VIII ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2017
A. Güemes, A. Benjeddou , J. Rodellar and Jinsong Leng (Eds)

KEYNOTE

MULTIDISCIPLINARY APPROACH FOR A COMMERCIAL TRANSPORT AIRCRAFT RUDDER WITH MORPHING CHARACTERISTICS.

MIGUEL Á. CASTILLO ACERO *

* VP Technology Development Aernnova,
Av. Manoteras, 20. 5th Floor, Madrid, 28050, Spain
e-mail: miguelangel.castillo@aernnova.com, www.aernnova.com

Key words: airframe, structures, additive manufacturing, multidisciplinarity, rudder, morphing, lateral, directional, aircraft, stability, control.

Abstract. The history of aviation is linked to the research and development of different physical and mathematical scientific fields. In our historic aviation records good examples can be found of studies and implementations. These cover not only new unconventional and disruptive aircraft configurations, but also the research and introduction of new materials and processes to make the airframe lighter and stronger. Also there have been continuous developments are available in the prediction of the aerodynamic loads that size an airplane to be safe, stable, controllable, and with adequate flying qualities.

Today there is a growing social demand to minimize environmental impact in all industrial sectors. Our aviation industry is also under this scrutiny. This is the reason why new requirements are emerging as eco- sustainability, in addition to compliance with the safety and certification requirements together with the challenges of being global economical competitive in an increasingly demanding world. In this line, it is remarkable to state that aircraft fuel consumption, and thus emissions of carbon dioxide, is directly linked by three key aircraft parameters, Breguet formula related: weight, drag and specific consumption of the power plant. The development of technology innovations in these three drivers must continue and this has to be approached from a multidisciplinary perspective.

This keynote focuses on summarizing the influence of the improvements in different aeronautics disciplines enabled by novel materials and additive manufacturing process, based on the introduction of a non conventional morphing curved rudder in a transport aircraft configured with under the wing podded engines. In particular, the morphed structure manufacturing and assembly aspects are detailed.

1 INTRODUCTION

The opportunity to consider an unconventional rudder arises from the observation of nature: birds can fly and manoeuvre modifying the curve of the trailing edge of the wings. Our commercial aircraft control surfaces are flat and rotate around its hinge line with a deflection angle in a simpler manner. There is an opportunity to improve, imitating nature, and make these control surfaces to be controlled by acting on their mean curve. The research on additive manufactured materials together with new actuators, enable new airfoils controlled deformation. The nature provides inspirational designs that are currently challenging conventional design principles as is the case of the configuration included in figure 1.

Figure 1: Biomimicry inspired airfoil structure [1]

The morphing research of a non conventional lifting or control surface requires a multidisciplinary approach. The search for airworthy and efficient morphing systems requires the concurrency of different disciplines. In consequence, the morphing system configuration is the result of the best compromise solution of different optimizations among the different perspectives: aerodynamics, materials, manufacturing processes and structures, power requirements, weight and flight mechanics, handling qualities and control. The figure 2 is representative of this compromise solution process.

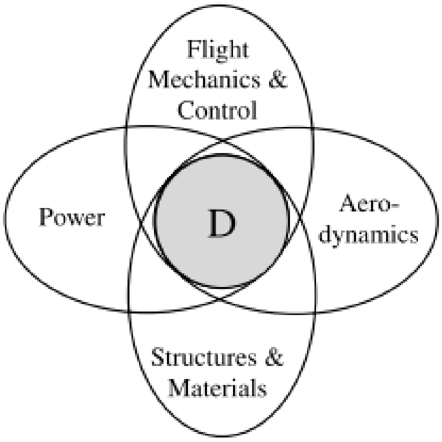


Figure 2: Disciplines involved in airframe morphing [2]

As an example of this highly multidisciplinary environment, to develop a morphing system, the figure 3 sketches an aerodynamic load alleviation system based on airfoil morphing controlled deformations.

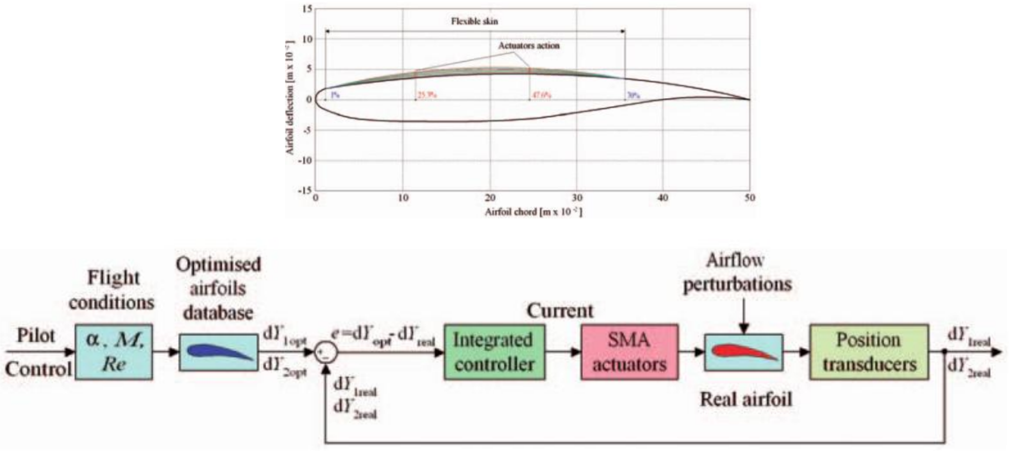


Figure 3: Load alleviation system based in morphing [3]

The adaptive trailing edge morphing design targets to be innovative, providing multi-disciplinary solution in order to create a structure able to withstand aeroelastic and aerodynamic loads. The design pretends to optimize aerodynamic efficiency by increasing the rolling moment, whilst reducing the drag and mass to the safe minimum, figure 4, [4].

