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DEMMOW – Detailed Model of a Morphing Wing: development of the full wing model

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Abstract
This paper presents the activities undertaken in the DEMMOW project (CleanSky 2, n°755621). The goal of the project was to develop a high fidelity integrated non-linear MBS-FEM model of a morphing wing, including several structural components (composite box, morphing winglet or wingtip, droop nose and adaptive trailing edge), with kinematic joints and actuators. Multi-body dynamics modelling of the mechanical system is addressed by the finite element method extended to multi-body systems including flexibility and non-linearities related to large displacements and rotations, and to morphing parts that can include compliant structures and non-linear materials, leading to a flexible wing concept.

1. The DEMMOW project

Figure 1 illustrates a typical wing architecture including high-lift devices like slats and flaps classically used to improve the performance of the aircraft depending on the flight conditions, as well as wingtip and winglet that are used to decrease the drag coming from wing tips vortices and to increase the fuel efficiency. These components are assembled on the wing box structure to form the full wing.

Figure 1: Illustration of a wing with classical high-lift devices, winglet and wingtip

In Figure 2, some conventional concepts for leading and trailing edges are described [1, 2]. They are based on “moving solid elements”, and rely on mechanical actuation and classical kinematic joints like hinges and sliders.

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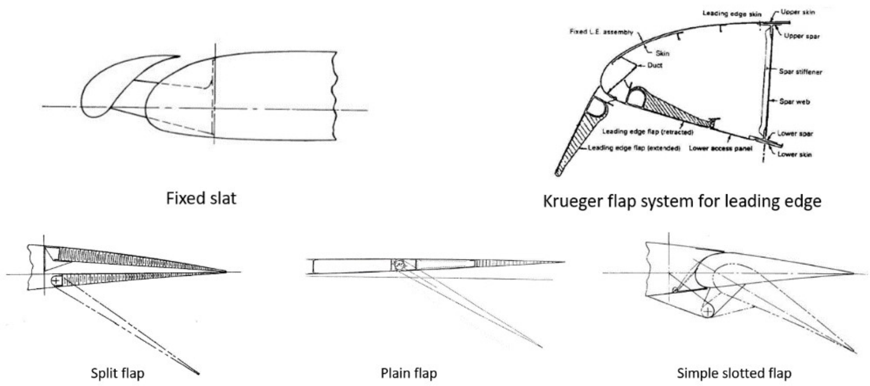

Figure 2: Conventional high lift devices for leading and trailing edges

Classical high-lift devices of Figure 2 are expensive, complex and heavy. They are therefore not acceptable solutions for the current trends on efficient and green aircrafts. As explained in [9], recent developments based on adaptive/morphing structures may overcome the limitations of classical high-lift devices, and so provide better solutions while reaching the objectives in terms of efficiency and environmental impact. The idea is to adapt the shape of the wing to the flight condition, by using morphing techniques. The compliant and/or kinematic mechanisms as well as the actuation system are now inserted in the wing and used to change its shape. Using morphing concepts allows shape change without the generation of discontinuities in the flow (no aerodynamic gap). Some concepts for a morphing leading edge (droop nose) are now presented [2]. The realization of the Dornier concept in [3] is very interesting, as it includes the finite element analysis, the manufacturing and the testing of the droop nose system. It is seen that a mechanism based on kinematic joints (hinges) is used to adapt the shape of the morphing part. The skin is made of GFRP composite material of variable thickness, what can provide the necessary flexibility to reach the desired deformed shape. In [4] it is explained how topology optimization can be used to determine the design of a compliant mechanism used for a morphing leading edge. In [2], lots of references are provided for morphing trailing edges. In [5], one idea is to create an articulated chain by connecting blocks (that may be considered as rigid in a first approximation) with hinges in order to enable a modification of the air foil camber line. A multi-material skin made of elastomers and aluminium is used to allow deformations while carrying aerodynamic loads. In [6], a concept for a morphing wingtip is proposed, with a flexible corrugated skin made of composite material. Finite element analyses are used to validate the design approach. A mechanical demonstrator is developed.

