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Design, Manufacturing and Wind Tunnel Validation of an Active Camber Morphing Wing Based on Compliant Structures

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Abstract

The paper summarizes the recent activities performed at Politenico di Milano in the framework of FP7-NOVEMOR Project related to the application of morphing technologies and in particular to the variable camber concept. After a short reminder on the tools developed aiming at the design of variable camber morphing wings, the paper describes the main results obtained from the application of this morphing concept to a typical regional aircraft. Finally, the design and development of a scaled wind tunnel model for validation purpose is reported.

1. INTRODUCTION

Looking at the huge literature concerning morphing aircraft it appears suddenly clear that morphing is believed as one of the most promising concept aiming at the design of more efficient aircraft. On the other hand, the increased efficiency has been recently recognized as a must for the designers to match the challenging targets defined by US and EU organizations to satisfy more stringent requirements in terms of environment impact. Indeed, morphing aircraft, able to adapt their shape to optimize their performances during the flight envelope, appear as potentially able to produce global improvements in terms of fuel saving and environment impact reduction. However, two main observations can be drawn at the moment. The first one is that many are the morphing concepts investigated but there is not a clear evidence of which is the most promising and mainly when there is a clear advantage in using it taking into account the many aspects such as certification issues, maintainability, fatigue, potential cost increasing. The second one is that there is the need for specific design tools that could assist the engineers in the design, since the conceptual phase, of both the morphing systems and the optimal internal structure that guarantees the required shape changes with the most efficient use of the actuators. Indeed, the most challenging aspect of the design of morphing devices is that they require the availability of ad-hoc developed procedures able to tackle the conflicting requirements such as the high deformability requested to change the wing shape combined to the load carrying capability and low weight.

Having in mind these open issues, about five years ago this research group at Politecnico di Milano started a research activity focused on the development of specific tools for the design of morphing wings. The core activity is dedicated to the design of active camber concepts based on the use of compliant structures. The main outcome of this research effort is represented by a complete framework for the design of morphing wing based on two main tools, named PHORMA and SPHERA. PHORMA is used to define the optimal wing shape in terms of mission profile performances, while SPHERA is used to design the internal compliant structure able to produce the target optimal shape once actuated. While the framework has been applied inside different national and EU projects, the paper mainly summarizes the results obtained inside the FP7 EU NOVEMOR project (Novel Air Vehicle Configurations: from Fluttering Wings to Morphing Flight). The project is coordinated by INSTITUTO SUPERIOR TECNICO (Portugal) and includes as partners POLITECNICO DI MILANO (Italy), THE UNIVERSITY OF BRISTOL (UK), KUNGLIGA TEKNISKA HOEGSKOLAN (Sweden), DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV (Germany), COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH (South Africa) and EMBRAER SA (Brazil).

The paper presents a short description of the developed tools and a summary of preliminary results obtained on a typical regional aircraft. Then, the design and methods adopted for the design and manufacturing of a wind tunnel model aiming at the validation of the proposed approaches and morphing solutions is reported.

2. THE PARAMETRIC FRAMEWORK PHORMA

PHORMA (Parametrical sHapes for aerOdinamic and structural Modelling of Aircrafts) is an Object Oriented code composed by a suite of tools that allow to exchange and handle different geometries in order to generate an optimized 3D model. These geometries can be provided in discrete, polynomial, spline, CAD-based and analytical form. PHORMA can be used from scratch, to define the parametric shape of wing or full aircraft or, starting form an already available CAD file. In this case PHORMA allows to identify and parameterize the shape so to be able to perform the shape optimization run. In this second way, starting from an user-provided CAD model, the shapes corresponding to a set of the most important sections of the aircraft model, are locally identified and associated to a set of attributes including the position and the orientation of each shape. These shapes are combined in the three dimensional space through a piece-wise linear or cubic interpolation so that local shapes changes can be spread out. The 3D parameterized geometry can be directly used to produce the CFD or FEM mesh of corresponding aerodynamic or structural models, to provide a fast interface to commercial softwares.

The core of PHORMA is the CSTv3 tool, based on the CST parameterization technique, originally proposed by Kulfan [5,6] and extended by PoliMI to morphing airfoils [7,8]. This parameterizations technique is called Class/Shape function Transformation (CST) method and allows to describe and manage the global shape of the aircraft sections without affecting their local regularity. It is based on merging four terms: a Shape Function, a Class Function and two additional terms related to the airfoil leading edge and trailing edge shapes. The details of the method and how the coefficients are computed are described in the reported literature so here just the relevant details are summarized.

