Conceptual Design and Topology Optimization of a Compliant Morphing Flap for Next Generation Hybrid-Electric Regional Aircraft

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Abstract

Due to the potential capability of reducing the environmental impact of the short-range aircraft, commercial aviation is increasingly focusing on hybrid-electric propulsion technologies. Additionally, a number of technological solutions are being considered for regional aviation market to make zero-emission aircraft a reality. Among them, novel high-aspect ratio wing designs equipped with morphing wing devices are expected to deliver enhanced aerodynamic performance (less fuel consumption) in the regional and short-range (less than 500 km) air mobility. This paper proposes the conceptual analysis and preliminary structural sizing of a compliant morphing flap concept integrated into a hybrid–electric regional aircraft wing. The work is framed within the EU funded HERWINGT (Hybrid-Electric Regional Wing Integration Novel Wing Technologies) project, supported by the Clean Aviation Joint Undertaking (JU). Within the scope of this project, the Italian Aerospace Research Centre (CIRA) is involved in the aero-structural design of a high-aspect ratio wing concept integrating a camber morphing flap that will be manufactured and tested on a single-bay ground test demonstrator. This work, performed by the CIRA Adaptive Structures Department, provides a description of the conceptual design of the camber morphing flap, obtained by the topology optimization of composite material integrated into a compliant mechanism. The main achieved results are here discussed in terms of aerodynamic performance and structural architecture.

Keywords: topology optimization; morphing flap; compliant mechanism; hybrid-electric propulsion

1. Introduction

Both aircraft market demand and environmental regulations are currently facing several challenges. The aerospace industry is progressively focusing on reducing carbon emissions and increasing the use of renewable energy sources. Hybrid-electric propulsion system (HEPS) appears as the most viable solution for an energy efficient, cleaner and quieter aeronautical propulsion. According to what reported in [1], HEP offers many advantages with respect to the traditional propulsion, such as:

- Reduced emissions and noise
- Augmented aircraft power distribution/quality
- Increased global aircraft efficiency

However, HEP promises significant changes in next generation aircraft designs and architectures. As estimated in [2], it will gradually impact on the future generation of aircraft technological developments in the next 30 years.

Further technologies are thus being developed to push aviation towards a sustainable and climate neutral flight. Among them, morphing wing devices are a viable option to improve aircraft aerodynamic performance (less fuel consumption) and reduce aerodynamic noise.

Within this scope, the European Union (EU) funded HERWINGT (Hybrid-Electric Regional Wing Integration Novel Wing Technologies) project, supported by the Clean Aviation Joint Undertaking (JU), will ambitiously drive the technological developments to the decarbonization of aviation systems, [3]. In particular, the project aims at developing, validating and demonstrating a number of key technologies to deliver an innovative wing design suitable for a 100-seat and short-range Hybrid Electric Regional Aircraft (HERA). All these solutions will allow for a 50% fuel burn reduction at the aircraft level (A/C) compared to a 2020 State-Of-Art (SoA) A/C, by acting on:

- Improved aerodynamic wing configurations, to ensure drag and fuel burnt reduction at the wing component level;
- Wing structures equipped with innovative integrated systems and new material technologies, resulting in a huge weight reduction at the component level;
- the development of technologies enabling the wing for a hybrid-electrical use case (H2/Batteries + fuel systems using Sustainable Aviation Fuels (SAF)).

Within the scope of this project, the Italian Aerospace Research Centre (CIRA) is currently involved in the design and development of a morphing flap concept to be integrated into a high aspect ratio wing of hybrid-electric regional aircraft. A compliant morphing concept is being developed to implement the wing morphing capabilities. Unlike finger-like mechanism-based morphing structures, using skeleton-like articulations (multi-hinge arrangement) to enable shape adaptation of the lifting surface, [4], complaint morphing concepts deal with the controlled deformation of the inner subcomponents to smoothly modify the overall shape of the assembly ([5]); the structural stiffness is properly tailored to ensure enough compliance to accommodate large deformations and enough robustness to preserve a given shape under the action of external aerodynamic loads.

