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AN ADAPTIVE TRAILING EDGE FOR LARGE COMMERCIAL AIRCRAFT

A. Concilio[1], I. Dimino[1], and R. Pecora[2]

[1] CIRA, The Italian Aerospace Research Centre, Adaptive Structures Division,
Via Maiorise, 81043, Capua (CE), Italy
e-mail: a.concilio@cira.it, i.dimino@cira.it

[2]University of Naples "Federico II", Industrial Engineering Dept. Aerospace Division,
Via Claudio, 21, 80125, Naples, Italy,
e-mail: rosario.pecora@unina.it

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Abstract. *This paper deals with the design of an adaptive trailing edge aimed at increasing the range capacity of a large commercial aircraft. Moving from the requisites, a brief discussion about the expected performance will be introduced together with a suitable layout. Then, the design of the structural system able to guarantee both the deformability and the structural resistance will be presented. The next step is devote to the actuation system design, able to be integrate din the structural body and bear the external aerodynamic load. The external skin contributes to load bearing but also to the actuation effort required. Details refer to other publications while here it is considered though its effect only. An aeroelastic study, ensuring the stability of the proposed device over the whole wing system will be finally dealt with. A discussion on the real applicability in the aeronautics will conclude the work, pointing out at the necessary improvement required. Other work on the same subject, but referring to other design and implementation aspect will be fully referred to.*

1 INTRODUCTION

Conventional high lift systems, such as flaps or slats, are the common way to modify aircraft wing geometry during take-off and landing in order to provide additional lift at low speed. However, they have limited efficiency due to the geometric discontinuities, require high installation efforts and offer no functional flexibility in cruise, as, for instance, differential surface deflection. For some last-generation aircraft as B787 and A350, additional functions, such as differential flap settings are ensured by innovative flap actuation system concepts.

In the framework of SARISTU project, research was conducted to develop an adaptive trailing edge device aiming at maximizing wing aerodynamic performance in cruise. Wing shape is controlled during flight in order to compensate the weight reduction following the fuel burning, by allowing the trimmed configuration to remain optimal in terms of efficiency (Lift to Drag ratio) or minimal drag. Trailing edge adaptations were investigated to achieve significant benefits in aircraft fuel consumption whose reduction ranges from 3% to 5% depending on flight mission. Target morphed shapes - to be reproduced in flight - were determined through CFD-based optimization analyses; the same applies to the overall dimensions of the morph-able trailing edge (chord/span, see Figure 1). In order to assure the necessary figures for the aerodynamic efficiency of the reference A/C wing, it was found that the morphable trailing edge portion should have spanned 3.0 meters along the inner wing (kink) and 9.6 meters along the outer wing region; the required chordwise extensions should have been equal to the 20% and to the 10% of the wing MAC (nearly 3.5 meters) respectively for the inner and the outer segments.

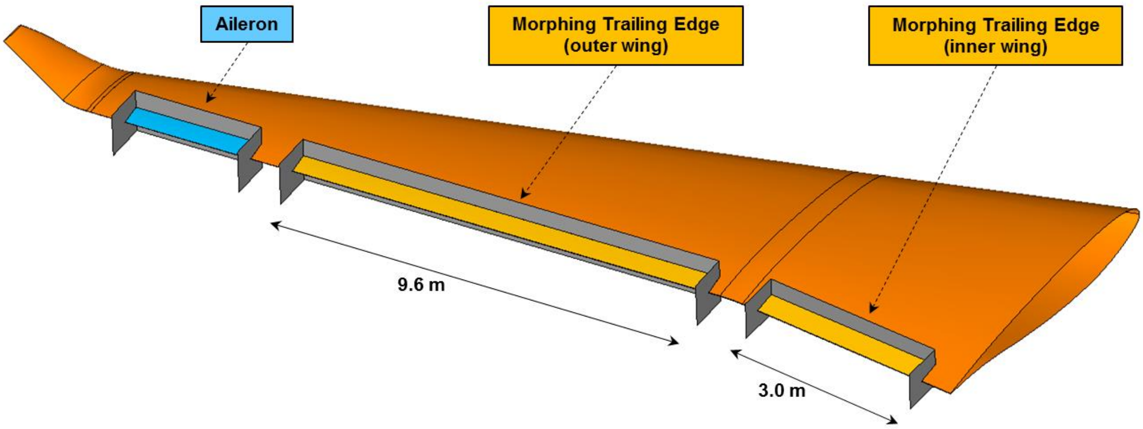

Figure 1: Morphing trailing edge regions [1].