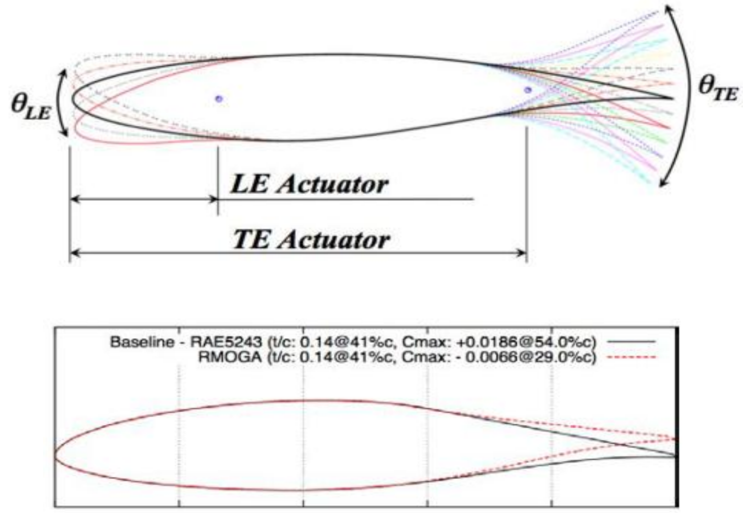


Figure 4: Morphing airfoil aerodynamic optimization [4]

The tendency of morphing technology will be essential to increase aircraft versatility and could be applied for commercial aircrafts. The flow control literature includes good advances in the adaptive lifting surfaces morphing domain. This is another good source of examples of the benefit on the multidisciplinary research with the purpose for flow control [5].

The modern transport aircraft fin is mainly sized by static loading stiffness and strength requirements. There are two static load cases that size most of the vertical empennage, fix and movable control rudder surface, the lateral gust during approach and landing, and the engine out during take-off. The later load case is even more critical than the lateral gust due to the trend to increase engine thrust for higher capacities on twin engines under the wing configurations. This platform is the preferred choice for big transport commercial aircraft due to its higher fuel efficiency and the reduction of maintenance costs in relation to four engined one. The focus of this study aims to increase rudder aerodynamic efficiency based on a morphing solution and, in consequence, enable its size reduction, not only because of the potential weight and drag reductions, but also because there are operational benefits on static and dynamic stability which can be achieved, which is the main goal of this research.

The airfoil morphing has been analysed to delay the boundary layer transition from laminar to turbulent has been previously analysed with SMA actuators, [6]. The aerodynamic improvement assessment of non-conventional curved rudder has proved to bring potential increment of 15% on lateral force when deflected [7]. The aerodynamic pressure distribution for morphed rudder is smoother than the resulting for a conventional one.

The new unconventional rudder can curve chord-wise, while maintaining straight lines span-wise. The new rudder deflection angle is measured as the one that forms the line connecting the hinge line with the aft trailing edge point. Therefore the only difference between the new and the conventional rudder for a given deflection angle, is that the unconventional one presents a curvature that is the base of the aerodynamic improvement. The development of an airworthy structural solution for such a rudder is the objective of previous works [7], [8], see figure 5 below.

