

High Bandwidth Morphing Aerofoil

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This paper presents the experimental development of a morphing aerofoil which has a dual goal of controlling flight mechanics and increasing flutter speed, both by active control of the aeroelastic wing designed as part of the project. In order to achieve these aims, the static camber variation of the aerofoil, as well as its actuation bandwidth, have to be sufficiently high. The morphing aerofoil sector is a NACA 0018 with a chord of 300 mm and a final span of 250 mm (however the preliminary test sector has a span of 40 mm). The non-deformable part of the sector is 3D printed in ABS and the active camber deformation is achieved by bonding to the trailing edge portion of the structure tailored (MFC) piezo-patch-sandwiches properly actuated by ad hoc high-voltage amplifiers. A linear trailing edge slider is used to allow the necessary skin deformation. A PID inner control layer on the tip displacement feedback is developed in a real-time environment using a laser displacement sensor. The preliminary design of the model, as well as the static and dynamic experimental tests on the prototype, is illustrated and discussed in the paper. A comparison with a traditional control surface aerofoil of same size is also be provided. For this purpose, low fidelity numerical calculations and CFD is used. A brief contextualization of this work within the aeroelastic wing project is presented. The morphing sector is one of four sectors which compose the aerodynamic shape of a flexible wing, with a 1 m span and 300 mm chord, designed to have the first bending and torsion mode frequencies lower than 10 Hz and a linear flutter speed around 15 m/s. This rig has the objective of providing experimental benchmarks for testing algorithms for linear/nonlinear aeroelastic control phenomena.

I. Introduction

As part of the EPSRC project entitled “*Nonlinear Active Vibration Suppression in Aeroelasticity*” (NAVSA), a flexible aeroelastic wing has recently been designed and manufactured to serve as a test rig for the development and experimental tests on active control strategies for flutter/vibration suppression. Besides the traditional leading and trailing edge flaps, morphing solutions have also been explored to achieve the required control authority. This paper presents, after a brief overview of the state of the art of the morphing camber aerofoils, the context of the NAVSA project and the experimental/numerical analysis of the morphing solution proposed.

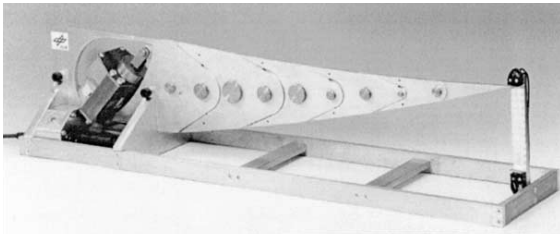
A. Morphing camber aerofoil

Many aerofoil morphing camber techniques have been explored in recent years; the most well known are summarized in Figure 1. The common goal of these works is the study of their aerodynamic performances especially compared to the traditional control surfaces. From an aeroelastic point of view, the major limitation of these configurations is the low bandwidth that most of them are able to achieve. Among the others, the solution proposed by Debiase *et al.* (Ref. [1] and Figure 1h) and the one presented by Bilgen *et al.* (Ref. [2] and Figure 1i), even if not designed with a high bandwidth aim, they seem to be able to reach quite high actuation frequencies thanks to the use of piezo-ceramic patches. For this reason, on the morphing sector proposed ahead, the same Macro-Fiber Composite (MFC) piezo actuator (M8528P1) is used as starting point.

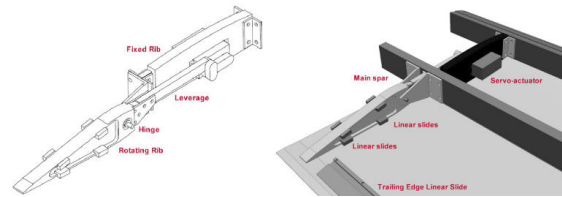
II. Context

The preliminary requirements of this wind tunnel model aeroelastic flexible wing, context of this work, are summarized in Table 1a and its specifications in Table 1b. The model consists essentially of a single aluminium alloy spar (load-carrying flexible beam) and four separate aerodynamic sectors (manufactured by 3D printing), separately connected to the main spar at a single point. Two types of active sector configurations have been designed: (a) one morphing sector and 3 passive sectors, and (b) 2 leading and trailing edge traditional control surfaces sectors and 2 passive sectors. In addition, a preliminary version, 3 passive sectors and one traditional trailing edge control surface tip sector have been manufactured.

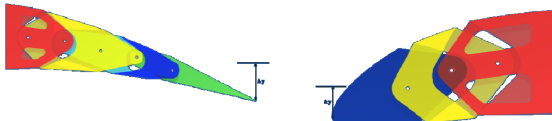
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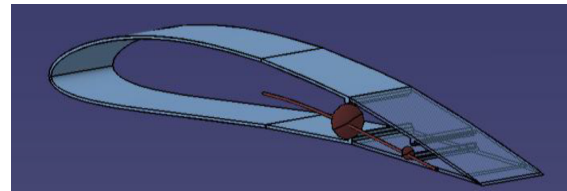
(a) Mooner [3,4].



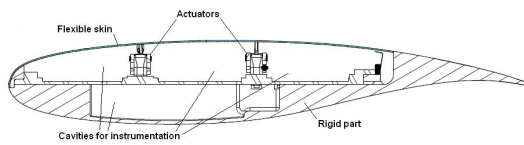
(b) Ricci [5].



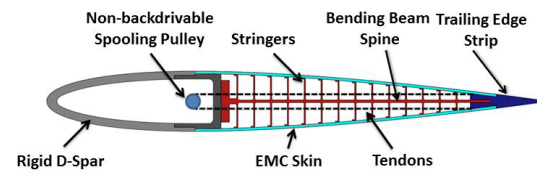
(c) Wang [6].



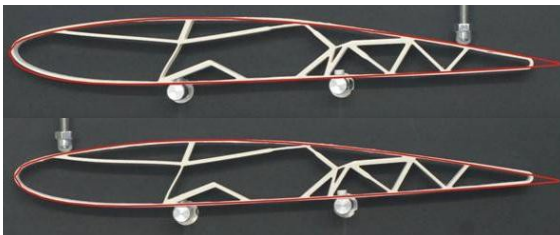
(d) Perera [7].



(e) Courchesne [8].



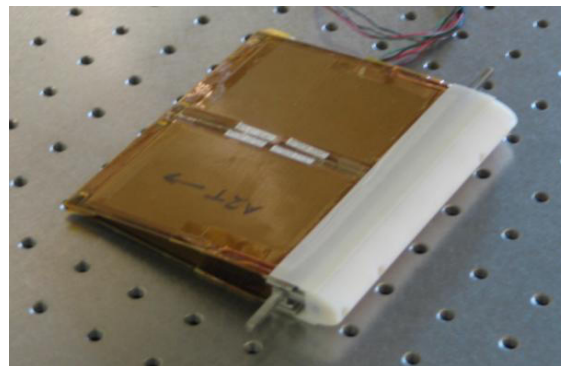
(f) Friswell [9].