Morphing is enabled by a multi-finger architecture driven by load-bearing actuators systems (hidden in Figure 2), designed to work synchronously to provide camber variation. After information gained from a widely distributed strain sensor network, the control system drives actuators movement. An adaptive, highly deformable skin, (shown in Figure 3), consisting of hard and soft segments, absorbs part of the external loads and insures a smooth profile. While the soft skin segments release a smooth, gapless transition between movable and fixed parts of the underlying kinematic structure, the hard skin segments compensate deformations due to air pressure gradients. The soft segments are based on elastomer foam while the hard segments consist of aluminum profiles. Both segments are covered by a thin layer to ensure a smooth surface. The system keeps its structural properties while actuated, then allowing the preservation of a specific target shape regardless the action of the operational loads. The soft segments are located above and under the rib hinges while the hard segments are connected to the rib structure.

Figure 2: The Adaptive Trailing Edge (ATED) device [5].

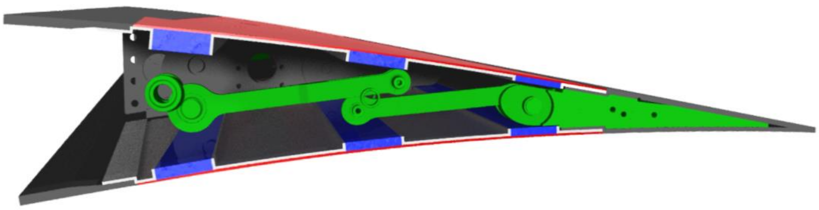

Figure 3: The morphing skin consists of hard and soft segments. Elastomer foam is used for soft segments which are located above and under the rib hinges. Hard segments are alumium profiles (grey). Hard and soft segments are covered with a thin elastomer layer [5].

These geometrical parameters were used as input for the definition of the structural concept enabling the transition from the baseline trailing edge configuration to the morphed one. The structural sizing of the concept was addressed while considering the effective operative loads expected in service and the applicable airworthiness requirements; nevertheless, for the economy of the project, detailed design activities were carried out with reference to the installation on wind tunnel demonstrator only. On the other side, the wind tunnel demonstrator replicated the last eight bays of the wing in full-scale size; the morphing trailing edge layout pertinent to the outer wing segment of the reference aircraft was then simply relocated along the wing span and supposed to be installed in the region usually occupied by the aileron (Figure 4). Its overall dimensions remained therefore unchanged with respect to real aircraft installation.

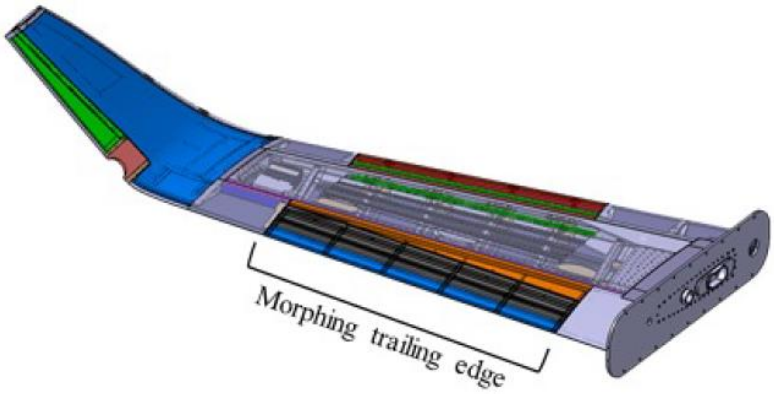

Figure 4: Wind Tunnel Demonstrator.