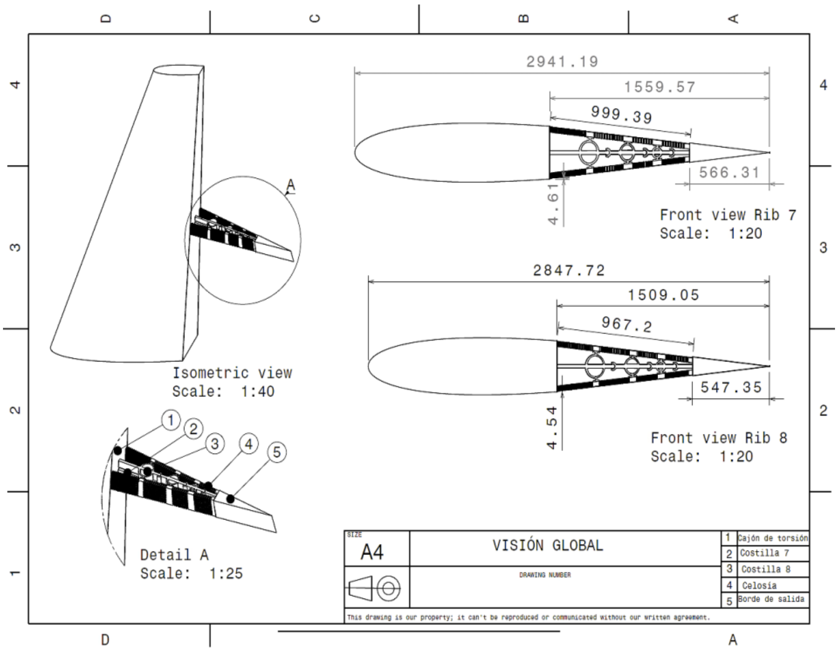


Figure 5: Morphing rudder structural architecture

There are expected difficulties in manufacturing and assembling a morphing rudder fully compliant with airworthiness requirements. The selection of the actuators is critical. They have to provide enough force and displacement at low weight and within space allocation constraints in the torsion box trailing edge volume. The selection of the actuator is coupled with the orthotropic stiffness of the morphing panels also weight constrained. The actuator power has to be selected to curve the rudder and so deform adequately he panel chord-wise. The manufacturing of these highly orthotropic panels by a certifiable aerospace, either standard or innovative, method is a challenge. The final integration of the solution must comply with functional, weight and performance requirements, therefore the assembly of the complex resultant mechanism must be very accurate and easy maintenance serviceable.

Studies that partially cover the airworthiness requirements of a morphing rudder, from static stability point of view, are required prior to flight clearance of the flight demonstrators. There is a need to study the lateral directional static stability of a transport aircraft in which the rudder has been reconfigured to provide a constant 15% more lateral load during deployment. The aircraft is under 1g stationary load cruise condition. The study of shape-morphing adaptive control surface of an airfoil has provided a significant number of research in compliant mechanisms for aircraft [9]–[11], wind energy [12], [13] and other UAVs, Unmanned Aerial Vehicles [14], [15].

The literature include recent developments on morphing tailless configuration aircraft flight control from different perspectives, as aeroelastic improvements [16]–[18]; the use of distributed shape-change effectors arrays in a flight control system [19]. Again, the study of new UAV configurations, has resulted on a relevant number of publications on lateral stability analysis and control [20].

The Aerodynamic studies based on CFD Open Foam, the flight Mechanics and control studies are performed on Static stability engine-out condition, at critical take off speed, aircraft velocity 85 m/s, air density at sea level, dry air 1.237 kg/m3. The lateral- directional aerodynamic coefficients were derived based on aircraft data and Matlab code. The Dynamic Stability was studied on lateral directional equations on the frequency domain, cruise condition. Power studies are based on the actuation selection which is driven by the morphing mechanism and also on the overall system weight, in comparison with the conventional rudder. These studies have been reported in previous author papers, [7]-[8].

2 STRUCTURAL DESIGN APPROACH

The Morphed Rudder design relies on a riblets. These riblets are articulated, figure 6. The number of riblets is a compromised solution between the achievement of smooth air contour, smoother as more discrete number of riblets, and the weight associated to a bigger number of them. The data and parameters considered in the conceptual design are selected in the initial stages of the design process.

$$d_0, \theta_0, k_1, k_2, n_{ribs}, d_{herr}, d_{tail}$$

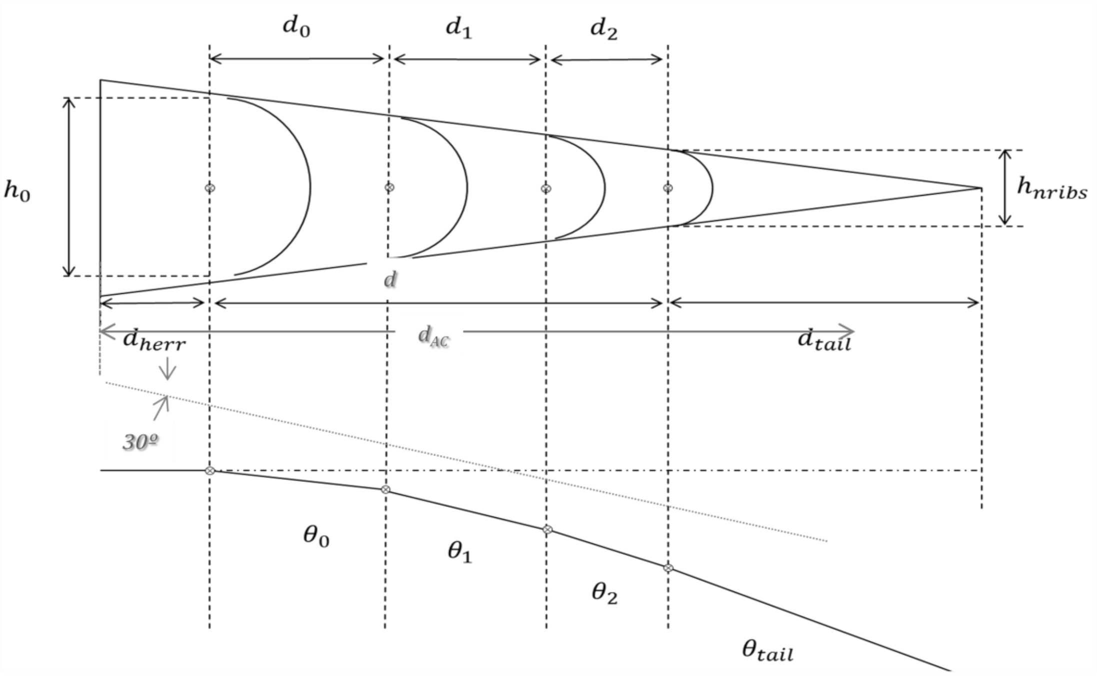


Figure 6 Morphing Rudder internal riblets geometry

The Morphed Rudder Structural analysis based on riblets geometries and rotation laws. Different approached can be considered. The mathematical models of such a geometries enable the computation in search of an optimum design.