(g) Campanile [10].



(h) Debiassi [1].



(i) Bilgen [2].

Figure 1: Morphing review.

Requirements		Preliminary specs	
flutter velocity	12 – 15 m/s	wing span	1 m
actuators bandwidth	20 Hz	sector span	.249 m
		sector chord	.3 m
		airfoil	NACA 0018
		mass axis position	.5c
		flexural axis position	.5c

(a) Preliminary requirements.

(b) Main specs.

Table 1: FEM analysis.

Figure 2 depicts the cross section chosen for the aluminum alloy main spar, the dimensions are summarized in Table 2c. This design has been chosen because it allows almost independent operation of flexural and torsional stiffnesses.

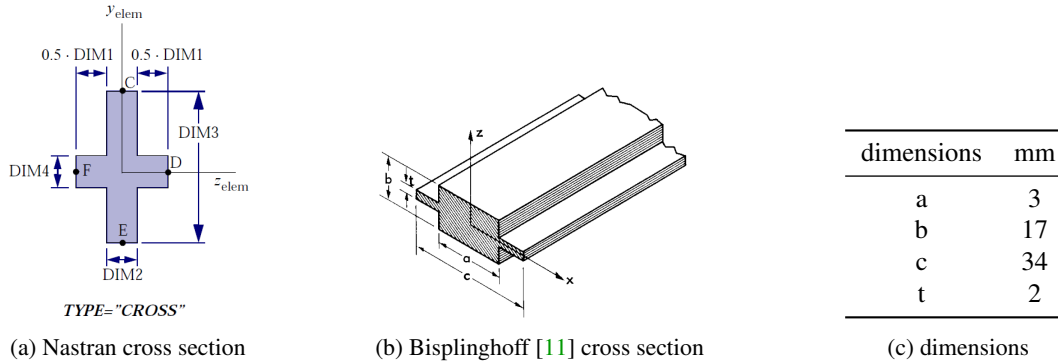


Figure 2: Cross Section specs.

Distribution and positioning of the sensors

The sensor web includes 8 mono-axial accelerometers, two in the middle of each passive sector and two in the tip sector, at 100 mm front and behind the flexural axis. This configuration allows the replacement of an active sector without changing the arrangement of sensors.

Description of the wing design

As shown in Figure 3, the wing is composed of a main aluminium alloy spar and four aerodynamic sectors and a tip sector. Each sector is connected to the main spar by two bolts at mid sector span (see Figure 4b). The reference coordinate system, as shown in Figure 3a, is placed at the root of the spar at .5c ahead of the flexural axis. All the passive sectors have a nose (.2c) and tip (.8c) rod to introduce balancing masses, if necessary. The active sector with a conventional flap has only the nose rod. The position of the hinge axis of the active sector is at .8c. The tip sector, Figure 3d, allows tip balancing masses to be introduced.

Description of the numerical model

The numerical model, Figure 6a, is a beam FE model with concentrated masses to which are added aerodynamic panels to solve the unsteady aerodynamic with MSC.Nastran DLM. Structural damping of 2% has been introduced in the numerical model. A static analysis has shown that the wing, under self-weight, has a tip displacement of 35. mm. The natural frequencies calculated with this model are summarized in Table 6c. The V_g/V_f diagram, computed with the MSC.Nastran SOL145, is depicted in Figure 6b and from it, it is possible to have a preliminary estimation of the flutter velocity $V_f = 14.8m/s$.

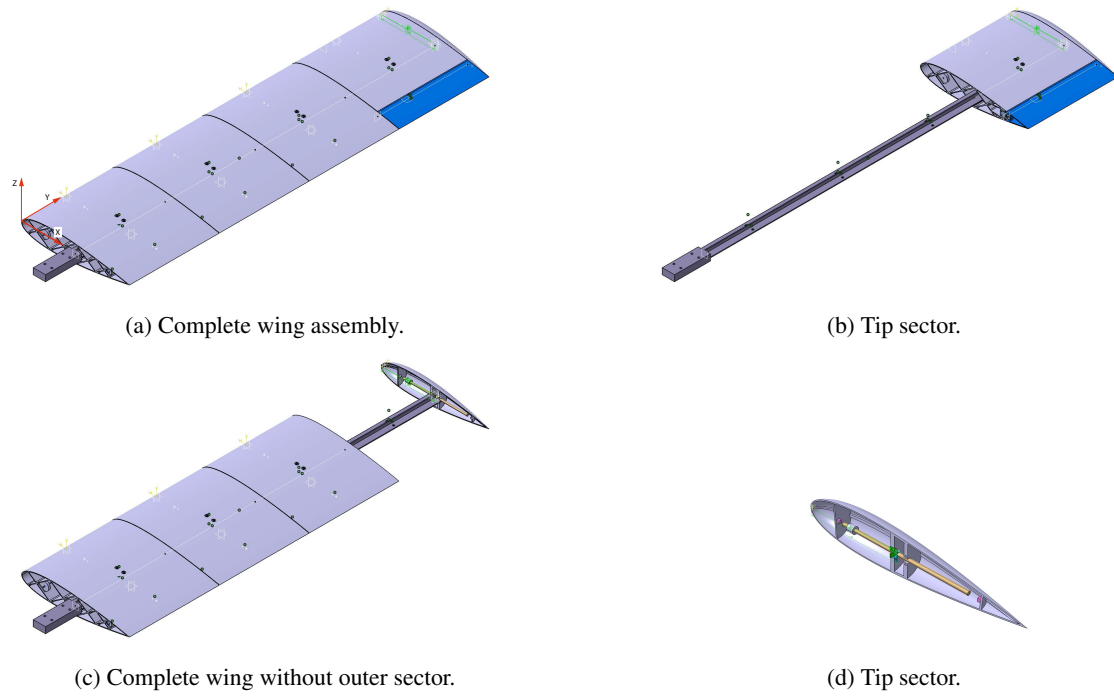


Figure 3: Flexible wing design.

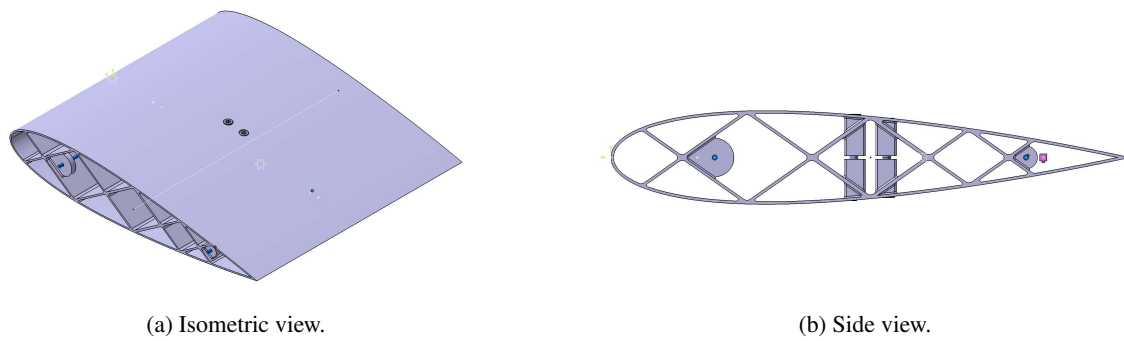


Figure 4: Passive sector.