The CST technique has been implemented using a Object-Oriented Programming (OOP) approach as a class with several methods in a dedicated framework. Once applied to the airfoil geometry describing the wing, thanks to its analytical nature, CST allows for the fast calculation of the first and second order derivatives that can be used to compute the length and curvature of the upper and lower surfaces. In addition, other implemented methods allow to compute the airfoil area, the arclength of both leading edge and airfoil surfaces with respect to a non--dimensional variable ψ, the camber or thickness analytical functions, the slope, the airfoil min/max values, etc. Moreover, simple arithmetical operations between airfoils are available. For all these reasons, the CST technique is suitable for use in shape optimizations.

The CST parameterization technique is well suited to represent the shape changes of morphing airfoils and it can be also used to describe the structural behavior of the skin. The length and curvature of airfoil upper and lower surfaces are geometrical quantities which could be strictly related to the structural properties of the morphing airfoil skins. Indeed, the stress into the skin consists of two term: the stress due to axial tension or compression σ_{axial} and the stress due to bending bending σ_{bend}. When the airfoil shape changes due to a morphing process it is easy to compute the length of both undeformed and morphing airfoil surfaces and to estimate the axial stress that is required to stretch or compress the airfoil skins. At the same time, the bending stress is computed calculating the curvature difference between the initial and the final airfoil shape. If for sake of simplicity it is supposed to represent into a 2D domain the airfoil skin as a sequence of beams, according to the Euler-Bernoulli beam theory, the maximum bending stress along the skin can be calculated, knowing the Young's modulus and the skin thickness as a function of the curvature difference between the undeformed and the morphing configurations. The availability of length and curvature variations of the airfoil's upper and lower surfaces, strictly related to the axial and bending stresses generated when the skin is forced to assume the morphing airfoil shape, can then be used as explicit constraint function to drive the shape optimization procedure.

One of the problem in analyzing different morphing concepts is related to the need to create in an efficient way all the necessary morphing geometry models representing the morphing devices in their different status, taking into account structural and aerodynamic requirements. The approach adopted by PoliMI is based on a procedure developed in a previous work [8] here tuned for specific morphing devices. The generation of the geometry model of the 3D full wing corresponding to the different position of the morphing devices is based on the use of PHORMA and it is done in three steps: a 2D identification of the initial airfoils, a 2D morphing shape optimization able to introduce the shape changes under all the design requirements and a 3D propagation to the full wing.

2.1 2D and 3D CFD modeling

Aerodynamic loads can be computed by a specific code embedded into the CST tool able to automatically produce a 2D structured mesh around the airfoils and to perform Navier-Stokes computations. The automatic generation of the structured mesh around the parameterized airfoil shape is based on a script for Ansys ICEMCFD. CFD computations are performed by means of EDGE code. Once the CFD analyses have been performed, the CST tool is able to extract the results in term of Cp distribution and to spread them along the airfoil shape used to produce the load path model.

While the optimal morphing mechanisms is computed at first on the 2D airfoil, then extended to the full wing, it is important that the aerodynamic loads considered during the 2D optimization are representative of the 3D wing. For this reason the aerodynamic loads can be also directly extracted from the 3D CFD computations, performed by. Afterwards PHORMA is able to extrapolate the aerodynamic results, around one or more sections arbitrarily positioned and oriented, and to match them to corresponding CST parameterized shapes. Once the 3D model is obtained in a parametrical way, unstructured surface meshes can be automatically generated without any user intervention.

2.2 FEM Modelling

One of the main classes in the framework is the OOP-based PFEM class which incorporates an in-house FEM code able to handle different types of elements and incorporate different solvers. As well as SPHERA is an object that inherits the PFEM properties to solve structural problem corresponding to the Load Paths representation, PHORMA is an object based on different sub-classes which interacts with PFEM methods to generate 3D aeronautical FEM models.

PFEM incorporates modal, buckling, linear and non-linear static analyses, allows to use different types of elements and provides several methods containing standard tools for the management of a FEM model. In addition to the basic BAR element and to some isoparametric element, such as Q4 bilinear qudrilateral element [9], the code includes Finite Volume Beam element [10].