2. Aim of the work

In this paper, a structural optimization process is applied to the conceptual design of a morphing flap aimed at increasing the high-lift performance of a hybrid-electric regional aircraft wing. At the current state of the project, the wing design and aerodynamic analyses have been performed in cruise and climb conditions, by accounting the related load factors to determine the sizing loads. An evaluation of the primary structural weight has been obtained by means of quasi-analytical multi-stations tool with a genetic algorithm optimization implemented, [6].

The geometrical constraints considered for the design of the flap system in high-lift conditions derive from both industrial requirements and aerodynamic computations. The optimization process shall provide the best compromise between airfoil flexibility, shape fidelity, structural weight and actuation authority under operative conditions. An example of optimized trailing edge device for morphing wing application is shown in Figure 1.

Such a lightweight morphing trailing edge architecture, obtained by using the SIMP approach [7], has shown to provide optimal structural performance while preserving the target shape during system operation under aerodynamic loads, [8].

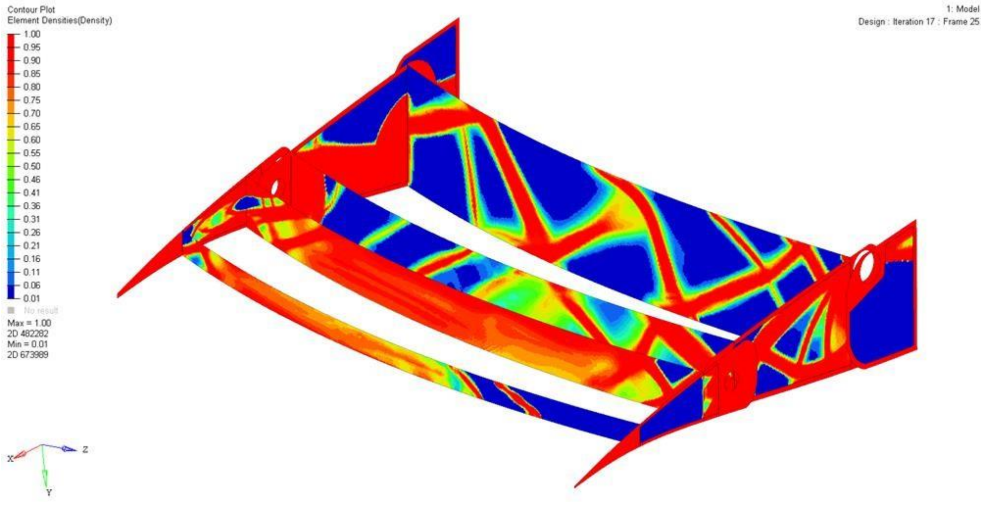


Figure 1 - Optimized trailing edge device for morphing wing application, [8].

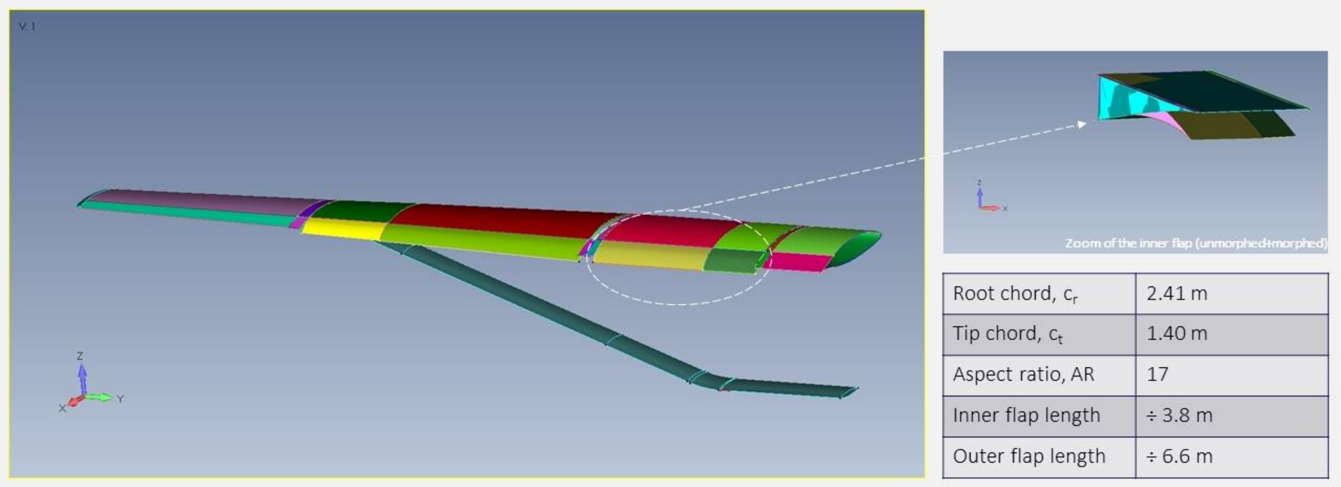
The aerodynamic performance of the devices is simulated by a low-order homebuilt solver (CIRA property) used to optimize the flap aeroshapes and the corresponding settings for both take- off and landing. The use of this low-fidelity code makes it possible to execute a full aerodynamic optimization with acceptable computational costs.