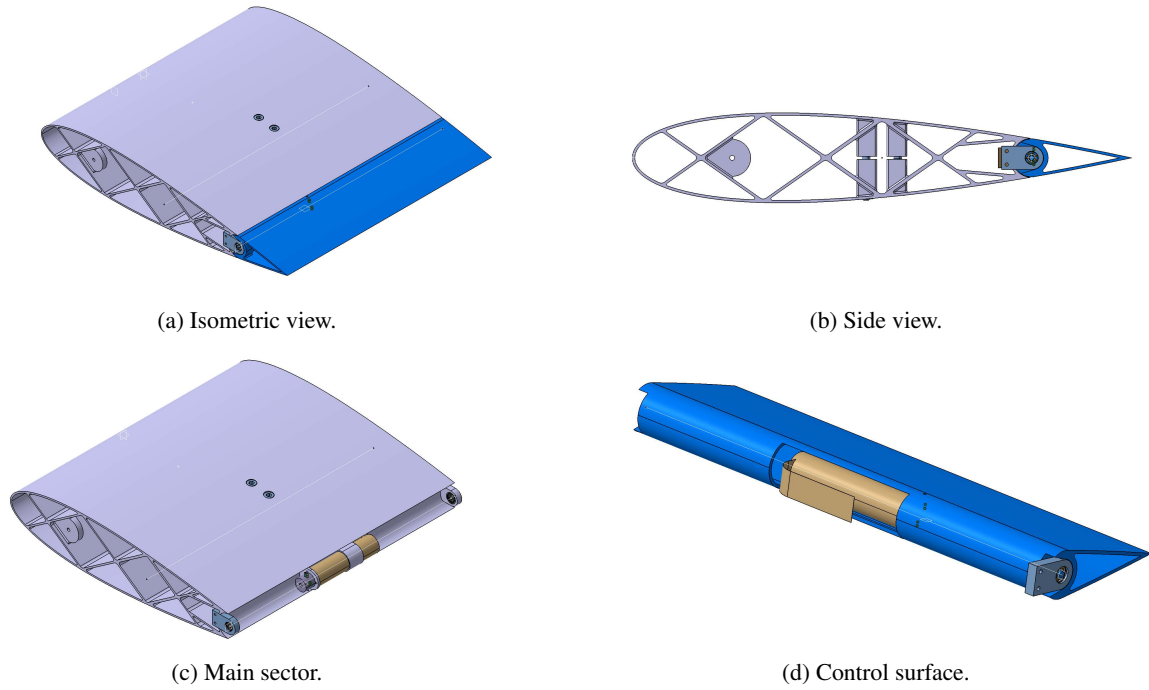


Figure 5: Active sector with conventional flap, ± 20 deg.

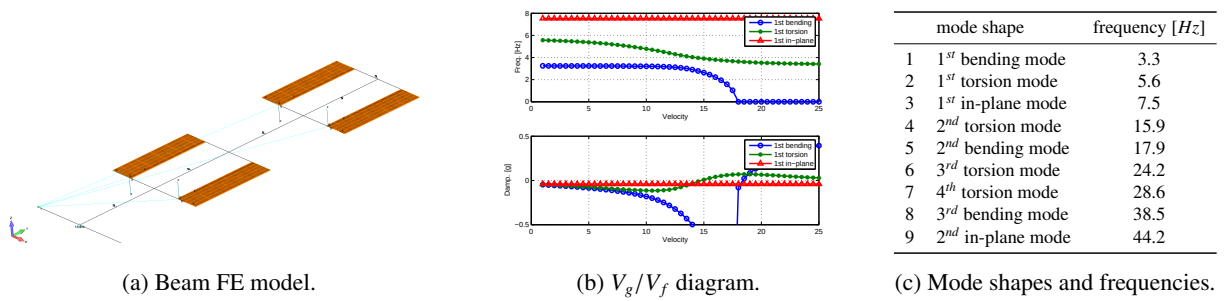


Figure 6: FEM analysis.

III. Morphing Sector

As previously introduced, the goal of this work is to design, manufacture and test a camber morphing airfoil to be used as an active sector in the flexible wing. This section presents at first the iterative design steps that led to the chosen configuration and then the procedure used to manufacture the components. Later on the results from static deflection and static load tests are shown and commented upon. Dynamics test results are presented, including the effect of a low-level PID controller. Finally some preliminary aerodynamic analysis on the morphed configuration are carried out and compared with a reference airfoil with traditional flap.

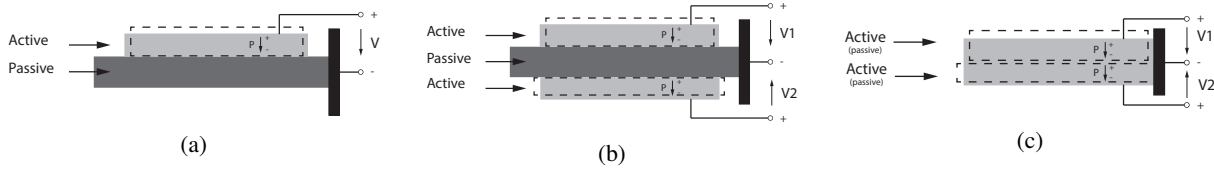


Figure 7: MFC sandwich configurations.

MFC piezo-patches developed by NASA and produced by the Smart Material Corp. are the essential elements of the design. These piezo-ceramic actuators are able to behave as a bi-metal when an electrical charge is applied. Different configurations have been preliminary tested in a stand-alone arrangement and are shown in Figure 7; the configuration chosen for this work is 7b where two MFCs are bonded, one to each side of a steel shim by epoxy glue.^a

A. Iterative development of the design and Manufacturing

The first steps of the iterative design are shown in Figure 8. A first concept with an embedded piezo-patch was manufactured, experimentally tested and was shown to have insufficient control authority. For this reason, a second version, with a trailing edge slider, was designed (Figures 8b and 8d). This proved to be a more interesting solution and a full scale 3D printed model was manufactured and tested. The results are illustrated on the following pages.