2 MORPHING TRAILING EDGE CONCEPT

In order to enable the transition of the trailing edge sections from the reference (baseline) shape to the target ones, a morphing structural concept was developed for ribs. Each rib (Figure 5) was assumed to be segmented into four consecutive blocks (B0, B1, B2, B3) connected to each other by means of hinges located on the airfoil camber line (A, B, C). Block B0 is rigidly connected to the rest of the wing structure, while all the other blocks are free to rotate around the hinges on the camber line, thus physically turning the camber line into an articulated chain of consecutive segments. Linking rod elements (L1, L2) - hinged on not adjacent blocks - force the camber line segments to rotate according to specific gear ratios compliant with the shapes to be achieved

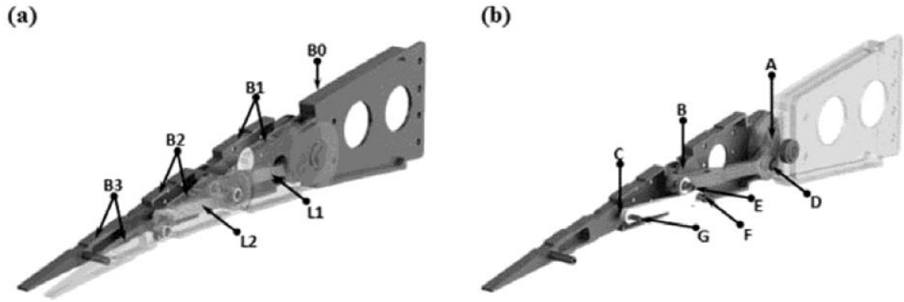

Figure 5: Morphing rib layout: (a) blocks and links, (b) hinges

These elements make each rib equivalent to a single-DOF mechanism: if the rotation of any of the blocks is prevented, no change in shape can be obtained; on the other hand, if an actuator moves any of the blocks, all the other blocks follow the movement accordingly. The rib mechanism uses a three segment polygonal line to approximate the camber of the ATED airfoil and to morph it into the desired configuration while keeping approximately unchanged the airfoil thickness distribution.

The ribs' kinematic was transferred to the overall trailing edge structure by means of a multi-box arrangement (Figure 6(a)). Each box of the structural arrangement was assumed to be characterized by a single-cell configuration delimited along the span by homologue blocks of consecutive ribs, and along the chord by longitudinal stiffening elements (spars and/or stringers).

Servo rotary load-bearing actuators coupled to quick-return mechanisms were adopted for the independent control of each rib of the device. An FBG-based system based on sensing elastic beams located at the middle of each bay was used to detect shape configurations and to generate the information for appropriate open- and closed-loop control actions.

The structural concept herein described resulted from an iterative design process consisting of three main loops; the executive layout was obtained by progressively updating a preliminary assessed configuration on the base of feasibility considerations and stress analyses outcomes. The updating process followed the design progress of the ATED main equipment (basically actuation/sensing system) and structural interfaces with the rest of the wing (dead box). Finally, in order to assure the safety of the wind tunnel test, aeroelastic investigations on wind tunnel demonstrator were carried out in order to show the clearance of the device installation from any flutter up to three times the maximum airspeed to be tested (80 m/s).