$$\theta_{i+1} = k_1 \theta_i \;\rightarrow\; \theta_i = (k_1)^i \theta_0$$
$$d_{i+1} = k_2\, d_i \;\rightarrow\; d_i = (k_2)^i d_0$$

The mathematical links between the parameters, have to be considered in order to further advance on the optimum solution.

$$d_{AC} = d_{herr} + d_{tail} + \textstyle\sum_0^{n_{ribs}} d_i \rightarrow d_{AC} = d_{herr} + d_{tail} + d_0 \frac{{k_2}^{n_{ribs}} - 1}{k_2 - 1}$$

$$d_{AC} \sin 30 = d_{herr} \sin 0 + d_{tail} \sin \theta_{tail} + \sum_0^{n_{ribs}} d_i \sin \theta_i \rightarrow \frac{d_{AC}}{2} = d_{tail} \sin \theta_{n_{ribs}+1} + \sum_0^{n_{ribs}} (k_2)^i d_0 \sin\left((k_1)^i \theta_0\right)$$

It has been studied morphable skin structures and many alternatives to the classic concept of rigid skin panel. The development of these structures is an important knowledge based on suitable deformable systems. For example, the “Double-C” shape-skeleton panels, figure 7. These skin panels consists of a substructure called skeleton formed by a series of stringers and additional geometry features in between which acts as a spring. As result of that the skin acquires flexible superficial properties in the morphing direction and rigid properties in the perpendicular one.

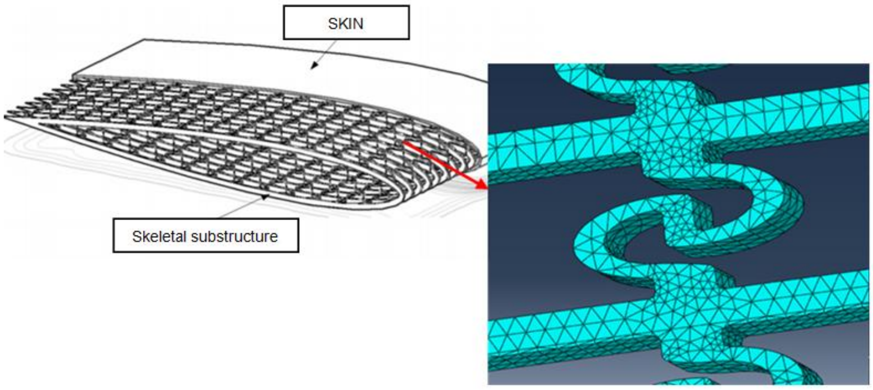
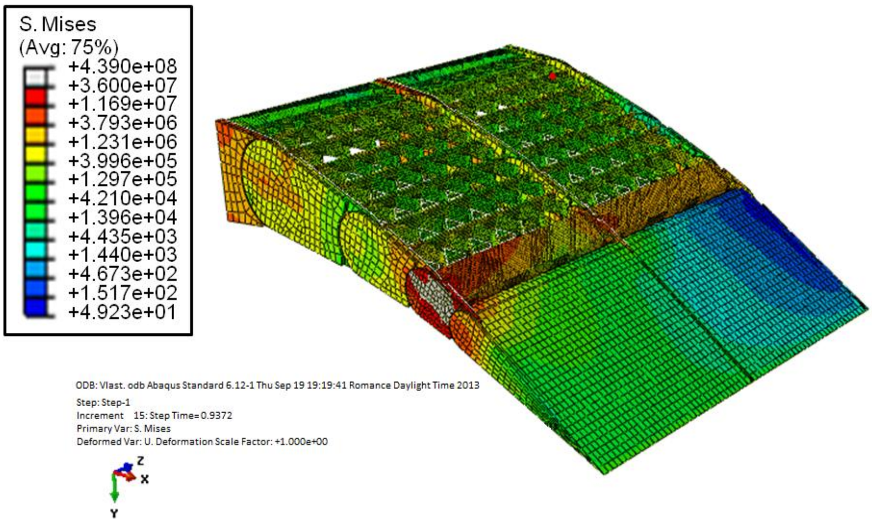


Figure 7: Double C shape skeleton panels

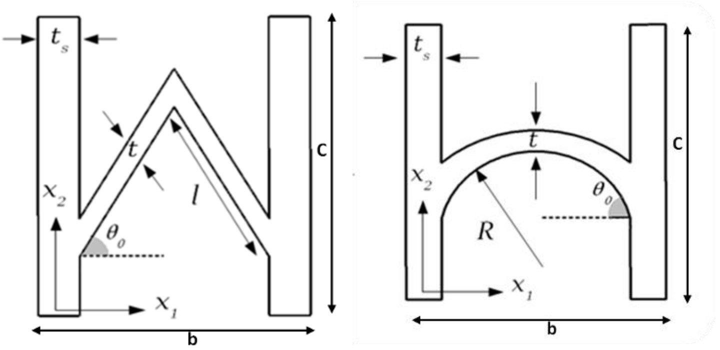
Structural integrity analysis is also implemented by means of Abaqus FEM, figure 8, to show a very preliminary test applying the concept of morphing mechanism.