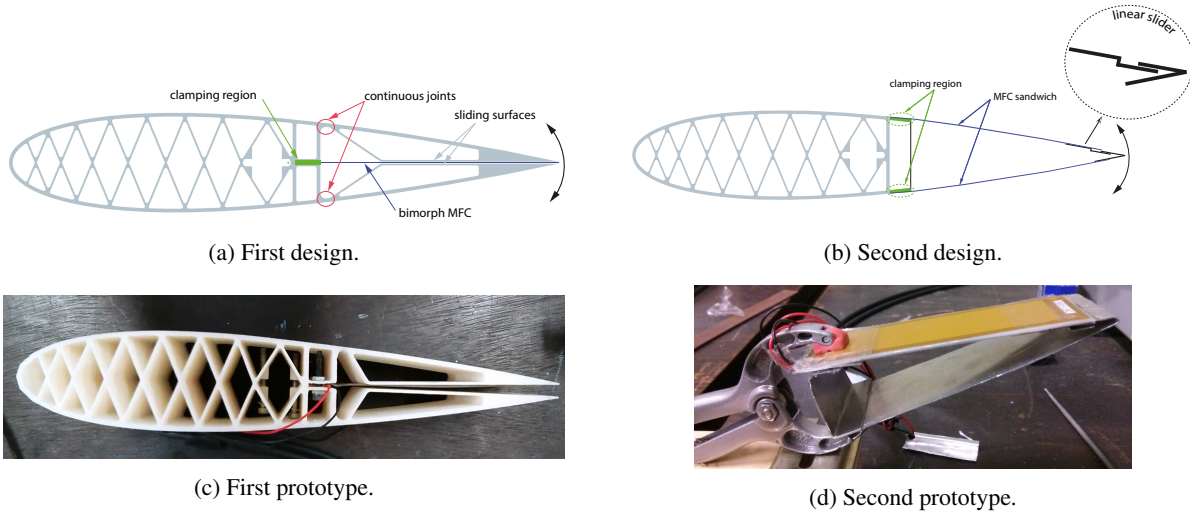


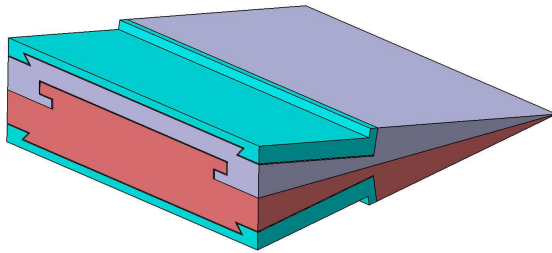
Figure 8: Iterative design.

Sliders description

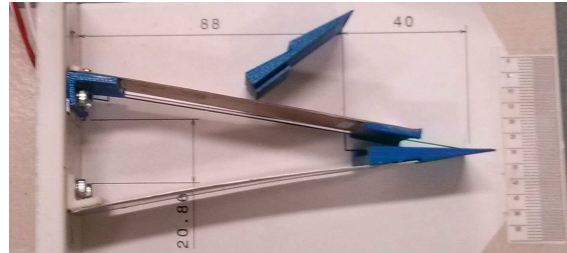
Figure 9 shows the final designs of the linear sliders that were manufactured; in this work, only the behaviour of the T slider has been explored. Figure 9a shows the CAD rendering that depicts the T shaped lower (pink) part inside the upper slider (grey). The length of the T portion was chosen in order to allow $\pm 8. mm$ of linear sliding which ensures

^aEpoxy: 3M DP460 epoxy,
Stainless steel shim thickness: .012 mm.

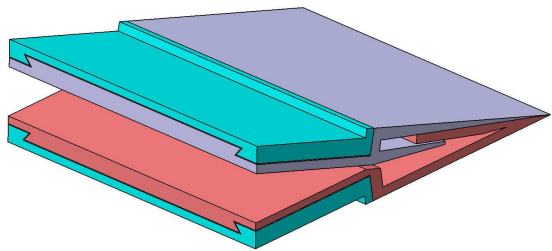
up to ± 20 deg of equivalent deflection. Both the sliders have been designed with a plug-and-play concept, by using the interface parts (light blue); this solution allows many different slider configurations to be tested without changing the MFC actuator.



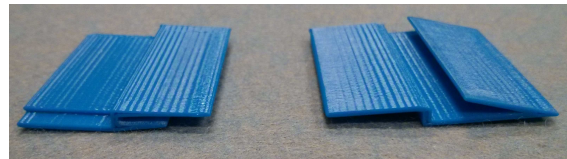
(a) T slider CAD.



(b) T slider experimental model.



(c) C slider CAD.



(d) C slider experimental model.

Figure 9: Trailing edge slider configurations.

B. Test rig

The experimental setup, shown in Figure 10, is composed of a vertical steel support plate, firmly constrained to a reference table, which is connected to two L shaped ABS plastic supports. The upper support is glued to an MFC sandwich that ends with the male T linear slider, while the lower one is glued to a .5 mm thickness aluminum sheet that ends with the corresponding female T linear slider. The voltage to the MFC sandwich is provided by a Real-Time (dSPACE) system through two tailored amplifiers.^b Three laser displacement sensors are used to read the camber variation in three points on the chord, as illustrated in Figure 10a.

C. Static Deflection

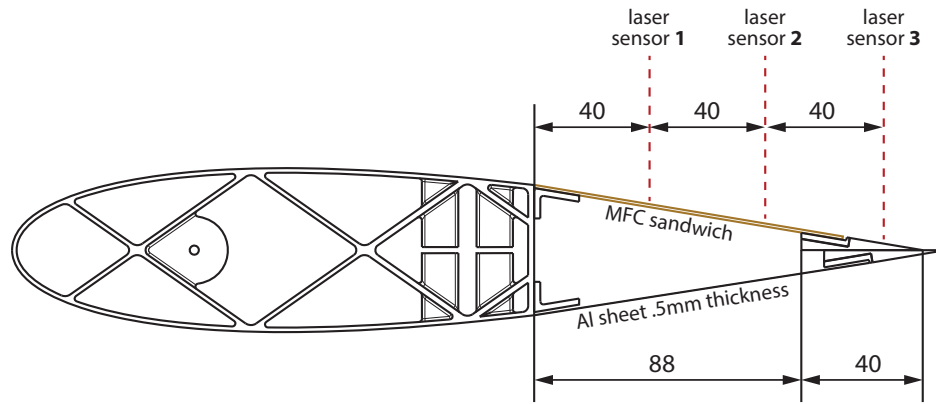
A static deflection test was carried out on the morphing rig previously described. An increasing and decreasing voltage is supplied to the MFC sandwich actuator from 0. up to the maximum (the Smart Material MFC operates asymmetrically between -500 and $+1500$ V, the sandwich configuration allows for symmetric behaviour by introducing an offset in the voltage applied to the MFC.), with an increment of 25 %; the 3 points displacements are plotted in Figure 11a and the up and down reconstructed deformation is shown in Figure 11b. Figure 12 depicts the two end conditions. Both the positive and negative deformation proved to be almost linear, the upper one reaches a maximum displacement value slightly smaller than the negative one (14.5 mm compared to 15.5 mm) probably due to the loss of symmetry as a consequence of the single MFC sandwich actuator and to its angle with respect to the vertical plate.^c