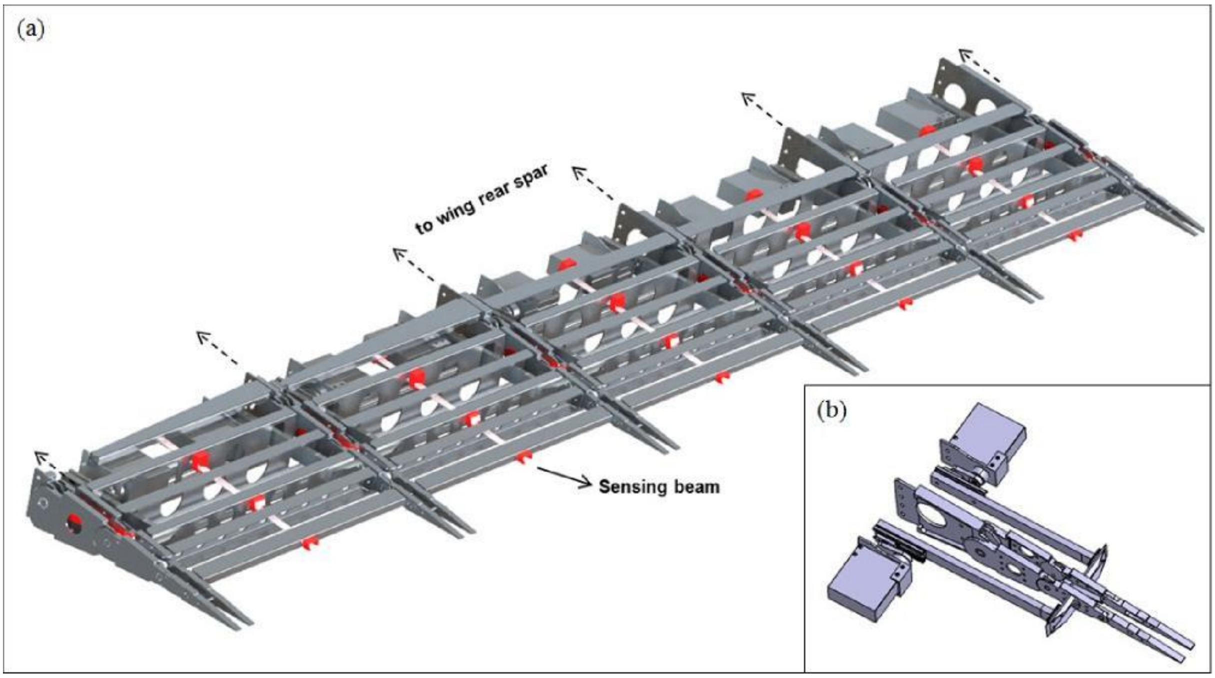

Figure 6: Morphing box architecture (a) and actuation system (b).

3 ACTUATION SYSTEM

Contrary to flexural joints-based compliant morphing mechanisms, the morphing trailing edge device combines a rigid-body mechanical system with a compliant adaptive skin. The actuation kinematics is based on a “direct-drive” actuation consisting of an arm (actuation beam) that is rigidly connected to the B2 block shown in Figure 6 (b). This arm rotates the resulting 1-DOF-based mechanical system and transmits the actuation torque from the actuator to the adaptive rib.

In order to minimize the actuation torque necessary to hold and move the ATE device, different actuation kinematics were assessed during the design phase. The size and shape of a suitable actuator were in turn estimated taking into account weight and safety constraints. The torque needed to activate the device is generated by an actuation force acting perpendicularly to this arm (if the friction can be considered equal to zero) resulting from the contact between a carriage and a linear guide. This force is generated by a rotational actuator via a crank rotating with the actuator shaft. A simplified sketch of the mechanism is shown in Figure 7. The actuation arm rotates around the “virtual hinge” (the point around which the second rib block rotates during the movement of the ATE device) and transmits the actuation load (torque) from the actuator to the second rib block. As shown in Figure 8, the mechanical advantage increases with the morphing angle and this is much more evident as higher is the ratio between the arm length L (distance between the second rib block virtual hinge) and the actuation crank radius R. However, the higher the L/R ratio is, the higher the actuator rotation angle has to be. This limits the palette of Commercial Off-The-Shelf (COTS) servo actuators suitable for the actual application.

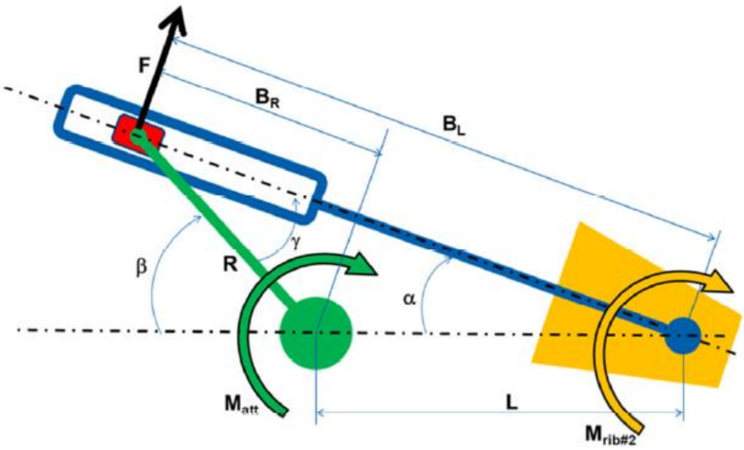

Figure 7: The actuation system layout [6].