As a first conclusion, morphing devices are based on an adaptation of classical high-lift designs. Kinematic joints and/or compliant structures are used as internal mechanisms to induce the deformation of the part. A key point is the design of the skins, which must have the necessary flexibility to reach the desired deformed shapes and the sufficient rigidity and strength to sustain the aerodynamic loading. Composite and non-linear materials like elastomers can be used. Science popularisation papers with general information are given in [7] and [8]. Additional information can be found in the very detailed review of [9].

The goal of the DEMMOW project is to develop a high fidelity integrated non-linear MBS-FEM model of a morphing wing (and of its components), as illustrated in Figure 3.

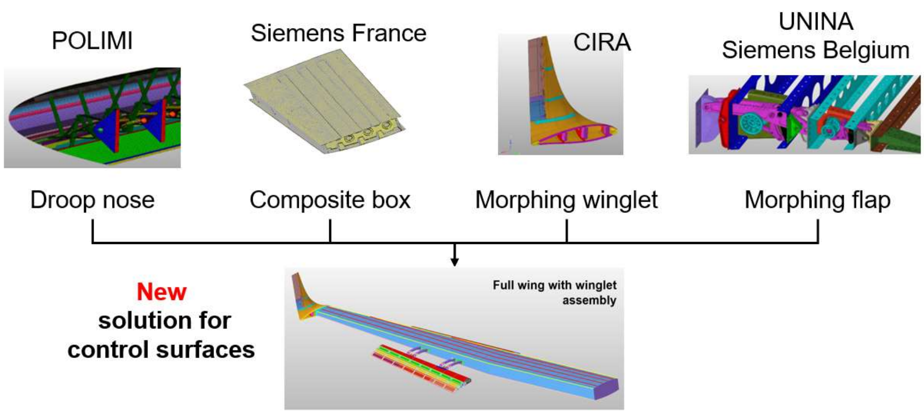

Figure 3: Goal of the DEMMOW project

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This research activity is done in the frame of Cleansky 2, with Leonardo Company Aircraft Division as Topic Manager. Specifications, design and/or finite element models of the components in different format (Abaqus, NASTRAN, SAMCEF) are developed by Leonardo partners in the context of Airgreen 2 program (POLIMI, CIRA, UNINA, Siemens, see Figure 3). These models are not suited for a MBS-FEM unified model of the full wing. They are therefore converted to SAMCEF format, including mechanical, kinematic and control elements, and so creating a full virtual prototype. The virtual prototype must be reliable and represent reality. It will then become the companion of the physical prototype. The principle is illustrated in Figure 4, in the frame of the pyramid of tests.