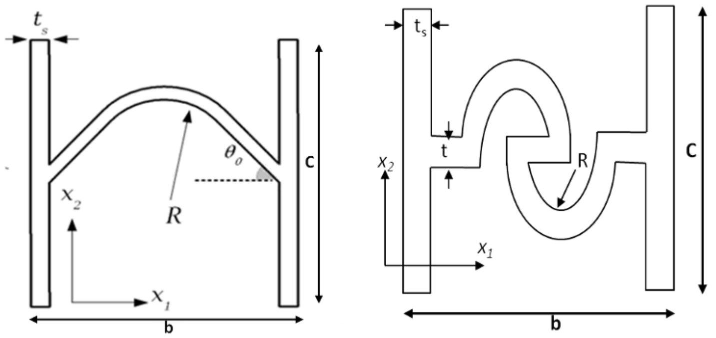
```
ODB: Vlast. odb Abaqus Standard 6.12-1 Thu Sep 19 19:19:41 Romance Daylight Time 2013
Step: Step-1
Increment    15: Step Time= 0.9372
Primary Var: S. Mises
Deformed Var: U. Deformation Scale Factor: +1.000e+00
```

Figure 8: Abaqus static mechanical testing for internal structure design

The design of morphing skin structures has been carried out further with emphasis in the design of the various skin lattice structures, figure 9. Numerical characterisation of the geometric unit-cell and optimisation is developed focusing on the mechanical behaviour of these morphing skins. Numerical simulations using Finite Element Method through Abaqus commercial program were performed for the best selection of the unit-cell configuration. Behind the development of the design concept, a lot of work has been realized regarding optimization and characterization of the structures, through FEM analysis figure 10.



Straight configuration *Curved configuration*



Mix configuration *Double C Configuration*

Figure 9: Unit cell of studied skin lattice structures

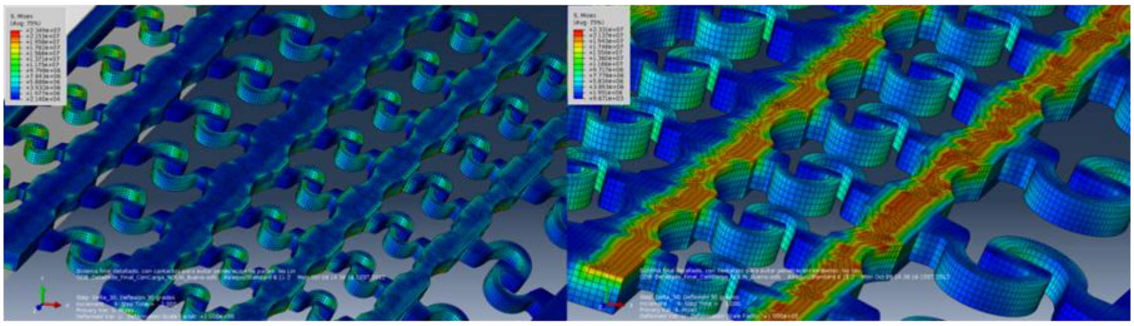


Figure 10: Double C shape skeleton panel Abaqus FEM analysis.

3 MATERIALS AND PROCESSES

Aernnova has carried out extensive research to select a suitable material candidate for the deformable skin skeleton design. The research leads to SLS (Selective Laser Sintering) technique; a technique which is very suited for morphing geometries such as the unit-cells presented as skeleton skin. The PA12 polyamide material is selected for this process due to its good ductile and toughness properties. In addition, the material is light weight and cheap, which favors the decrease of weight penalties, a crucial part in the implementation of a morphing device. However, the material is damaged due to its hygroscopic nature and humidity impoverishes its material properties, making it brittle. Tests have been performed by saturating the manufactured pieces of PA12 in water particles and then performing static tests to analyze it’s tensile and fracture effects. Variations of PA12 materials with incorporated hard particles are also looked into for property enhancements and compensation for the moisture drawback. Materials investigated included GFN containing glass beads, HST containing ceramic fibers and PA12 base material. For humidity study, specimens are created for each component and these are submerged in water at a constant temperature of 90ºC in order to accelerate the water saturation process. Specimens are also kept at a dry constant temperature of 90ºC for dry condition testing, figure 11Figure 11. The process is carried out for the different types of PA12 materials specimen which are later used for the mechanical testing.