3. Reference wing and investigation region

In order to develop the aero-structural design of a full-scale compliant camber morphing flap (MF), a tailored design-through-optimization procedure has been applied to a one-bay demonstrator (DEMO, in what follows) MF model, spanning 0.5 m, by choosing as a domain region a portion of the inner flap of the reference HERA wing, .

Figure 2 shows the CAD representation of the reference strut-based HERA wing, developed by TU Delft, with a zoom on the inner flap in morphed and unmorphed conditions, and the main geometrical features.

Figure 3 depicts the MF DEMO investigation region chosen by CIRA in this work, corresponding to the root inner flap, properly selected based on its rectangular shape. The morphing architecture is completely embedded into the flap main body. Discrete morphing deflections are considered to replicate the target aeroshapes for both the takeoff and landing configurations. Geometrical constraints are also imposed to ensure the aerodynamic shape quality under operative loads.



Root chord, c_r	2.41 m
Tip chord, c_t	1.40 m
Aspect ratio, AR	17
Inner flap length	÷ 3.8 m
Outer flap length	÷ 6.6 m

Figure 2 - HERA strut-based reference wing CAD and geometrical features, with a zoom of the inner morphed and unmorphed flap

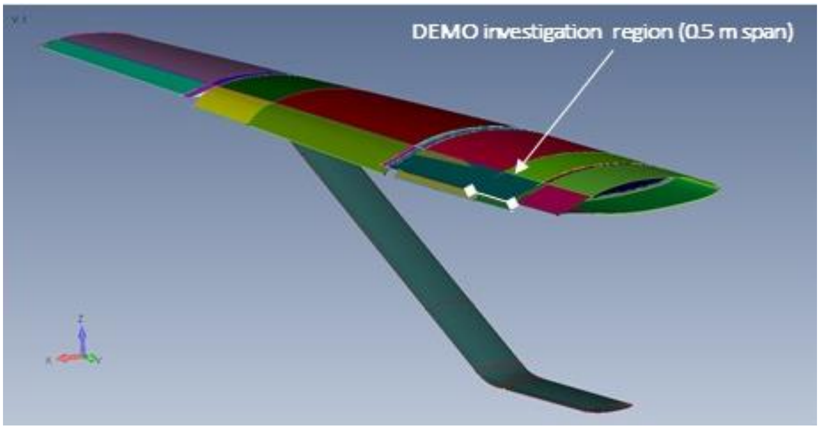


Figure 3 - Morphing Flap DEMO investigation region

4. Aerodynamic assessment

The aerodynamic loads, acting on the overall wing and needed for the sizing process of the MF DEMO, have been calculated through the UZEN (Unsteady Zonal Euler Navier Stokes) RANS (Reynolds-Averaged Navier Stokes) flow solver by selecting high-lift conditions with the corresponding load factors, according to the project requirements. Such a code solves the compressible RANS equations on structured multi-block domains, [10].