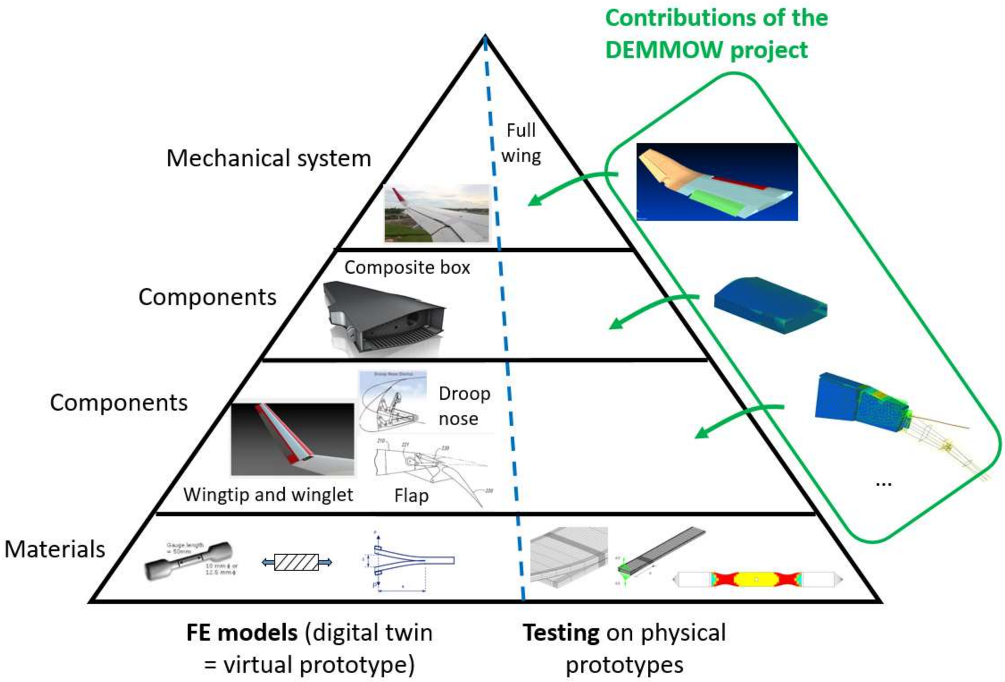

Figure 4: Pyramid approach to develop the model of the full morphing wing

2. Modeling approach

SAMCEF (Siemens PLM Software) is a general purpose commercial implicit finite element software including specific modules dedicated to linear analysis (static analysis; modal analysis; buckling analysis; time and harmonic dynamic responses; random vibrations), and non-linear analysis (static, kinematic and dynamic non-linear analyses). As illustrated in Figure 5, SAMCEF includes a structural finite elements library (bars, beams, shells, solid elements, solid shell elements, axisymmetric, multi-harmonic elements,…), a kinematic joints elements library (hinges, sliders, spherical joint, prismatic joint, screw, flexible joints, …) as well as a utility elements library (springs, user non-linear force, general constraints element, node on surface element, distance indicator, distance of a node to a curve element, local stiffness elements with non-linearities, friction, a controller element,…). SAMCEF has got specific capabilities for modelling and analysing laminated structures (composite structures). The SAMCEF Mecano module can take into account non-linear materials (plasticity, viscoplasticity, hyperelasticity, damage of composites, delamination…) and geometric non-linearities in a general formulation allowing large rotations and displacements. All these non-linearities can be naturally included in a MBS-FEM model as explained in [10], where the formulation and solution of the FEM problem are described: the system of equations to be solved is given in (1), where **M** is the mass matrix, $\ddot{\boldsymbol{q}}$, $\dot{\boldsymbol{q}}$ and $\boldsymbol{q}$ are the accelerations, the velocities and the displacements, respectively, while **g** are the forces.

$$\mathbf{M}\ddot{\mathbf{q}} = \mathbf{g}(\dot{\mathbf{q}}, \mathbf{q}, t) = \mathbf{g}^{external} - \mathbf{g}^{internal} \tag{1}$$

When constraints $\boldsymbol{\phi}$ are considered in the problem (e.g. relations between degrees of freedom to make a motion useful to a desired purpose, i.e. kinematic constraints), the problem to be solved is based on the stationarity of an augmented Lagrangian defined by the kinetic and potential energies and two additional terms related to the constraints including a penalty and the Lagrangian multipliers. It turns that the system of nonlinear equations to be solved is given in (2),

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with **B** the gradient of the constraints, p the penalty factor and k a scaling factor. As far as time integration is concerned, the Newmark or the HHT schemes are used. The nonlinear system is solved by the Newton-Raphson method.

$$\begin{cases} \mathbf{M}\ddot{\mathbf{q}} + \mathbf{B}^T(k\boldsymbol{\lambda} + p\boldsymbol{\Phi}) = \mathbf{g}(\dot{\mathbf{q}}, \mathbf{q}, t) \\ k\boldsymbol{\Phi}(\mathbf{q}, t) = 0 \end{cases} \qquad \textbf{(2)}$$

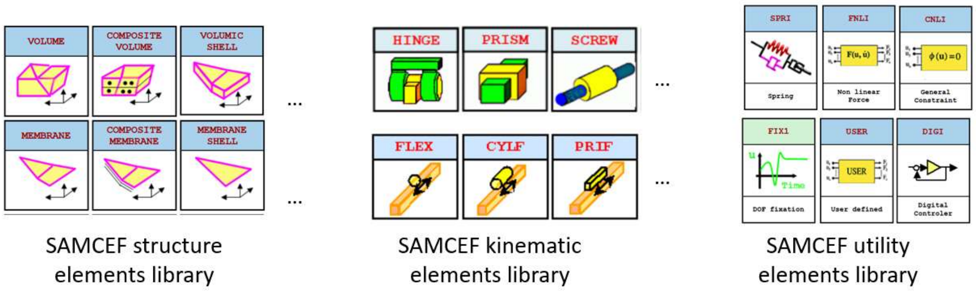

Figure 5: SAMCEF elements library for developing non-linear MBS-FEM models (from the SAMCEF documentation)

This principle is illustrated in Figures 6 and 7, on simplified designs of a trailing edge and of a droop nose. Additional illustrations can be found in [11, 12] for the development of a MBS-FEM model of a robot with controllers.