2.3 Fluid-structure interface

Once the aerodynamic results are computed, a fluid-structure interaction method is used to transfer these loads from the aerodynamic mesh to the structural grid points placed oN the airfoil skins. For this purpose, a tool based on the Radial Basis Function (RBF) [11-13] is available in the procedure. This method ensure the conservation of the energy transfer between the fluid and the structure. By applying this tool to the trailing and leading edges of morphing airfoils and using it as aeroelastic interface, aerodynamic loads are distributed along the beam nodes and reduced to lumped forces.

2.4 Aero-structural Shape Optimization problems

Morphing shape optimizations used to introduce shape changes into the reference model can be performed by evaluating the aerodynamic performances in 2D or directly in 3D space. In both cases, two nested optimization loops are required: the first one is a 2D structural shape optimization where only structural constraints are at first satisfied on the airfoil skins, in the second one an aerodynamic optimization is performed starting from physically realizable airfoils.

In the 2D shape optimization, the process is applied to each airfoil shape extracted from the reference CAD model. After the structural shape optimization, PHORMA automatically produce the mesh of both clean and morphing airfoils, in order to perform as many 2D high–fidelity aerodynamic shape optimizations as the number of identified sections are.

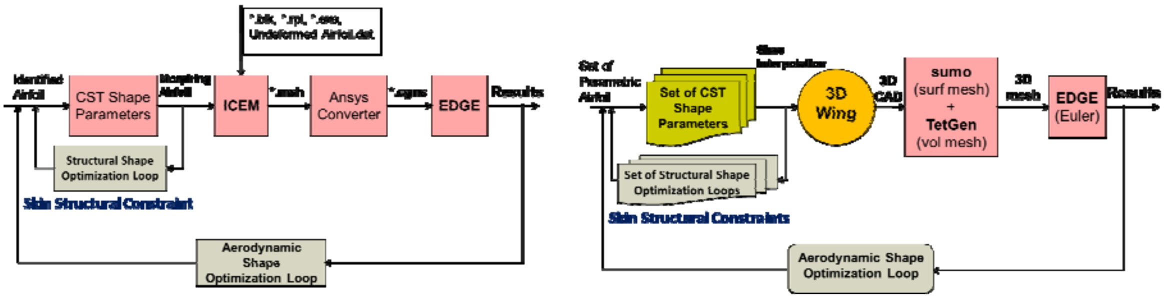

Figure 1. 2D AND 3d aero-structural shape optimization.

1.

Combining the different optimal airfoil shapes coming out from the 2D shape optimizations represented in Fig. 1, the 3D CAD model corresponding to the morphing wing configuration is generated.

In the 3D shape optimization, the process previously described is applied to a set of parameterized airfoils previously subjected to the skin constraints via a number of structural shape optimizations equal to the number of identified sections. The aerodynamic shape optimization directly produce the final 3D morphing model.

3. THE TOOL SPHERA

SPHERA (Synthesis of compliant mecHanisms for Engineering Applications) is a general tool for the synthesis of compliant mechanisms [14], with specific features dedicated to the design of morphing airfoils. These features are inherited from an integrated multiphysics environment, based on the CST parameterization. Once the 3D wing geometry is identified and corresponding parameterized shapes are available, different models can be linked to a common geometry representation. The framework includes features for the generation of CAD, CFD, FEM and load paths models and contains solutions for the coupling between different models. It can be used for structural and fluid analyses, or for the synthesis of compliant mechanisms.

The overall framework has been efficiently implemented and the most important parts have been designed as objects and classes interacting each other by means of the Object-Oriented Programming (OOP) techniques. This allows to group the most important data structures, consisting of data fields and methods together with their interactions, into separate entities. The OOP concept allows an independent development of each component and an easy interface with any other application which can take advantage of its capabilities.

SPHERA allows to conciliate the conflicting requirements of deformability, load–carrying capability and low weight design systems by means of the synthesis of compliant mechanisms based on the distributed compliance concept, in which only flexible elements are employed instead of rigid links connected by flexible hinges. These lightweight systems are optimized to spread elastic strain over the entire structure so that all its elements share the actuator input load to produce large deformation. A compliant structure without stress concentrations is suitable for load bearing applications, as requested by aircraft structures.

Once the morphing airfoil shape optimization is completed, SPHERA allows the design of the best airfoil internal structural configuration able to match, once actuated, the optimal shape defined by PHORMA.

3.1 Load path representation for the design of morphing

SPHERA is based on the load path representation which is a particular design parameterization of the stiffness tensor employing load paths to represent different structural topologies, cross–sectional beam areas for the sizing problem and the position of essential points for the shape problem [2]. This unified approach is based on beam element models so that the results are steered to solutions based on distributed compliance concept. This approach is valid for the synthesis of Single–Input Single–Output (SISO) compliant mechanisms and it can be successfully applied to the design of Single–Input Multi–Output (SIMO) compliant mechanisms for the structural shape control [7,8].