More in detail, the aerodynamic loads calculation used for the scope of this work is the one related to the high-lift condition with the following features:

- Maximum flap extended speed, $V_F = 90$ m/s
- Load factor, n=2
- $P_{fs} = 101325$ N/m^2
- Aerodynamic mean chord, c = 2.38 m

In view of a preliminary 2D aerodynamic assessment, the assumption of a constant load distribution along the span of the wing has been considered. The 2D profile for the calculation was selected as the one corresponding to the peak of the wing load. The overall profile was meshed into 880 consecutive aerodynamic elements (namely, boxes). The calculation through the aforementioned flow solver was performed at the center of the aerodynamic boxes, giving as a result the data depicted in Figure 4:

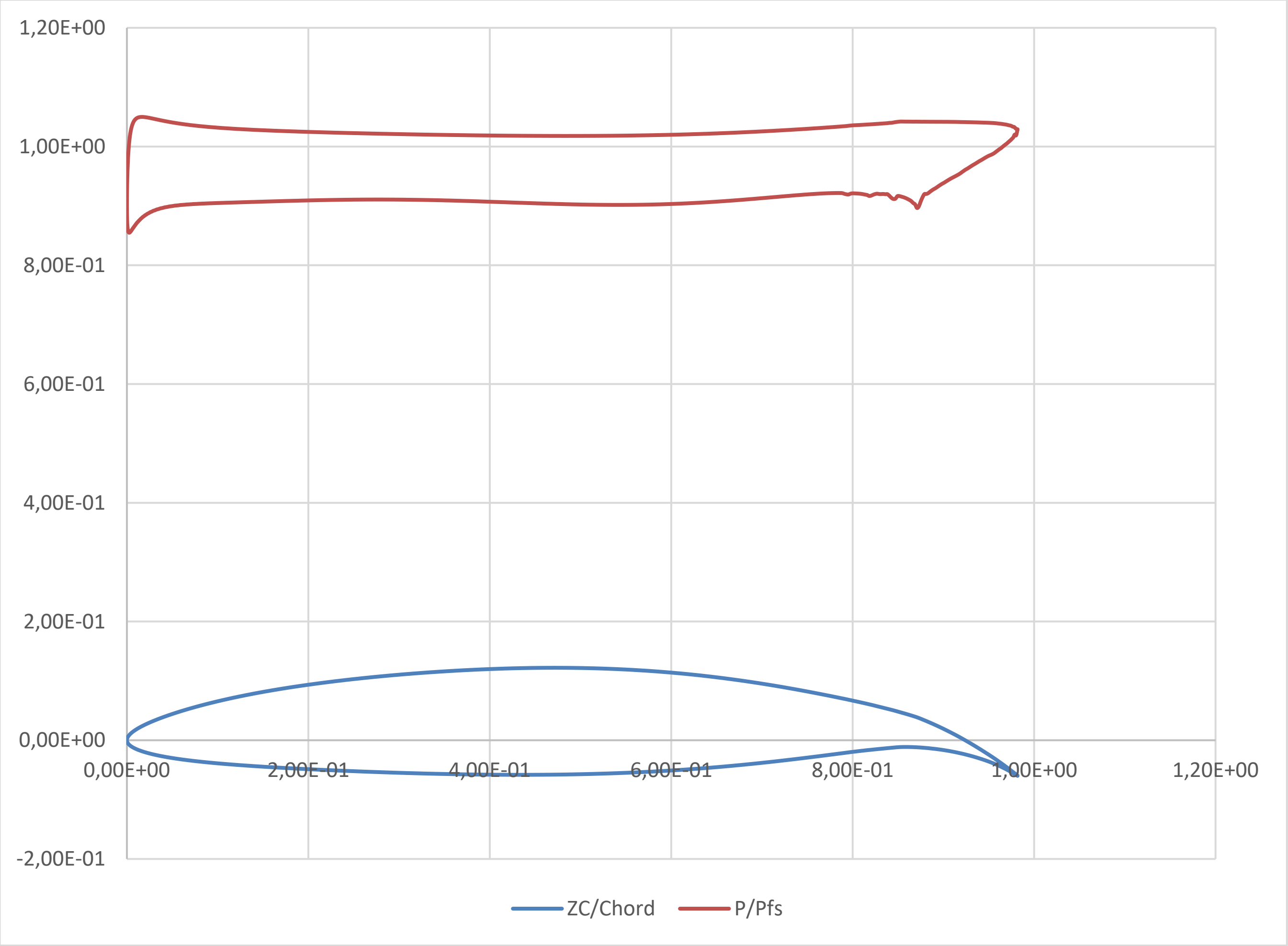


Figure 4 - 2D Aerodynamic pressure distribution (red curve) and reference airfoil profile (blue curve) in morphed configuration at VF and load factor = 2

The coordinate system for the aerodynamic load calculation was considered centered at the tip of the leading edge, with x axis in the profile axial direction, y axis in spanwise direction, and z normally to both x and y axes (local coord. system).