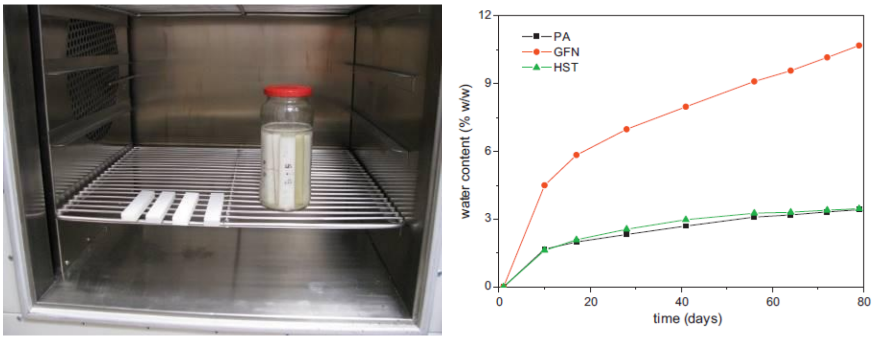


Figure 11: Drying and Water saturation process

Various mechanical tests are performed to investigate the behaviour of these types of PA12 materials after the water saturation and drying process. The experimental testing and characterisation are carried out following standard norms of test justification involving static tensile, compression, fracture and fatigue testing. Mechanical properties from the experimental testing showed interesting results. The yield strength Improves under dry conditions and no toughness alteration for altered PA12 with spheres and fibre compounds. Materials presented impoverished toughness and tensile properties. This is especially affected the toughness properties of the base PA12 material, figure 12.

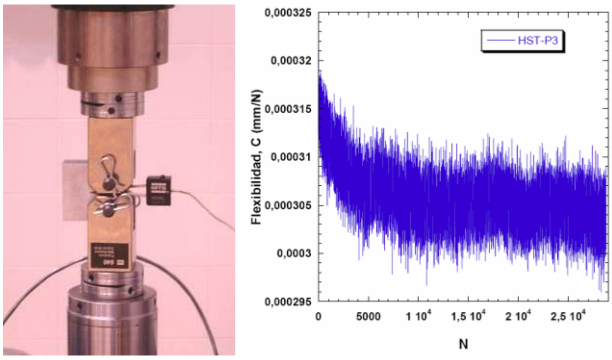


Figure 12: Fatigue testing and cyclic loading application

4 FLUID- STRUCTURES INTERATION

The structural implementation of the solution has to be checked from local deformations at deflection of the surface exposed to the air flow. The airfoil pressure distributions and skins internal loading can create local deformations that are translated into deviations of the actual airfoil in relation to the theoretical one, figure 13.

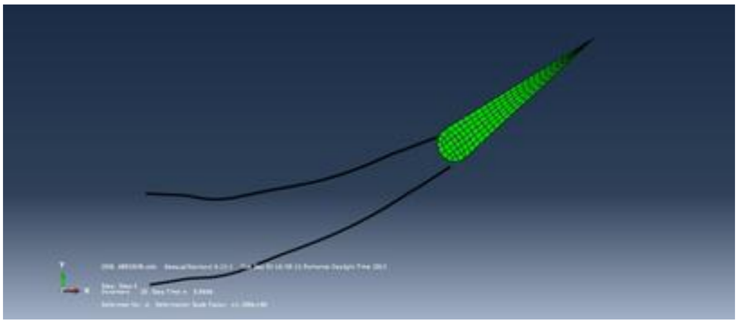


Figure 13 Local deformations study of the morphing structural concept

The aeroelastics analysis is pending and it is relevant given the change in the vortex-frequency due to the rudder morphing [7], and the weight and stiffness effect of the new design in relation to the conventional one.

5 MANUFACTURING AND ASSEMBLY

The EU FP7 SARISTU project has given essential experience on morphing structures from the manufacturing and assembly point of view. Starting by preliminary dummy demonstrator, then the ATED 2-bay demonstrator, figure 14, experience is obtained from these phases which achieved an important milestone. This leads to the improved manufacturing and assembly process of the final 5-bay demonstrator of ATED.

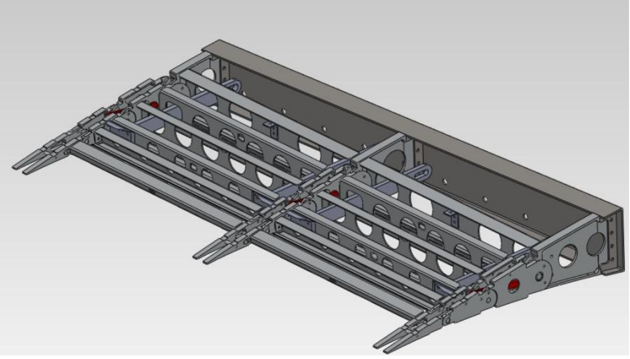


Figure 14 Internal Structure display

The manufacturing process was performed successfully by selecting the optimal materials for the further machining and bending processes. The internal structure of the ATED is a skeletal structure which is crucial for the correct transmission of movement from the actuator and structural integrity as load support. Holes are also included in the design phase in the components of the internal structure for the accommodation of cable routing, sensor installation and furthermore reducing the overall weight of the structure. The manufactured components included the following features:

- Segmented ribs, carrying rotational movement for the structural morphing.
- Spar-x that supports the metallic skin sections of the morphing skin.
- Rear spar which carries the actuators and also structurally supports de whole ATED.

The actuator chain and bars were manufactured to control the morphing movement in the ATED by transforming the produced rotations into displacement of the actuation bar. The actuator chain was mounted at the base of the ATED rear spar and the actuation bar was fitted through the spar-x and connected to the actuation chain, figure 15.