D. Static Load test

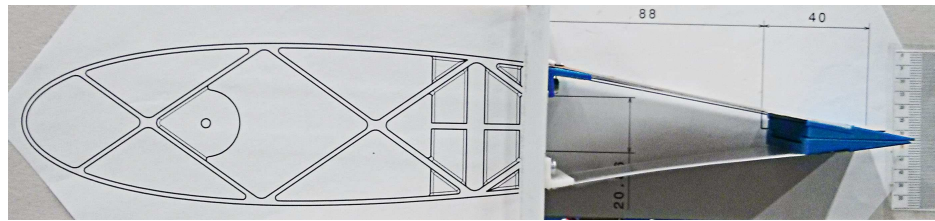
After the static displacement test, also a static load test was conducted. The full positive voltage is provided to the actuator and a mass is hung to the trailing edge, as shown in Figure 13b; the load is increased from 0. g up to 110. g with and increase of 50. g. The continuous lines in Figure 13a describe the 3 points displacements under the different load conditions while the dashed ones represent the 3 points displacements as well, but without any voltage applied to the piezo-actuator. The morphing actuator has proven capable of delivering a force greater than 1. N.

^b designed by Treka and marketed by Smart Material Corp.

^c due to the design of the L shaped connection parts.

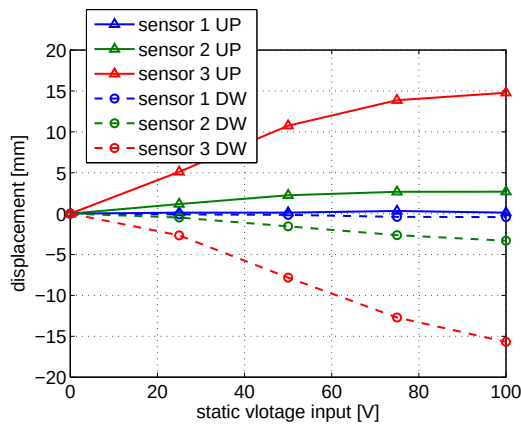


(a) schematic.

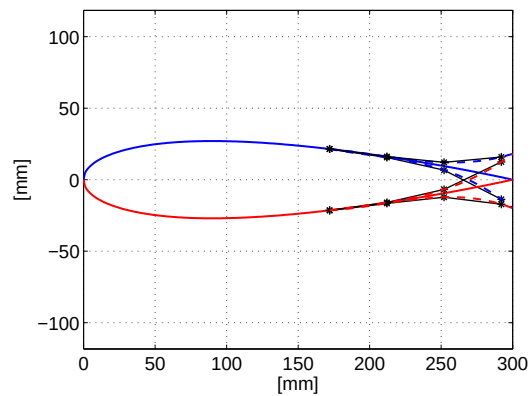


(b) test rig.

Figure 10: Experimental setup.

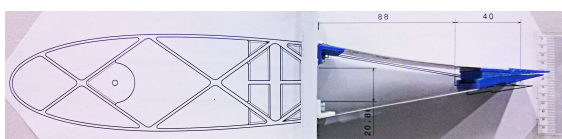


(a) 3 points displacements.

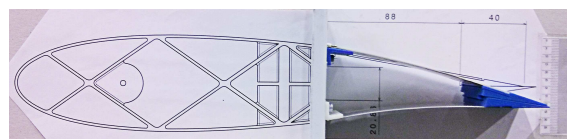


(b) Deformed airfoil.

Figure 11: Actuator static displacement test.

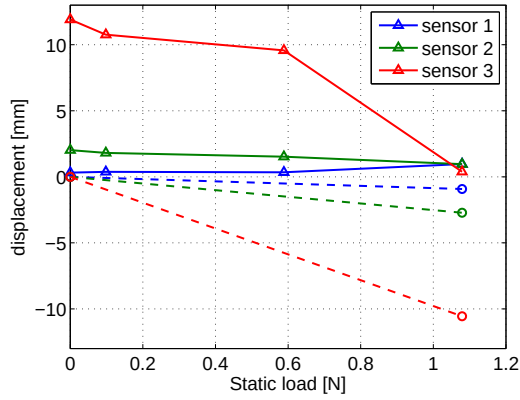


(a) max positive deformation.

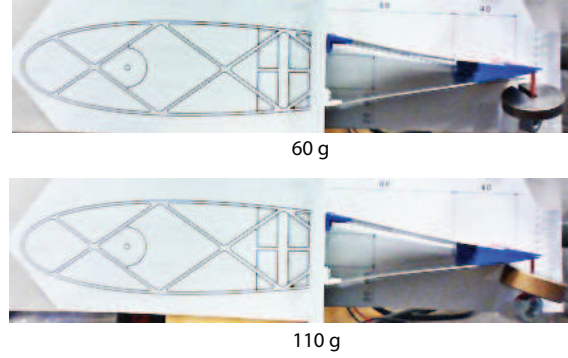


(b) max negative deformation.

Figure 12: Morphing rig static deformation.



(a) static load displacement.



(b) static load experimental setup.

Figure 13: Actuator static load test.

E. Dynamic test

As stated before, the main goal of this actuator design is to have a bandwidth greater than 20. Hz . For this reason a dynamic test campaign has been carried out with the aim to verify if this requirement has been accomplished and to have an insight into the dynamic behaviour of the whole actuator. By using a Siemens PLM system, a stepped-sine modal analysis test was performed; a frequency range from 1. to 30 Hz with a resolution of .05 Hz and delay of 7 cycles has been explored and the results are shown in Figure 14. Table 2 summarizes frequencies and damping computed by

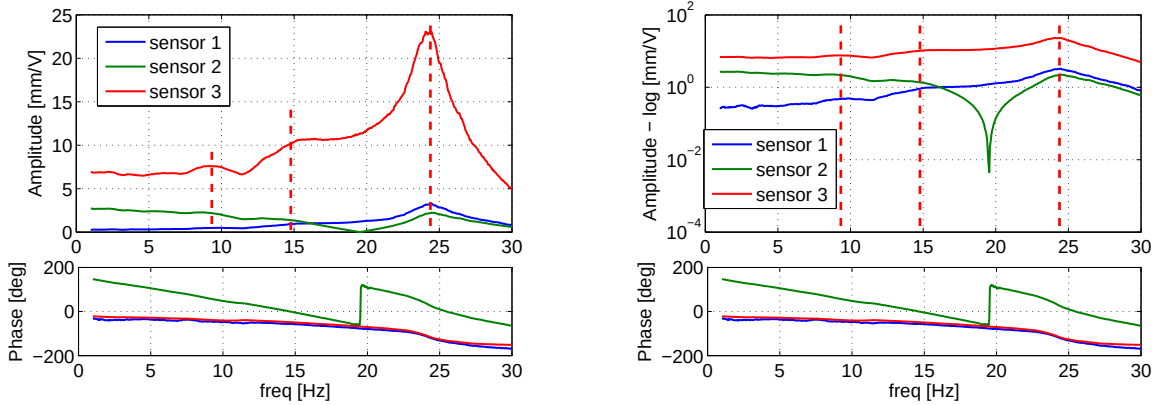


Figure 14: FRF MFC actuator.

the Polymax algorithm. Even if two low frequency poles are present, they seems to be due to minor system dynamics. The real resonance, that shows a clear phase shift, occurs at 24.3 Hz .