When the load path representation is applied to the shape control problems like the morphing airfoils, it allows to optimize a compliant structure able to transfer the input actuator force to a set of so-called active output points placed along the boundary of the structure, in order to change its shape and minimize a functional, under several constraints.

Load paths are physical connection sequences between three different types of points: the input actuator, structure constraints and active output points. The three types of essential points define as many load paths connecting load input and active output points (InOut paths), load input and constraint points (InSpc paths), and constraint points and active output points (SpcOut paths). A fourth type of characteristic points is represented by the structure internal points which are the load path intermediate connections.

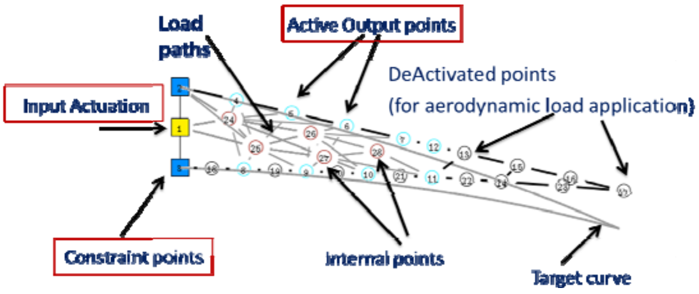

Figure 2. A demonstrative connected load path representation of a SIMO compliant mechanism and the corresponding four types of characteristic points: active output points (cyan), deactivated output points (black) for the external load application, internal structure points (red), input actuation point (yellow), and constraint points (blue).

When the load path representation is applied to shape control problems, the design variables include path sequence, binary path existence variable, internal point coordinates and cross sectional load path sizes. Moreover, the design variables also include load path output destinations and structure boundary sizes.

A number of points placed along the airfoil skin contour, greater or equal to the number of active output points, is used to minimize the Least Square Error (LSE) between the deformed shape and the target shape which comes out from the morphing shape optimization performed by PHORMA described in section 2.4. The optimization problem tries to minimize the least square error under size constraints for the load path beam elements and structure boundary elements, internal point boundaries, two global connectivity equations, stress and buckling constraints and the elastic equilibrium equation. In order to calculate the deformed curve every set of load path is transformed into a sequence of Finite Volume Beams [10].

When the output active point number and locations are defined, the designer can specify the minimum discretization mesh size of the skin finite volume beam model, in order to improve the resolution of the results. A number of points placed along the airfoil skins model, greater or equal to the number of active output points, can be used to minimize the LSE. The additional points introduced along the boundary allow to spread the pressure load, coming out from the aerodynamic analysis, on the airfoil skins.

Moreover. the designer can define, in an graphical interactive way, both the internal point locations and a set of load paths. SPHERA is coupled to the CST tool in order to assist the engineer in the preparation of the optimization problem. Besides providing the target curve, the CST tool defines the design domain and analytically imposes the structure internal point boundaries included in the optimization constraints. Moreover, it allows to identify the optimal position of the active output points and helps to compute the external aerodynamic load. Morphing airfoil meets the load-carrying requirement if they are able to adapt their shape and to maintain it under the external aerodynamic load corresponding to the considered flight conditions. SPHERA includes the interaction between the mechanism/structure and the fluid by means of a technique based on the Radial Basis Function (RBF) in order to define the interface between structural and aerodynamic models.

3.2 Genetic Algorithms based on Multi-objective approach

Because the deformation of the airfoil skins is influenced by both the topology and the dimension of the compliant mechanism, it is important to unify and simultaneously address the topology and size design of the airfoil structure. For this purpose, SPHERA incorporates a customized Genetic Optimizer where the individuals making up the population, are composed by mixed-type design variables and the generation of each new population is produced by selection, crossover and mutation dedicated strategies which represent the kernel of the whole design tool. Writing dedicated selection, crossover and mutation subroutines allows to combine the topology synthesis, the size and shape optimization into the same process, by imposing connectivity, stress and buckling constraints simultaneously.