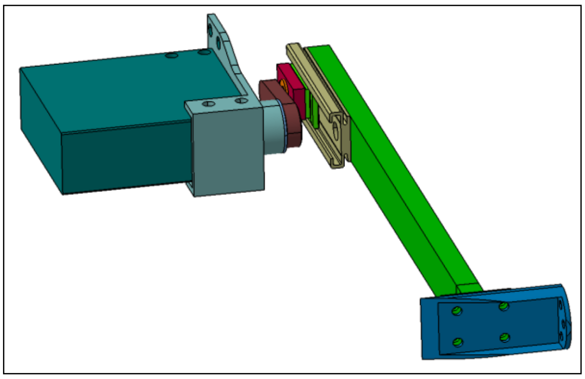


Figure 15: Actuator chain DMU

The Dead Box (DB) skin is an interface between the Wing Box and the Trailing Edge structure. It is made of an upper and lower skin panel as shown in figure 16. The union position at the ATED is located at the rear spar flange, 1st spar-x flange and the rib flange (1st section only).

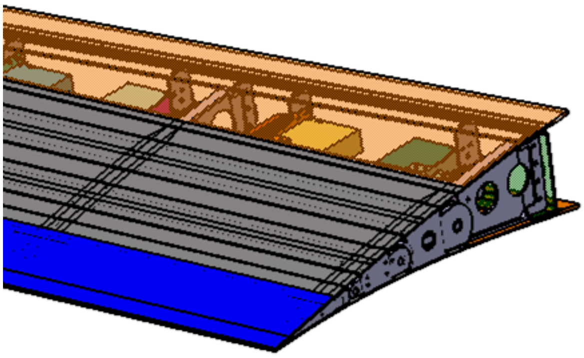


Figure 16: Skins connecting ATED and torsion box

The morphing skins are located in the upper and lower surfaces of the trailing edge. The 2-bay demonstrator offered important acquired experience to be implemented for the manufacture and assembly of the ATED 5-Bay Demonstrator, figure 17.

Figure 17: Internal structure of 5 Bay Demonstrator

A proof of concept of the morphing skin was manufactured by the already mentioned SLS additive manufacturing process, as a physical demonstrator, it can be observed in figure 18.

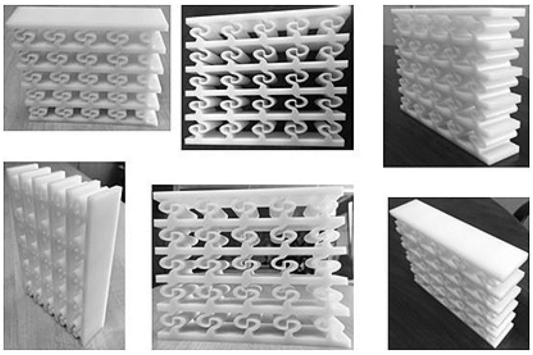


Figure 18: SLS manufactured Double C configuration PA12 material.

6 CONCLUSIONS AND CHALLENGES FOR FUTURE STUDIES

From previous author studies, the new morphed rudder presents the following enhancements:

- 15% potential improvement in aerodynamic lift, [7]
- Higher frequency of the vortices detachment, [7]
- It is enabled by new highly orthotropic panels produced by additive manufacturing, [8]
- The new panels show secondary module from a certain level of deflection, [21]
- Static stability, increased yawing moment available 8% at engine out, in consequence decrease in the minimum speed lateral control 4%, [22]

- Studies on dynamic stability free control commands result in a decrease of the yaw amplitudes on Dutch Roll frequencies [23]
- For fixed controls, the yaw divergence is predicted to appear sooner, [23].

This paper presents additional manufacturing and assembly experience on similar morphing structures on EU FP7 SARISTU project. These developments have brought to a current technological maturity close to TRL 3 for a morphing rudder at an aircraft system level.

The most relevant remaining challenges for future studies are listed below:

- Selection of actuators, structural sizing and complete weight impact assessment.
- Wind tunnel tests to verify aerodynamics morphing effects without and with NLF, HLFC system
- Stability analysis of more load cases to complete studies of flying qualities.
- Keep on investigating methods to optimizing the highly orthotropic panels geometric configuration.
- Miniaturization of geometric cells and step into three dimensions features
- New additive manufacturing features and use of different raw materials.
- Complete test campaign of the highly orthotropic 3D printed panels
- Complete rudder static, fatigue and Damage tolerance tests.
- Ground vibration test , FEM correlation and Aeroelastic studies and assessment.

REFERENCES

[1] Elzey D. M.; A. Y. N. Sofla and Wadley H. N. G. (2003). “A bio-inspired, high-authority actuator for shape morphing structures.” Proceedings, de SPIE, vol. 5053, pp. 92–100.

[2] Vasista S.; Tong L. and Wong K. C. (2012). “Realization of Morphing Wings: A Multidisciplinary Challenge,” Journal of Aircraft, vol. 49 (January), pp. 11–28.

[3] Grigorie T. L.; Popov A. V.; Botez R. M.; Mamou M. and Mebarki Y. (2011). “On-off and proportional-integral controller for a morphing wing. Part 1: Actuation mechanism and control design,” in Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 2011, vol. 226 (Jul), pp. 131–145.

[4] Lee D. S.; Gonzalez L. F.; Periaux J. and Onate E. (2012). “Robust Aerodynamic Design Optimisation of Morphing Aerofoil / Wing using Distributed MOGA,” 28TH International Congress of the Aeronautical Sciences, ICAS 2012, vol. 25, pp. 13–24.