Table 2: Frequencies and Damping.

	freq [Hz]	Damp [%]
	9.841	21.14
	14.351	24.18
resonance	24.358	2.67

In order to have a countercheck on the FRF, also a low level dynamic test was done. The morphing actuator is provided with the 50 and the 100 % of the maximum voltage in the range between 1. and 30. Hz and a frequency

step of 2.5 or 5. Hz ; the 3 points displacements are recorded for a generic 10.s window, the data are filtered^d and the maximum displacements are plotted in Figure 15a. As expected, close to the resonance, the amplitude starts growing; for this reason the point at 25 Hz has been omitted and the full voltage test has been performed only up to 15 Hz . However, even if the amplitude starts growing from 15 Hz , a clear counterphase behaviour is shown only at 30 Hz .

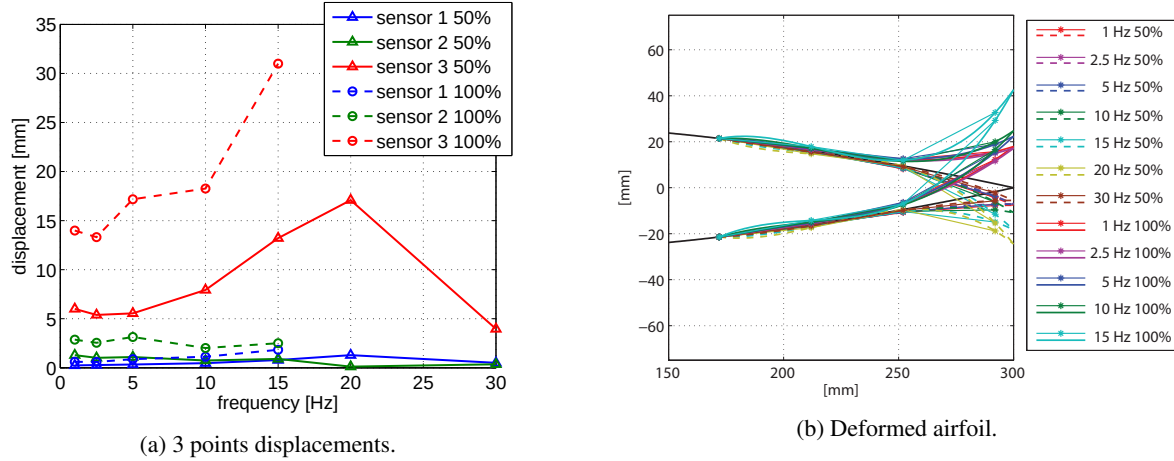


Figure 15: Actuator dynamic displacement test, 50 and 100 percent.

Figure 15b shows the reconstructed deformation of the actuator; the dashed curves, lower part of the diagram, for 50 % of the maximum voltage and the continuous lines, upper part of the diagram, for the 100 %.

F. Low level actuator control - PID

A PID controller has been designed and forms the inner control layer in the final aeroelastic wing; on the top of that, the different control laws for flutter suppression/vibration reduction will be applied. Figure 16 shows PID simplified block scheme: the reading from the laser displacement sensor number 3 is used as position feedback to compute the error with the desired deflection. The real-time dSPACE system takes care of supplying to the amplifiers with the correct output voltage to properly follow the reference signal. Figures 17 and 18 show, for 1 and 2.5 Hz , on the left, the

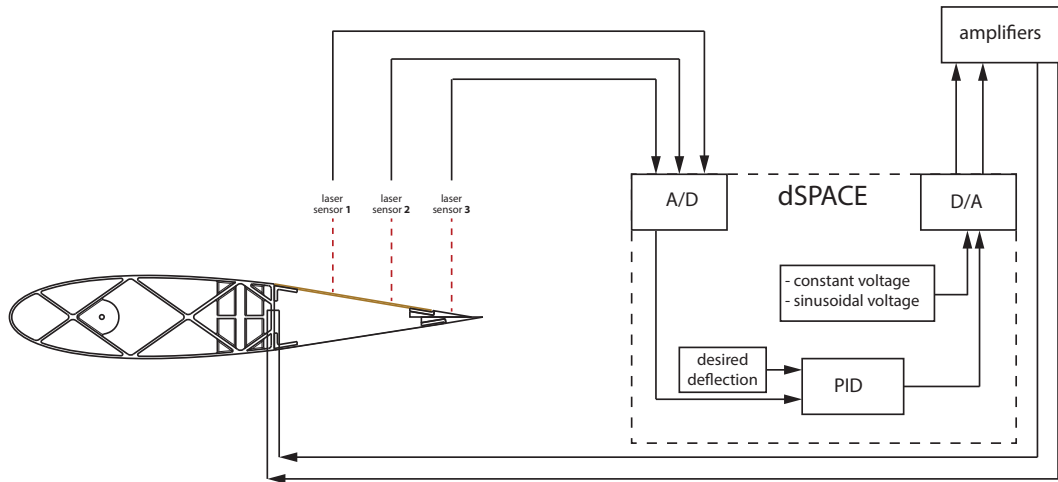
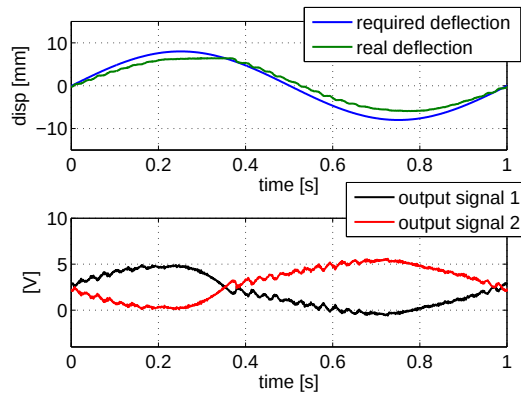


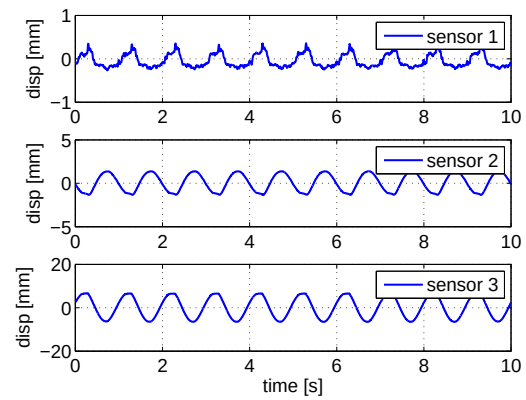
Figure 16: PID controller scheme.