Moreover, in order to design a compliant mechanism able to meet both kinematic (motion) and structural (load-carrying) requirements, the design must be decomposed into several parts considering the mechanism design and the structure design, respectively, for a number of load conditions corresponding to the flight condition analyzed. This is a typical multi-objective design problem that can be efficiently incorporated into the genetic algorithm. The approach hereafter used for solving this kind of problems applied to our purposes is the so called Elitist Non-Dominated Sorting Genetic Algorithm (NSGA-II) [15].

When SPHERA tool is applied to a morphing leading or trailing edge wing section, two main objectives have been considered. At first, the minimization of the SE (Strain Energy) solving a system where the input point is fixed and the external aerodynamic loads correspond to the first load condition analyzed (structural requirement). Then the minimization of the LSE (Least Square Error) because the displacements of the output points allow to match the target shape change defined by PHORMA, under the input actuation load and the external aerodynamic loads corresponding to the considered flight condition (kinematic requirement).

4. THE REFERENCE AIRCRAFT

Aiming at the availability of a common test case, not based on restricted data and freely available for the evaluation of new technologies such as morphing, NOVEMOR partners decided to develop from scratch a complete, realistic aircraft, potentially distributed as an open source model to be freely adopted by the world community. This key duty was covered by EMBRAER, the only industrial partner of NOVEMOR consortium. The Reference Aircraft (RA) is a typical regional airplane capable to provide operational flexibility to accomplish different missions at the transonic regime. In particular, the establishment of the operational requisites, for the reference aircraft, was obtained considering missions that encompass 600nm. Nevertheless, the same reference aircraft is capable of accomplishing missions up to 2300nm. The Reference Aircraft was designed to achieve an optimum cruise performance at the Mach number 0.78 and the lift coefficient, CL, of 0.47. The aerodynamic design was performed by means of an optimization process considering a medium fidelity solver, namely BLWF, then validated by higher fidelity analyses performed with the CFD++ solver.

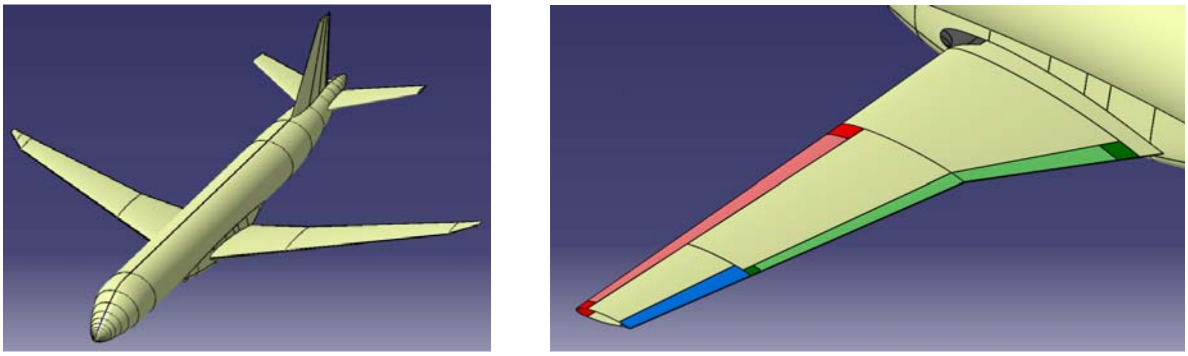

Figure 3. The different LE and TE morphing configurations investigated.

The framework based on the two previously described tools, i.e. PHORMA and SPHERA, has been applied to Reference Aircraft aiming at reducing the fuel consumption during the entire mission. Two specific applications have been investigated: a low speed flight segment based on the adoption of a morphing Leading Edge in place of a traditional slat; a long range mission where the TE morphing device is used to increase the efficiency. The results have been already presented in [16, 17], so here only the final results are reported. The optimal shapes adopted using PHORMA allowed a fuel weight reduction of 5% in case of LE morphing while a reduction of 1.05% in case of TE morphing. Starting from these optimal shapes, the internal structure was optimized in terms of topology and sizing using SPHERA for both LE and TE devices (see Fig. 4).

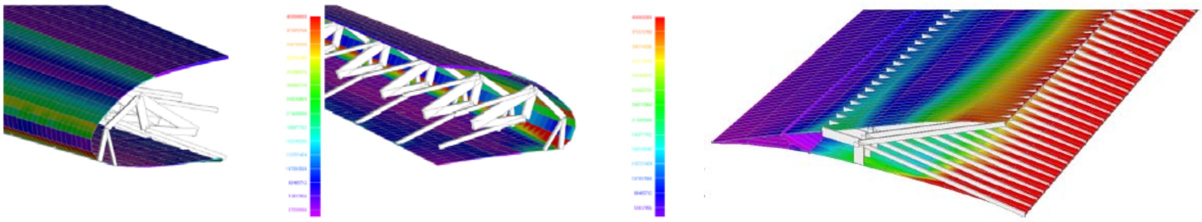

Figure 4. Compliant devices for morphing LE and TE of Reference Aircraft.