5. Structural Design

The structural design of the MF DEMO is here described in terms of methodology, geometry, preliminary FE model, aero-structural mesh matching, preliminary FEA results.

5.1 Methodology

A pre-requisite for the optimization problem is the definition of the structural regions to be optimized, called "design space", and those excluded from the process, called "non-design space", [11]-[14]. The optimization problem consists in the composition of the void and structural material in the design domain, such that the surface $\Gamma(u)$ (function of the state field, u) of the flap will deform to a target surface $\bar{\Gamma}$ in the morphed domain. Simultaneously the stored strain energy from a surface traction must be minimized for stiffness maximization. The problem is illustrated in Figure 5.

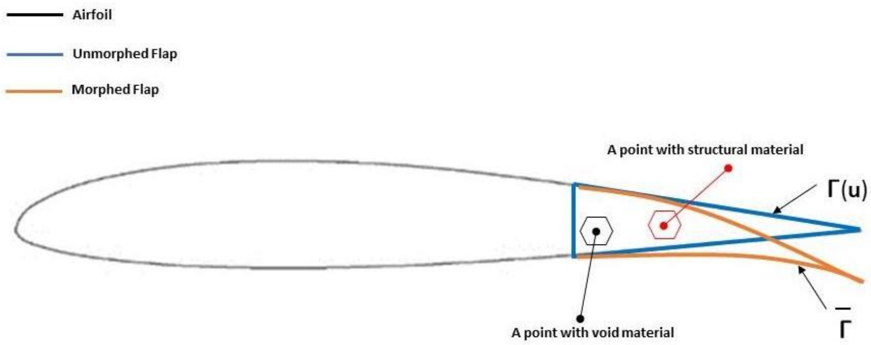


Figure 5 - Design problem for the compliant morphing flap concept

In the present study, the approach is firstly applied to the design of a single flap rib. Advanced topology optimization and more consolidated design options are combined to deliver the preliminary design of a camber morphing flap equipped with a compliant morphing mechanism. Compliant flexural hinges are included into the design space to enable the mutual rotation between the ribs' segments. The structural ribs, webs and spars are also considered. The actuation mechanism is part of the non-design space together with the structural connections to the wing-box rear spar.

5.2 Geometrical description

The structural design requirement of the HERWINGT single-bay DEMO camber morphing flap here proposed aims at reaching the target morphed-down shape through an equivalent tip rotation angle of about 17° under high-lift condition, Figure 6.

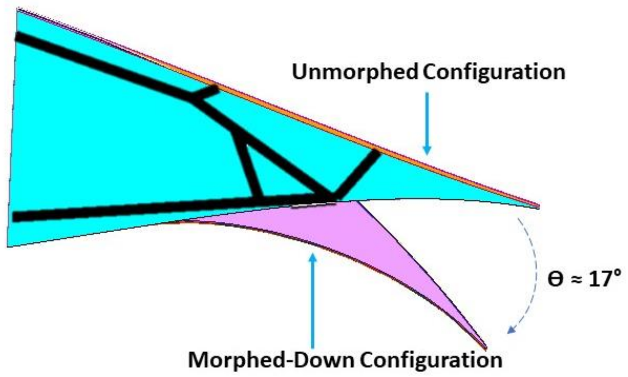


Figure 6 - Compliant morphing flap concept, in unmorphed and morphed-down configurations

In order to achieve such a goal, CIRA has conceived a preliminary architecture capable of smoothly modify the overall shape of the assembly, while withstanding the external loads, composed by a flexible composite skin and two compliant ribs (right and left), properly constrained to the skin itself.