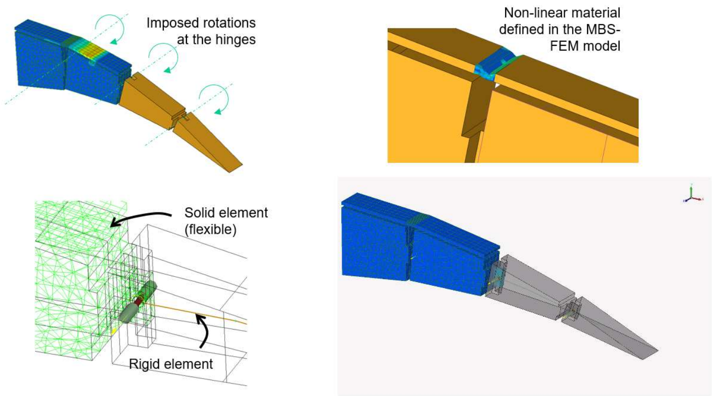

Figure 6: Using SAMCEF to develop a first (simple) model of an adaptive trailing edge component: definition of the hinges between the blocks

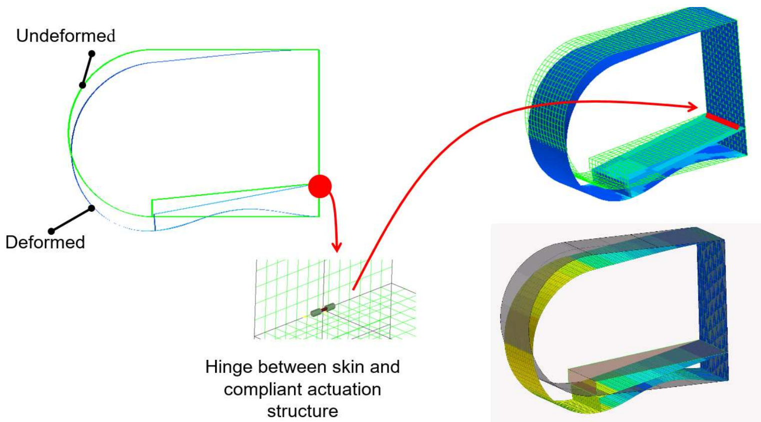

Figure 7: Using SAMCEF to develop a first (simple) model of a droop nose

DOI: 10.13009/EUCASS2022-3586

3. Models of the wing components

The modelling principle described in the previous section is now applied on the components of the morphing wing. In Figure 8, the model of the droop nose is developed, and a comparison is done regarding the way the elements of the internal actuation mechanism are modelled, either with solid or shell finite elements. Comparison between these two modelling approaches reveals that results are very similar. The droop nose model is then adapted in order to be mounted on the wing box, as illustrated in Figure 9.