5. WIND TUNNEL VALIDATION

The Wind Tunnel validation of morphing configurations including the mechanisms used for shape control is not an easy task and strongly depends on the scale factor and manufacturing strategy adopted. For this reason, it was decided inside NOVEMOR consortium to proceed with two different experimental validation campaigns. The first validation campaign is based on the use of a pure aerodynamic wind tunnel model, implementing the morphing shapes but not the mechanisms, to be tested in a transonic wind tunnel to validate the CFD simulations used during the design and optimization process. The model was manufactured and tested by CSIR, one partner of the NOVEMOR consortium. A half model, composed by a wing + body with a wing span of 1.2 m was tested at two different Mach number, 0.3 and 0.78. Figure 5 shows a picture of the model inside the CSIR wind tunnel.

Figure 5. The RA model inside the CSIR transonic wind tunnel.

The second experimental campaign aimed at the validation of the optimization procedure to design the compliant devices able to produce the optimal morphing shape. This campaign is now under way so in the following just an overview of the models and methods adopted is reported.

5.1 Design of the Morphing Devices for Wind Tunnel Testing

It appears as clearly understandable that it is not possible to take the compliant structure designed for full aircraft and simply down scale it to the right size available in the wind tunnel. It is necessary to redesign completely the morphing structures working directly on the real size of the wind tunnel model.

The wing model here considered has to be tested in the small scale wind tunnel available at POLIMI, equipped with a testing chamber of 1x1.5x3 m for a maximum speed of 55 m/s, sketched in Fig. 6.

Figure 6. The wind tunnel used for morphing devices validation at POLIMI.

Figure 7. The morphing geometries investigated.

The wing model has a span of 1m and a chord of 0.4m. To reduce the complexity of the experiment, the wing is untapered. The airfoil adopted is similar to the one used for the Reference Aircraft and the maximum deflections adopted during the optimization of compliant structures is equal to 10 degs down for LE and 10 degs up and down for the TE morphing devices. The chord extension of morphing devices is equal to 12% and 72% for LE and TE, respectively. Figure 7 shows a sketch of the morphing airfoil here investigated.

Looking at a single test speed equal to 40 m/s, PHORMA framework has been applied to obtain the optimal aerodynamic shape. In particular, in the case of LE the 2D aerodynamic optimization aims at the maximum efficiency while, as structural constraint on the skin, a null length variation so to minimize the axial stresses. In the case of TE, the 2D aerodynamic optimization aims at the maximization of the CL with a limitation on the maximum skin deformation.

Once obtained the optimal shapes from PHORMA, the framework SPHERA has been adopted to define the optimal internal compliant structure able to produce, once actuated, the desired external shape. In the case of LE a standard multi-objective problem has been setup, combining the kinematic and the structural requirements. On the other hands, in the case of TE optimization, due to the double requirement of moving the surface up and down, the multi-objective function has been selected by combining the kinematic constraints (LSE error between the actual and the target deformed shape) in both up and down configurations.

Figure 8 shows the optimal compliant structure for morphing LE in the deformed configuration, the complete Pareto front and the 3D LE configuration obtained by propagating the optimal 2D solution

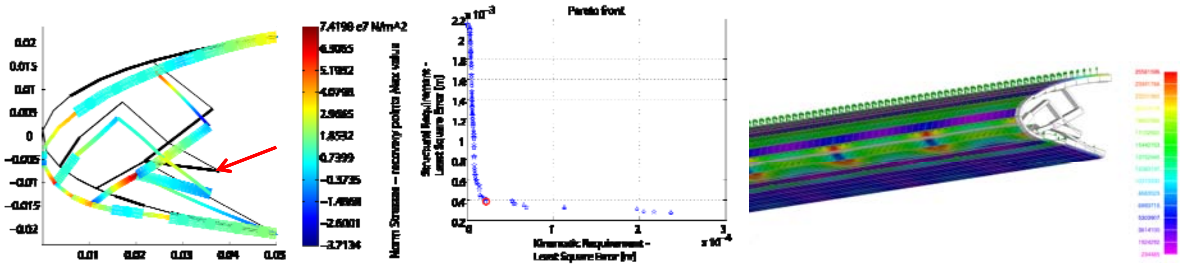

Figure 8. The optimal LE compliant structure: deformed configuration (left), the Pareto front (middle) and the 3D configuration (right).