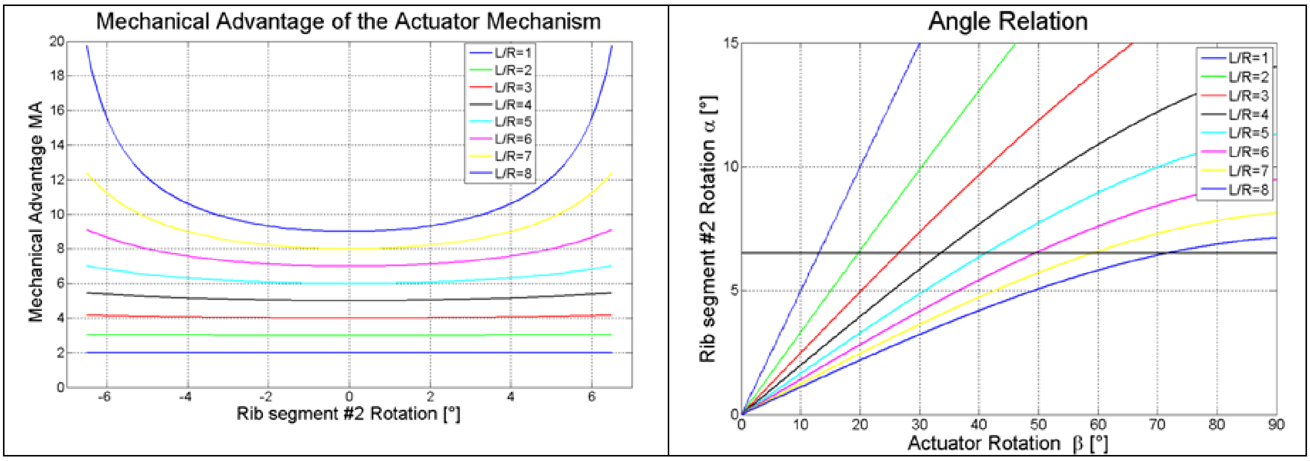

Figure 8: Mechanical advantage and actuator shaft angles of the actuation system.

4 FLUTTER ANALYSIS

In order to assure the safety of wind tunnel tests, flutter analyses were carried by considering the morphing trailing edge device integrated into the full-scale SARISTU wind tunnel demonstrator. The finite element used for static analyses was condensed into a dynamically equivalent one characterized by a reduced number of degrees of freedom. Dynamic condensation was based on the generation of direct input matrices at grids [7] to capture both inertial and stiffness properties of the device.

Reduction grids were rationally selected to get optimal modes shape resolution. The condensed dynamic model was then assembled to the FEM of the test article (Figure 9) and the overall system modes were evaluated.

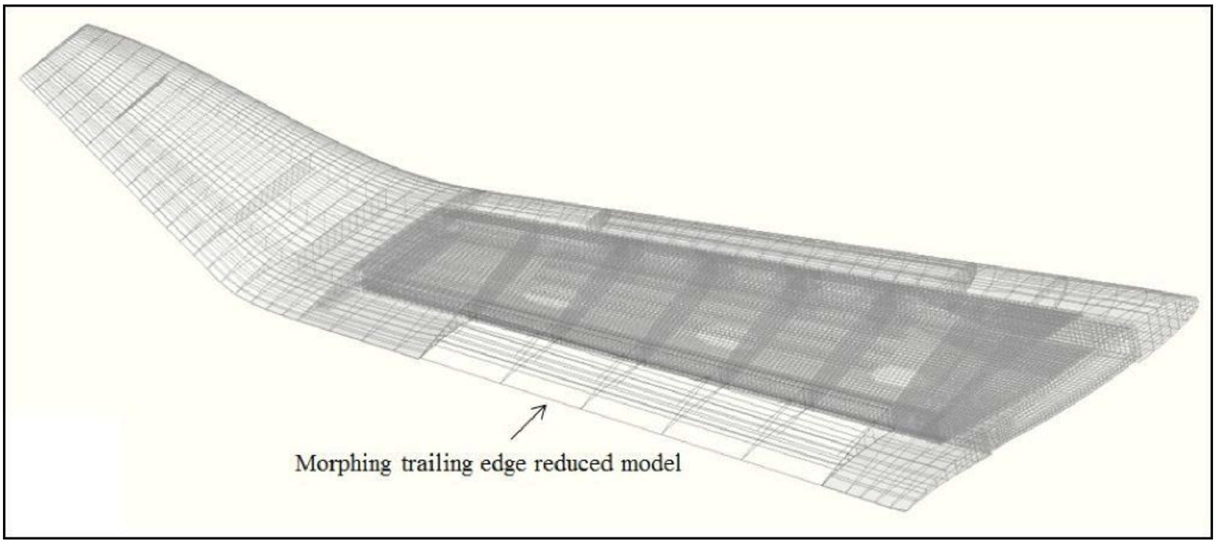

Figure 9: Structural model used for aeroelastic computations.

