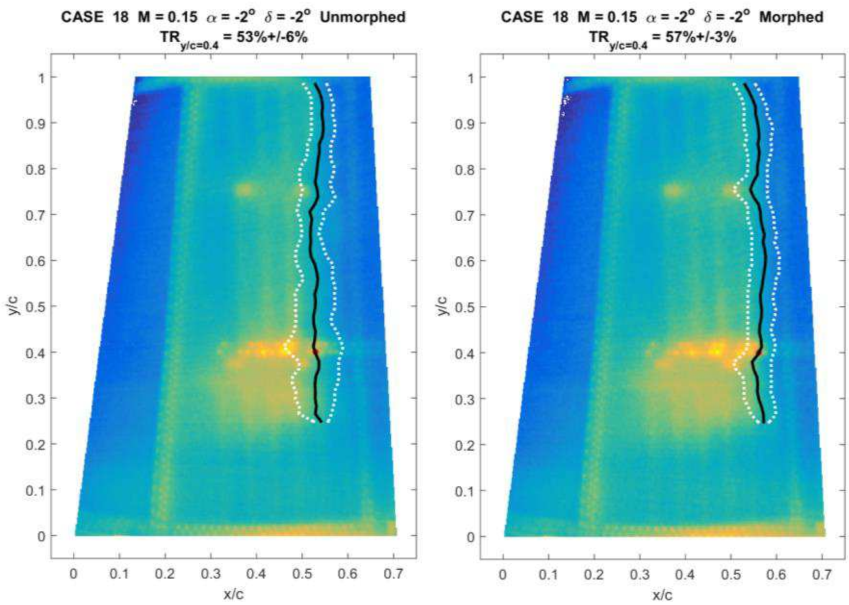

Figure 9: IR visualisation for Mach=0.15, α=-2˚, δ=-2˚ flow case

5 Conclusions

The paper presented the morphing wing technology benefits on a wing-aileron prototype designed, developed and experimentally tested in wind tunnel during a collaborative research project between industry and academia. 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 data 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. 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.

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