reference signal and the real position (and below the voltage supplied to the amplifiers) and on the right the generic 10.s time history of the 3 laser sensors readings. The reference signal requires a sinusoidal displacement of the third point with an amplitude of 8. mm, for the uncontrolled condition instead the amplifiers are supplied with a sinusoidal voltage

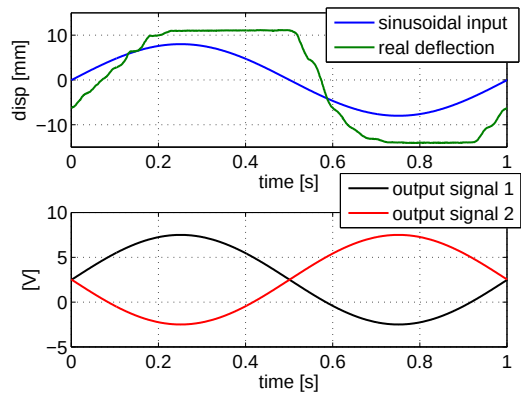
^ddouble direction, lowpass equiripple FIR, 30 Hz .



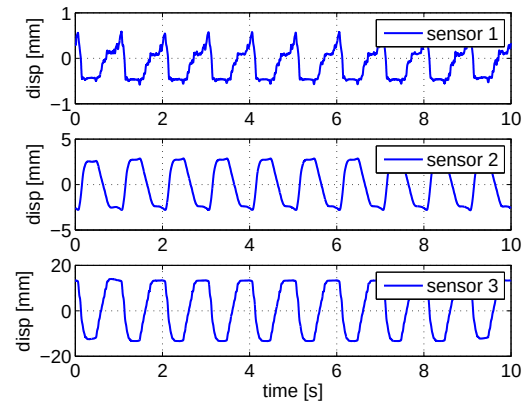
(a) PID controlled deflection.



(b) Laser readings.



(c) PID uncontrolled deflection.



(d) Laser readings.

Figure 17: Controller 1 Hz.

with an amplitude of 5. V.^e Even if the tuning of the PID is only preliminary, it is possible to see, comparing Figure 17a

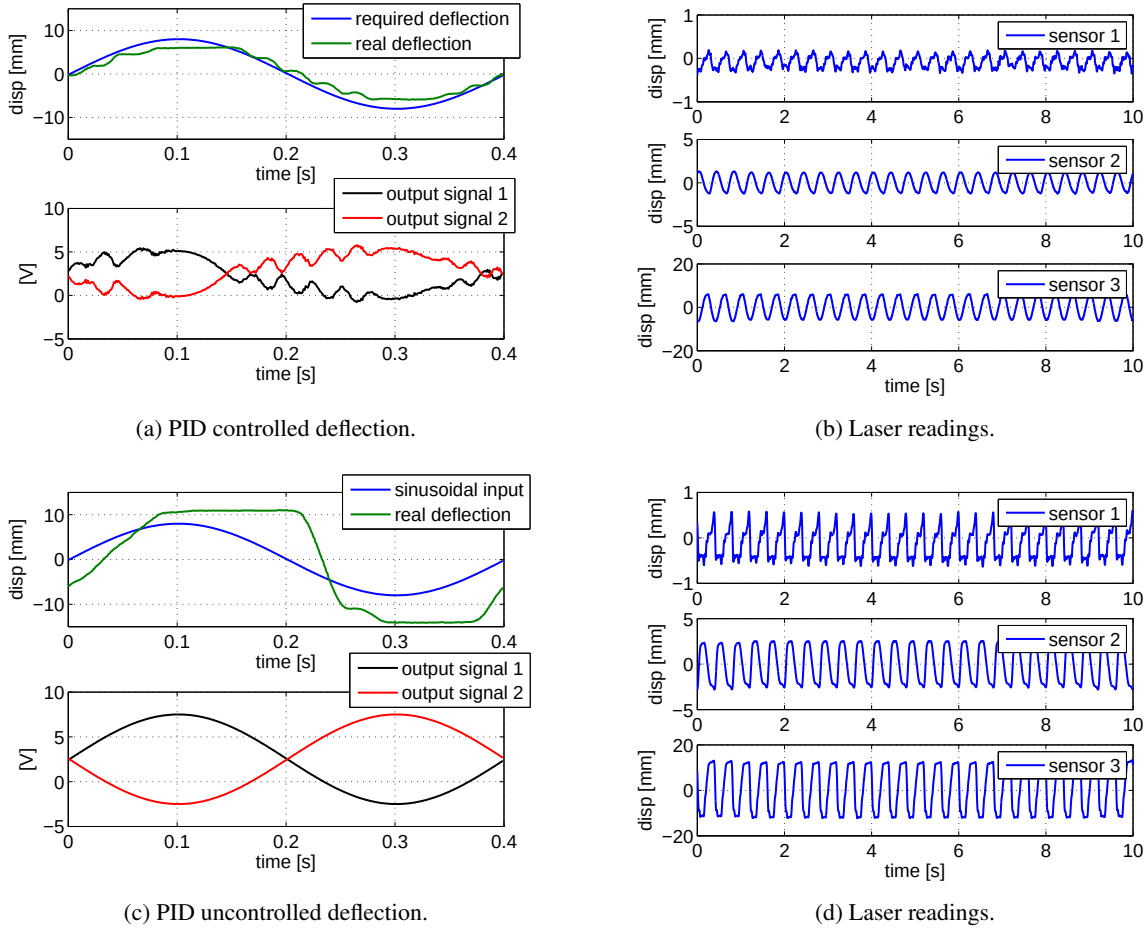


Figure 18: Controller 2.5 Hz.

with Figure 17c (and also Figure 18a with Figure 18c) that the controller is able to tailor the supplied voltage in order to achieve the prescribed displacement. Instead, the uncontrolled actuator reaches, after a ramp transition, the upper (and the lower) plateau; after a closer analysis it seems that this is not due to the slider end of stroke but to saturation of the morphing actuator.

G. Aerodynamic computational model

An automatic procedure to run aerodynamic analysis on the morphed airfoil has been developed. The reconstructed deformed airfoil shape is extracted and properly post-processed in order to be ready-to-use for a low fidelity aerodynamic software, Xfoil and for a meshing software, ICEM. For the last one, an automatic grid generator scrip *ad hoc* developed allows to change the geometry and automatically generate the new mesh for the CFD solver.

Xfoil solver

Xfoil is a free software, written by Mark Drela, based on high order panel methods with the fully coupled viscous/inviscid interaction method used in the ISES code. Figures 19 show the inviscid and viscous analysis performed on the morphed airfoil compared with the same analysis run on an airfoil with a reference trailing edge flap with the hinge axes placed at the .8 c and a deflection of 15. deg.