Doublet lattice method was adopted for the evaluation of the unsteady aerodynamic coefficients; a suitable 3D paneling was implemented for such a purpose (Figure 10). Surface splines were used to interpolate modal displacements along the centers of the aerodynamic panels and generalized aerodynamic forces were evaluated with reference to the airflow conditions expected during tests.

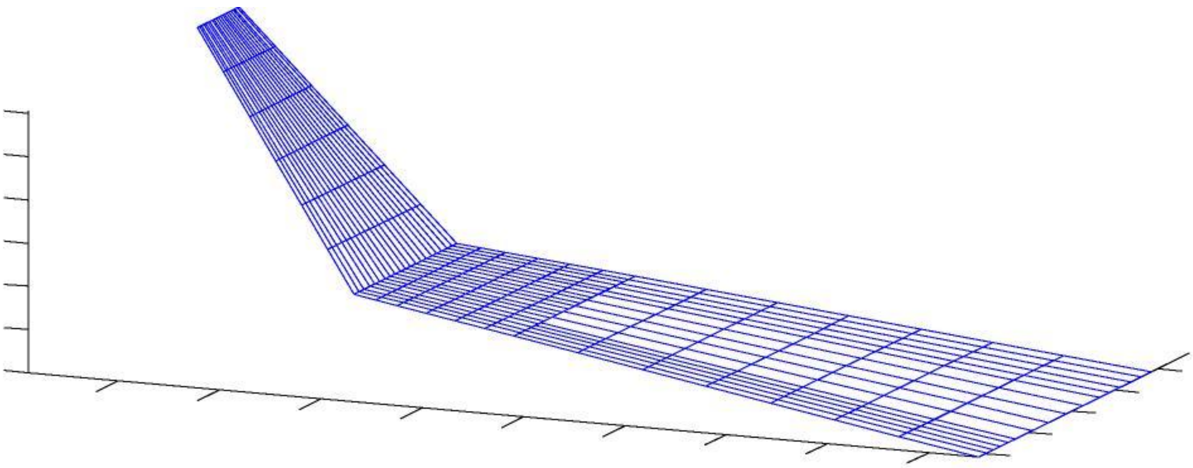

Figure 10: Test article aerodynamic model.

PK method [9] was adopted to investigate the occurrence of flutter in the speed range 0-3*Vmax, being Vmax the maximum speed expected during tests (=80 m/s). 1% critical damping was conservatively assumed for all elastic modes. No flutter was detected up to 240 m/s (Figure 11); a first instability was found at 250 m/s and essentially due to the coupling of test article bending and trailing edge elastic deflection (Figure 12).