The benefits of using compliant components relies on their selective stiffness, which can be properly tailored and optimized to obtain large deformations without sacrificing robustness capabilities.

The upper and the lower skin are continuous (one-piece arrangement) at the tip point of the trailing-edge. More, the lower skin is equipped with a stretchable/sliding strip spanning along the overall interface area with respect to the wing-box.

According to this conceptual design, the morphed-down activation is provided by the action of two linear actuators per bay. The upper and lower actuator act separately on the compliant rib and on the stretchable/sliding skin strip, respectively.

When the upper actuator pushes against the compliant rib, provoking its controlled deformation, at the same time the lower actuator pulls the stretchable/sliding skin, ensuring the reaching of the target morphed shape. The baseline configuration can be obtained by reversing the direction of the axial actuator forces.

Both the couples of actuators are properly hinged to the wing-box rear spar, synchronized each other and located on linear guide-rails to avoid inconvenient movements while operating.

A sketch of the actuation conceptual design of the MF DEMO is shown in Figure 7:

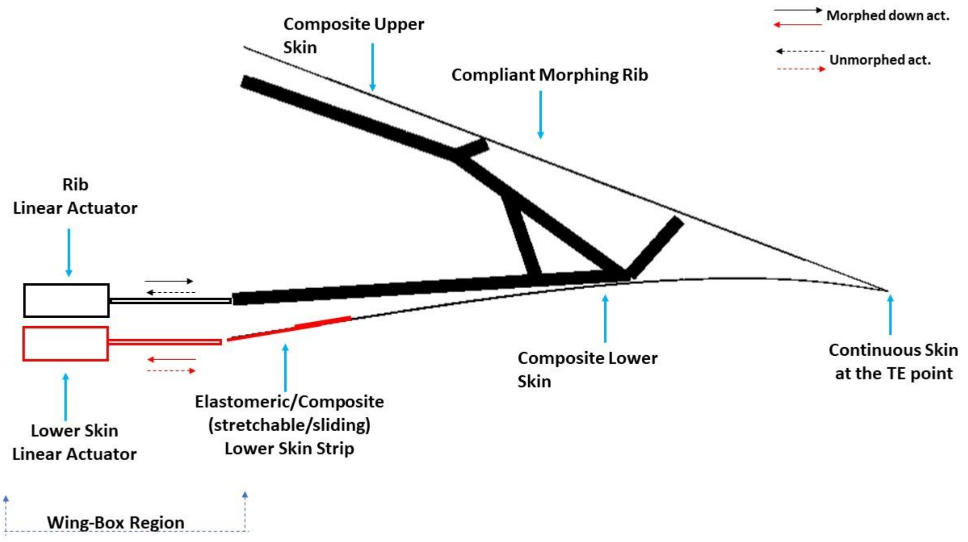


Figure 7 - Conceptual actuation scheme and structural components of the compliant morphing flap

5.3 Preliminary FE model

Based on the geometry described in the previous section, a preliminary FE model (total elements: 9912; total nodes: 10148) has been obtained in Patran® environment by using elements with:

- shell properties, for the skin
- beam properties, for the ribs

Multi-Point Constraints (MPCs) have been introduced to link the beam element nodes to the ones, properly selected, belonging to the skin.

A representation of the preliminary FEM with composite skin and aluminum ribs is shown in Figure 8.