^eplus the necessary positive offset of +2.5 V.

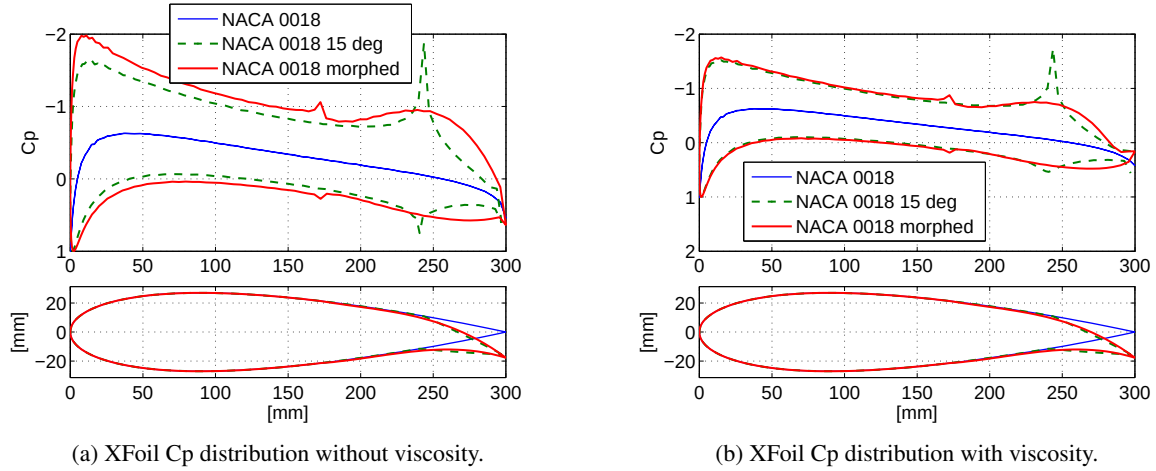


Figure 19: Aerodynamic analysis on the morphed airfoil with XFOIL.

Table 3: XFOIL parameters and results.

airfoil	VISC OFF alpha 0 deg	VISC ON alpha 0 deg, M = .059 Re = 4.e5		
	C_L	C_L	C_D	C_{Dp}
NACA 0018	0.	0.	1.54267	0.31007
NACA 0018 15 deg	325.8143	not conv	not conv	not conv
NACA 0018 morphed	407.4125	312.0648	2.16749	0.87040

CFD - Fluent

A similar analysis is performed with CFD solver, Fluent. The 2D mesh, automatically generated by ICEM, is a C mesh with a chord to length ratio equal 20 and 200000 elements. The size of the boundary layer elements is chosen in order to have the correct Y^+ to satisfy the wall functions requirements. The solution is pressure-based and the turbulence model chosen is Spalart-Allmaras. The preliminary CFD results of Figure 20 shown a good agreement with the low fidelity aerodynamic model previously described.

IV. Conclusions

The work presented in this paper has proven that the MFC sandwich paired with a linear trailing edge slider can be a good substitute of the traditional flap/actuator systems, at least for wind tunnel aeroelastic model. Both static and dynamic tests has been carried out, as well as preliminary aerodynamic analysis. Moreover, a semi-automatic procedure has been implemented and a validation process established. From now on, the numerical/experimental test sequence above described will be used as benchmark for the development of future and different actuating systems.

A. Future Works

Since this is only a preliminary work, a long list of future works is planned ahead.

Test different MFC sandwich configuration: as shown in Figure 7, mainly three MFC configurations are suitable for the purposes of this work, up to now, only the 7a and 7b have been tested, however better performances are expected from the 7c.

Test experimentally the C slider: even if designed and manufacture, the C slider 9d has still not been tested through the actuator validation procedure described above, this will be done soon and the performances compared with the T slider. Moreover, it will be interesting investigate closely the aerodynamic consequences of a not sharp trailing edge for both the sliders.

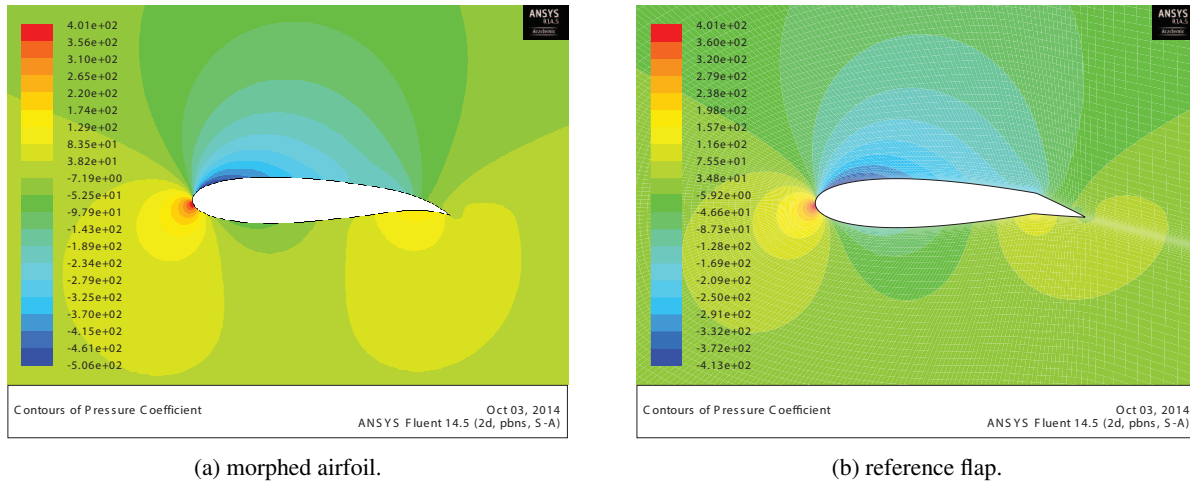


Figure 20: CFD Cp distribution.

Aerodynamic structure interaction: the coupling between the aerodynamic loads, consequence of the camber variation, will be explored numerically by an iterative procedure that will involve a FE model of the sectors and its aerodynamic XFoil/CFD model.

Morphing actuator filler: the need to support the upper and lower skins with a filler (honeycomb) will be evaluated.

Strain gauges as feedback sensor: since it will not be possible to use the laser displacement sensor as feedback signal in the flexible aeroelastic wing due to its complex behaviour coupled with the actuator dynamic; the actuator displacement information will be retrieved by a strain gauge bonded to the MFC sandwich. Of course a careful tuning of the PID will be necessary.

Wind tunnel tests: a greater span version (100. mm) of the morphing sector is planned to be tested in the wind tunnel.

Full span sector: downstream the above investigation, a full span (250. mm) will be manufactured; wider MFC (M8557P1) will be used for the sandwich and, if necessary, a row of them will be adopted.

Last but not least, the morphing sector will be plugged in the flexible aeroelastic wing and used to introduce the desired control laws in the model.

Acknowledgments

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