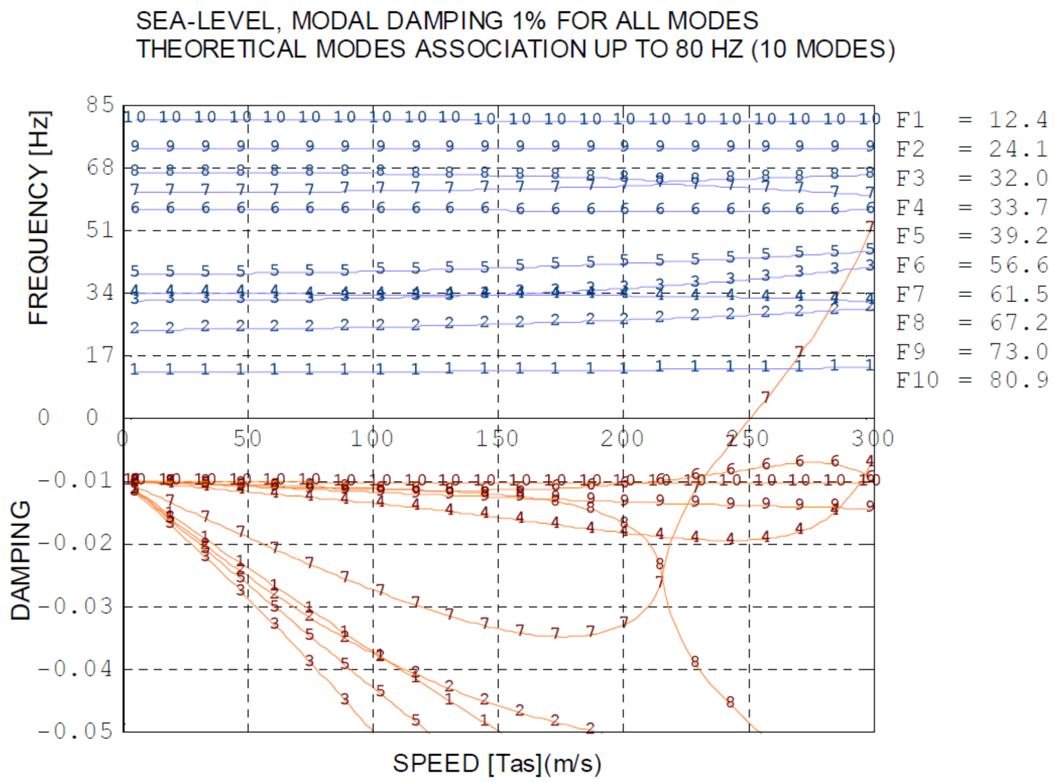

Figure 11: Flutter Vg plot.

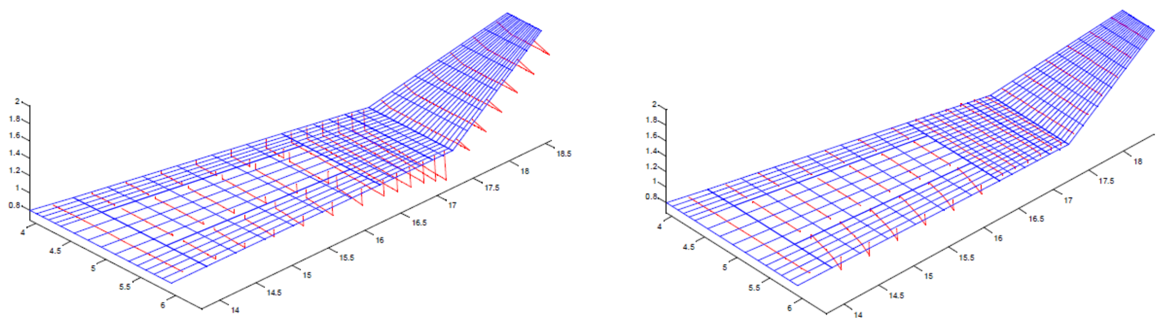

Figure 12: Modes highly participating into flutter dynamic : test article bending (left), trailing edge elastic deflection (right).

5 CONCLUSIONS

A novel architecture enabling wing trailing edge camber morphing was addressed with reference to large aircraft end-applications (EASA CS-25 category). The conventional monolithic box arrangement was replaced by a multi-box solution characterized by conventional spars and segmented adaptive ribs. Single-degree-of-freedom mechanisms, driven by load-bearing electro-mechanical actuators, were implemented to change the wing trailing edge shape by controlling the adaptive ribs individually. A compliant multi-material skin was used to accommodate the large deformation induced by ribs kinematics while providing enough stiffness to properly withstand external aerodynamic loads.

A brief and general description of the approaches and methodologies followed for the structural assessment of the overall device was presented; design strategies and consequent

results were outlined. Some open issues still remain on the developed architecture, installation aspects and implementation strategy. The specifications should be improved by considering a complete aircraft, so to compute the overall effect of the trailing edge device on the overall aircraft aerodynamic polar. The layout of the device shall also derive from the global reference geometry, so to find the best arrangement along the wing span and its chord. Further complications are also expected, following the implementation of a complex kinematic system on a movable surface such as a flap. On the other hand, the available room should be far more adequate to host the innovative components with respect to the wing tip zone. Indeed, studies to verify the possibility of inserting such systems in the aileron are currently performed by this same team and other researchers.
The actuator system design shall be integrated within the structural design, so to come to a unique active structural, load-bearing system, instead of merging to components, separately developed. Finally, control system capability, not addressed in this paper, should move from adaptive feedforward architectures, based on pre-built strain maps, to real-time feedback systems, sensible to the selected objective parameter; therefore included into the overall aircraft avionics.

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