Figure 9 shows the optimal compliant structure of morphing TE in both maximum up and down configurations, together with the complete Pareto front. The structure is driven by a single linear actuator applied to the lower skin able to slide horizontally.

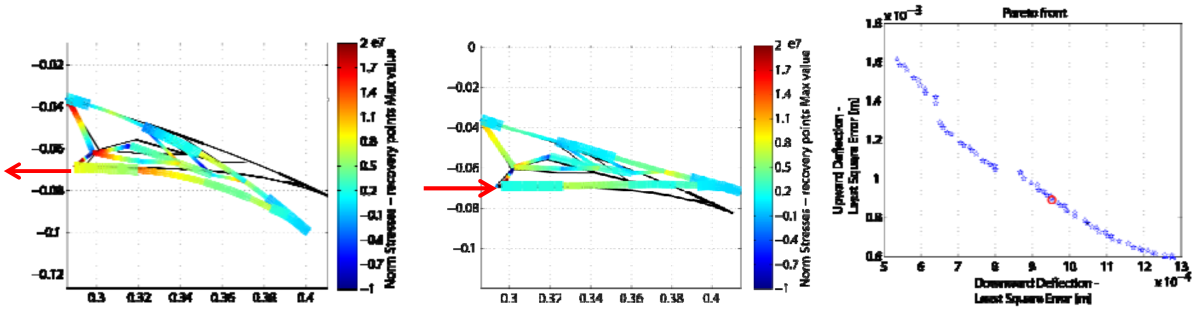

Figure 9. The optimal TE compliant structure: deformed configurations down (left) and up (center) and the Pareto front (right).

5.2 The Wind Tunnel Test Setup

The wing model is designed as a modular structure made of aluminum ribs and C shaped from and rear spars, while a transparent polycarbonate skin allow to control the actuation mechanisms inside. The morphing LE and TE are attached to the front and rear spars. The actuation system is based on the use of off-the-shelf servo actuators used for robotic and aircraft modeler applications. The wing model is connected from the side rib to an already available rig used for dynamic stall investigation on helicopter blades, allowing for a automatic variation of the angle of attack. The rig includes a load cell to measure the loads acting on the wing model. Details of the wing model are sketched in Fig. 10.