[5] Stanewsky E. (2001). “Adaptive wing and flow control technology,” Progress in Aerospace Sciences, vol. 37, pp. 583–667.

[6] Barbarino M. (2014). “Airframe noise reduction technologies applied to high-lift devices,” en las actas, proceedings, de “3AF / CEAS Conference Greener Aviation: Clean Sky breakthroughs and worldwide status”, 12- 14 March 2014, Brussels, Belgium.

[7] M. A. Castillo-Acero, C. Cuerno-Rejado, and M. A. Gomez-Tierno, “Aerodynamic Modelling for a Morphing Rudder,” in RAeS Applied Aerodynamics Conference 2014, Bristol, UK, 2014.

[8] M. A. Castillo-Acero, M. A. Gomez-Tierno, and C. Cuerno-Rejado, “Morphing Structure for a Rudder,” in 4th Aircraft Structural Design Conference, RAeS, Belfast, UK, 2014.

[9] Pecora R.; Amoroso F. and Magnifico M. (2013). “Design and Experimental Validation of a Morphing Wing Flap Device” proceedings, “6th ECCOMAS Conference on Smart Structures and Materials. SMART2013”, 24-26 Junio 2013, Politecnico di Torino, Italia.

[10] Sofla A. Y. N.; Meguid S. A.; Tan K. T. and Yeo, W. K. (2010). “Shape morphing of aircraft wing: Status and challenges,” Materialds and Design, vol. 31 (Mar), pp. 1284–1292.

[11] Osborn R. F.; Kota S.; Hetrick J. A.; Geister D. E.; Tilmann C. P. and Joo J. (2004). “Active Flow Control Using High-Frequency Compliant Structures,” Journal of Aircraft, vol. 41 (Mayo), pp. 603–609.

[12] Puterbaugh M. and Beyene A. (2011). “Parametric dependence of a morphing wind turbine blade on material elasticity,” Energy, vol. 36 (Jan), pp. 466–474.

[13] Lachenal X.; Daynes, S. and Weaver P.M. (2013). “Review of morphing concepts and materials for wind turbine blade applications,” Wind Energy, vol. 16 (Feb), pp. 283–307.

[14] Gamboa P.; Vale J.; Lau F. J. P. and Suleman A. (2009). “Optimization of a Morphing Wing Based on Coupled Aerodynamic and Structural Constraints,” AIAA Journal, vol. 47 (Sept), pp. 2087–2104.

[15] Cadogan D. (2004). “Morphing Inflatable Wing Development for Compact Package Unmanned Aerial Vehicles,” proceedings, 45th AIAA/ ASME/ ASCE/ AHS/ ASC Structures, Structural Dynamics and Materials Conference, 19-22 April 2004, Palm Springs, USA.

[16] Yang J.; Nangia R.N.; Cooper J.E.; Simpson J. A. e Ibp F. (2014). “Optimisation of Morphing Wings for Improved Environmental Performance Dept of Aerospace Engineering , University of Bristol , BS81TH , UK,” proceedings, de “3AF / CEAS Conference Greener Aviation: Clean Sky breakthroughs and worldwide status”, 12- 14 March 2014, Brussels, Belgium.

[17] Simpson J.; Anguita-Delgado L.; Nilsson B.; Vaccaro V. and Kawiecki G. (2005). “Review of the European Research Project ‘Active Aeroelastic Aircraft Structures (3As),” proceedings, “European Conference Aerospace Science (EUCASS)” 4-7 Jul 2005, Moscú, Rusia.

[18] Courchesne S.; Popov A. V. and Botez R.M. (2012). “New aeroelastic studies for a morphing wing,” INCAS bulletin ISSN 2066- 8201. Vol. 4, Issue 2/2012, pp.19- 28.

[19] Thomas F. O.; Corke T. C.; Iqbal M.; Kozlov A. and Schatzman D. (2009). “Optimization of Dielectric Barrier Discharge Plasma Actuators for Active Aerodynamic Flow Control,” AIAA Journal, vol. 47 (Sept), pp. 2169–2178.

[20] Kamuran T. and Jafarov E. M. (2006). “Lateral Dynamic Modeling of Hezarfen Unmanned Aerial Vehicle (UAV) and H_∞ Loop Shaping Robust Control System Design,” Proceedings, “10th WSEAS International Conference on SYSTEMS”, Vouliagmeni, Atenas, Grecia, 10-12 Jul 2016, pp. 369–374.

[21] Castillo Acero M. A., Cuerno C. and Gómez Tierno M. A, “Highly Orthotropic Panels Structural Stability, Farrar and Bloch Waves Theory,” in *3rd Int. Conference on Buckling and Postbuckling Behaviour of Composite Laminated Shell Structures*, Oct 2015, Braunscweig, Germany.

[22] Castillo Acero M. A., Cuerno C. and Gómez Tierno M. A. “Morphed vertical tailplane assessment for certification requirements,” in *5th CEAS Air & Space Conference 7-11 Sept 2015 Delft University of Technology (The Netherlands)*, 2015.

[23] Castillo Acero M. A. (2016). “Studies to configure a non-conventional rudder on a commercial transport aircraft: aerodynamics, structures and lateral- directional static and dynamic stability.“ Proceedings 6th EASN International Conference, Porto, 18th October 16, Portugal.