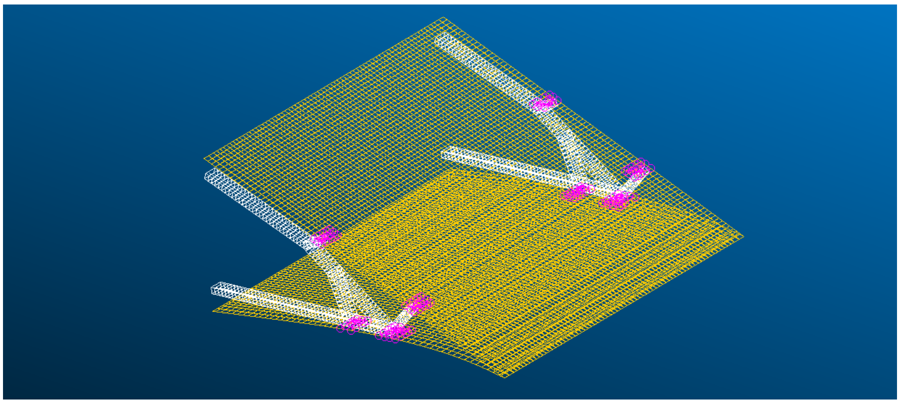


Figure 8 - Preliminary FE model of the DEMO compliant morphing flap

5.4 Aero-structural mesh matching

Referring to the aerodynamic loads already discussed in Section 4, under the high-lift condition here reported for the sake of completeness:

- Mach=0.20
- Re=4.58x10^6 (1/m)
- V_F = 90 m/s
- n=2
- P_{fs} = 101325 N/m^2

in order to implement such loads into the preliminary FE analyses, a dedicated procedure to match the aerodynamic and the structural mesh was conceived by the authors.

At first, the extraction of the loads acting only on the morphing flap was achieved, starting from the ones related to the overall airfoil profile. The aerodynamic mesh was defined with respect to a reference local system different from the global structural model one.

Thus, an iterative calculation tool was properly developed to overlap the two spatial (aero. and structural) discretization by means of the root mean square error (RMSE) minimization of the distance between the structural grid points located on the forward line of the DEMO FE model (both on the upper and the lower skin mesh) and the internal grid points along the profile. The final position of the internal structural grid points, corresponding to the minimum error position due to the overlapping with the aerodynamic discretization, was used to identify four strips (two for the upper and two for the lower skin), where calculating the pressure loads to be applied for the sake of FE analyses.

A sketch of the described aero-structural matching procedure output is reported in Figure 9.

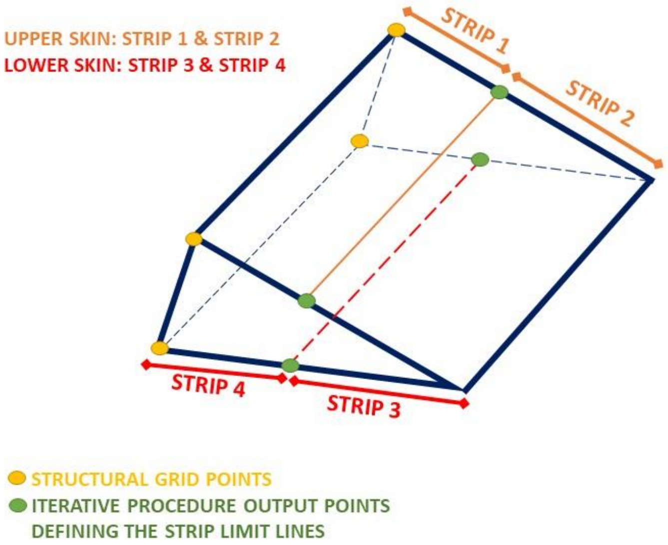


Figure 9 - Aero-structural matching procedure output schematization

5.5 Preliminary FEA results

A first static FE analysis was performed on the MF DEMO model by using Nastran® post-processing to assess the morphing capabilities of the DEMO model under the simulated high-lift condition (see section 5.3 and 5.4), and to have preliminary results in terms of stress distribution and translational displacements. The obtained results are shown in Figure 10 (Von Mises stress distribution) and Figure 11 (translational displacements).