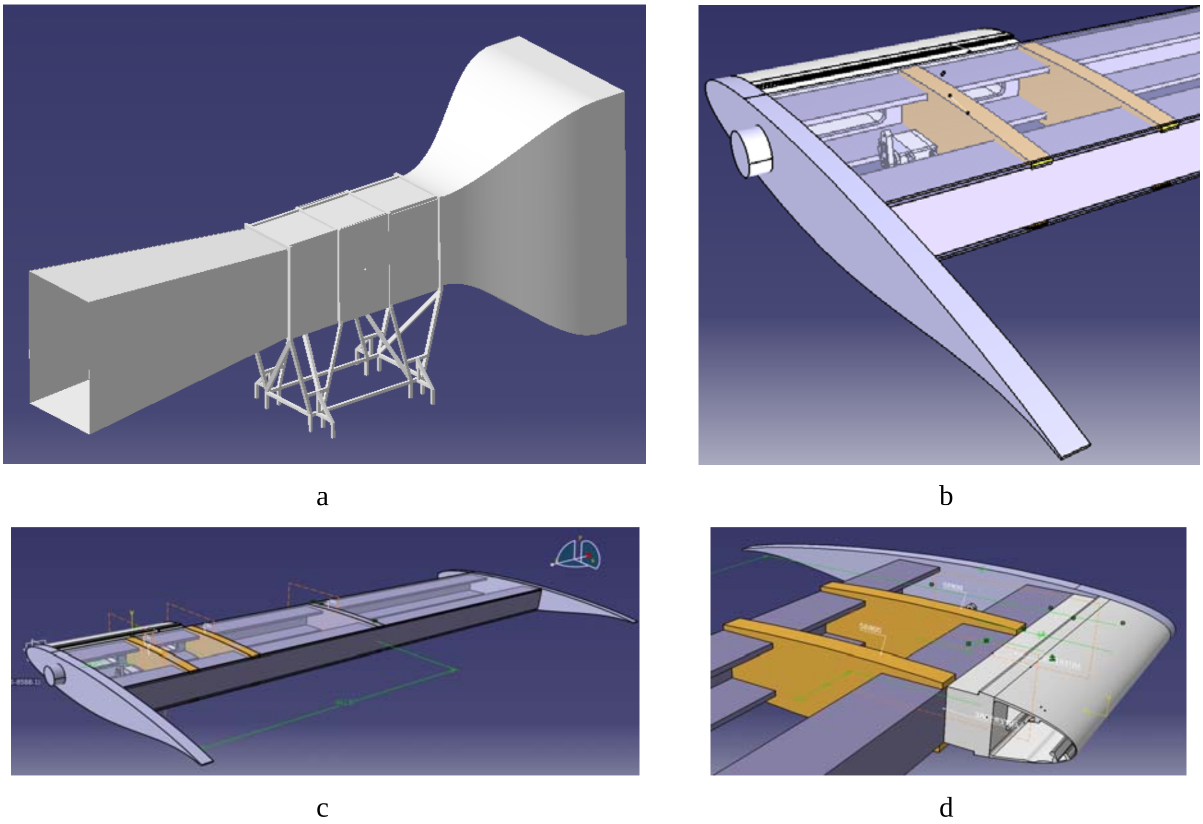

Figure 10. The wind tunnel model setup: the wind tunnel (a), the side rib for the connection to the rig (b), overview of the complete wing model (c), morphing LE attached to the front spar (d).

The manufacturing of the compliant structures on a such as small scale represents a challenge due to the need to exactly reproduce the thickness distribution as well as the need to obtain small thicknesses due to the reduced scale adopted. For this reason, different approaches have been investigated. One of the most promising appears at the moment the one based on the 3D printing technology. This technology is commonly referred with a single word, i.e. 3D printing but it includes many and different additive material techniques, such as for example FDM, SLA, SLT and polyjet. The original idea was to be able to manufacture the complete morphing LE and TE in a single piece. Figure 11 shows as an example the production chain in case of a demonstrator of LE starting from the CAD model, then the 3D printing file and finally the complete structure.

Figure 11. Production sequence of a morphing LE based on FDM technology.

The first test on FDM technology were not fully satisfactory, due to the low accuracy in the finally obtained thickness distribution. Much better results have been obtained by polyjet technology (see Fig. 12) so that this technique has been selected for the first wing model prototype.

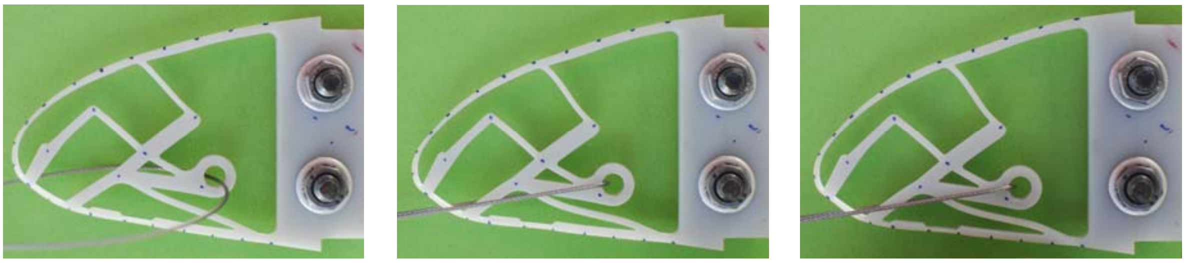

Figure 12. Preliminary static test on a morphing rib manufactured by Polyjet technology: unloaded structure (left), intermediate load (middle) and maximum load (right).

6. CONCLUSIONS

The paper summarizes the recent activities performed at Politecnico di Milano in the framework of FP7-NOVEMOR in the field of morphing aircraft. In particular, the variable camber concept by means of LE and TE compliant structures has been investigated. The numerical activity was focused on the development of dedicated tools for the optimal design of both the external wing shape as well as the internal structure which, thanks to its compliance, is able to deform once loaded so matching the optimal shape.

The experimental activity is now under way for the final validation of the design tools and the obtained morphing wing configurations. At this aim, two different wind tunnel campaigns have been decided. The first one, just completed, is dedicated to the validation of the morphing shape in terms of aerodynamic performance by means of a transonic test at CSIR wind tunnel on a rigid model. The second one, now under way, is focused on the validation of the compliant structures and will be performed at POLIMI wind tunnel.

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