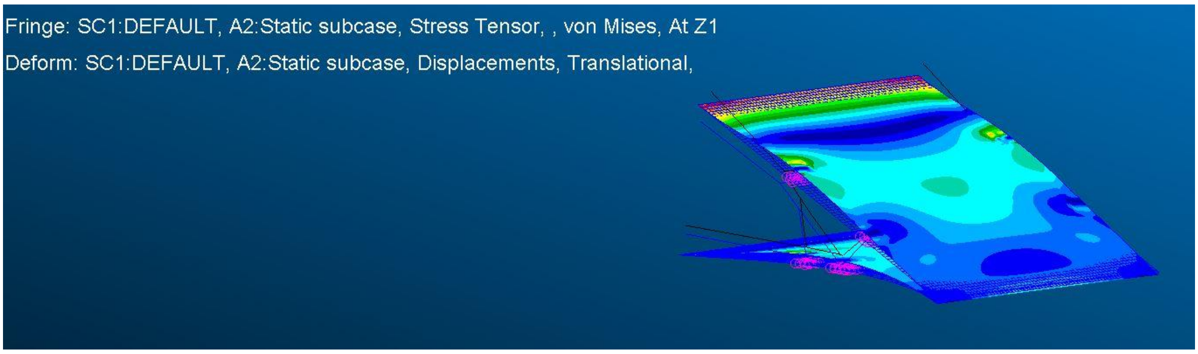


Figure 10 - Von-Mises stress distribution [N/m^2] on the MF DEMO under high-lift load condition

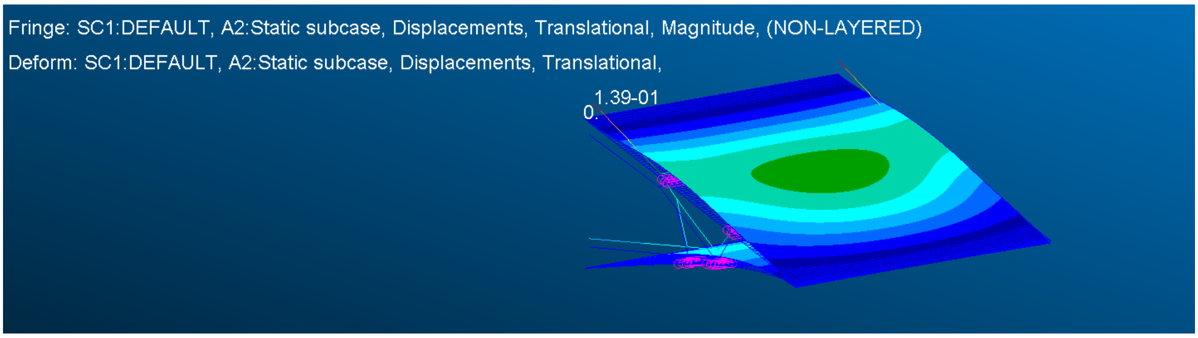


Figure 11 - Translational displacements distribution [m] on the MF DEMO under high-lift load condition

6. Conclusions

Morphing wing structures represent one of the technologies addressed to improve aerodynamic efficiency of next generation hybrid–electric regional aircraft. Namely, they are capable of adapting their shape in a continuous manner during aircraft flight. The growing interest in more automated methods for manufacturing, assembly and integration of aircraft subcomponents has given the chance to unlock the light-weight potentials of simulation driven design concepts and to leverage the full potential of topology optimization methods. Additive manufacturing, for instance, is a viable technique to produce either structural parts with complex shape or small parts as fittings, joints and ribs, in a very effective way with respect to traditional processes for metals.

In the present work, the conceptual design of a compliant morphing flap concept is addressed by considering the aerodynamic loads computed at the early stage of the project. The design work is currently in progress for a full exploitation of topology optimization in the advanced design of the morphing flap device. In order to bring the proposed concept to the demonstration phase, both actuation and manufacturing constraints will be further investigated to consolidate the concept. After that, the optimization process will be extended to the 3D structure including the actuation system mechanism. Further structural improvements to the concept will be indeed needed by removing material redundancy and by assessing stress distribution in order to avoid peaks. Failure modes of the system will be finally assessed to identify key design drivers for both the final architecture design and performance evaluation under actual loads.

7. Acknowledgments

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8. Nomenclature

A/C: Aircraft

CIRA: Italian Aerospace Research Centre

DEMO: Demonstrator

EU: European Union

FEA/FEM: Finite Element Analysis / Finite Element Model

HEP: Hybrid-Electric Propulsion

HERA: Hybrid Electric Regional Aircraft

HERWINGT: Hybrid-Electric Regional Wing Integration Novel Wing Technologies

JU: Joint Undertaking

MF: Morphing Flap

SAF: Sustainable Aviation Fuels

SoA: State of the Art

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10. Copyright Statement

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