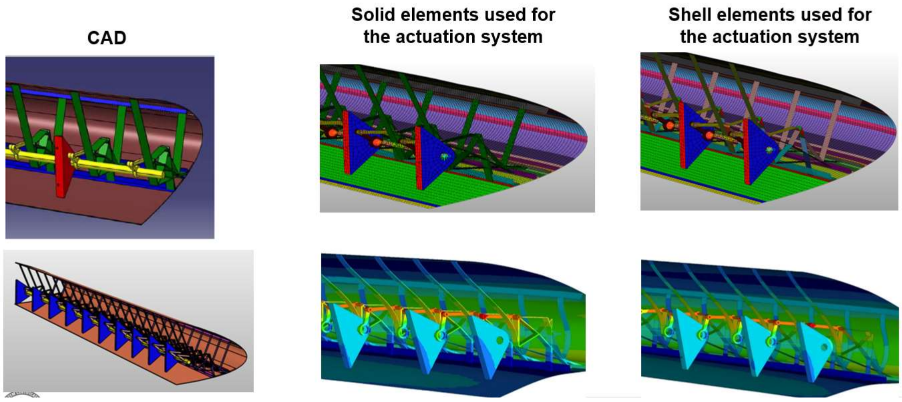

Figure 8: Model of the droop nose – comparison solid-shell

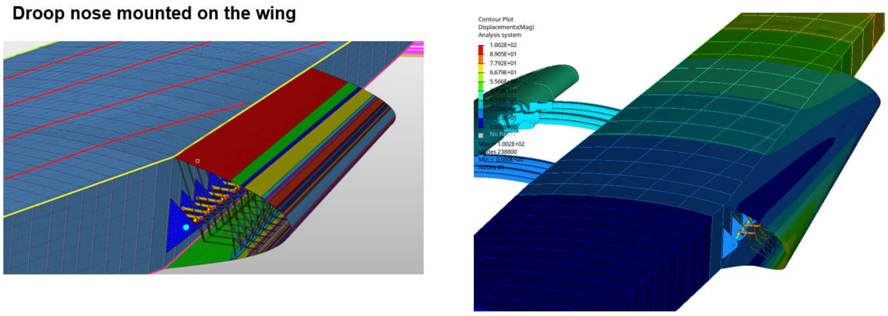

Figure 9: Droop nose mounted on the wing box

Figures 10 and 11 show details of the models developed for the winglet and for the morphing flap.

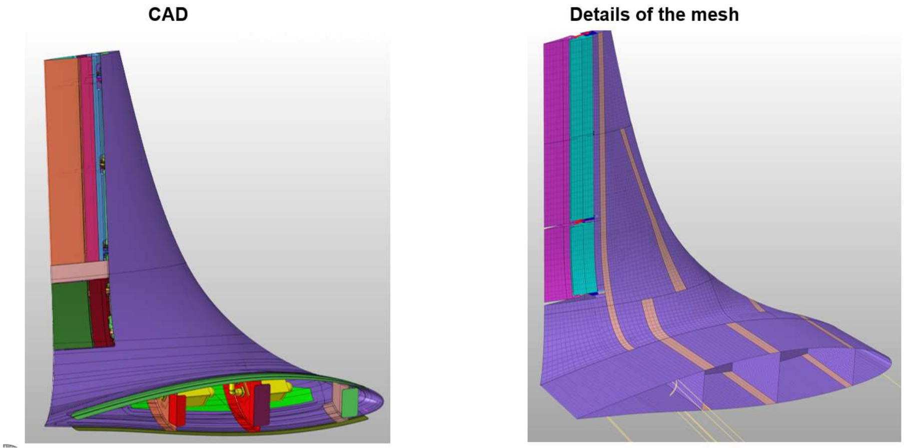

Figure 10: Model of the adaptive winglet

DOI: 10.13009/EUCASS2022-3586

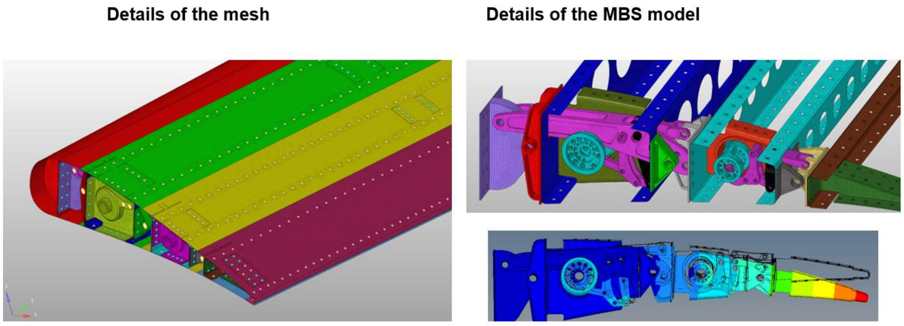

Figure 11: Model of the morphing flap

4. Models of the full wing

Two models of the full wing were developed. The first one including a winglet, and a second one with a wingtip. The two models, with their common components (droop nose, morphing flap and adaptive winglet, mounted on the wingbox) are illustrated in the next sections.

So far, the different models have been loaded with arbitrary but relevant loading scenarios, in order to check that the global deformations are physically acceptable and that there is no inconsistencies in the boundary conditions and assemblies of the different parts of the components of the wing.

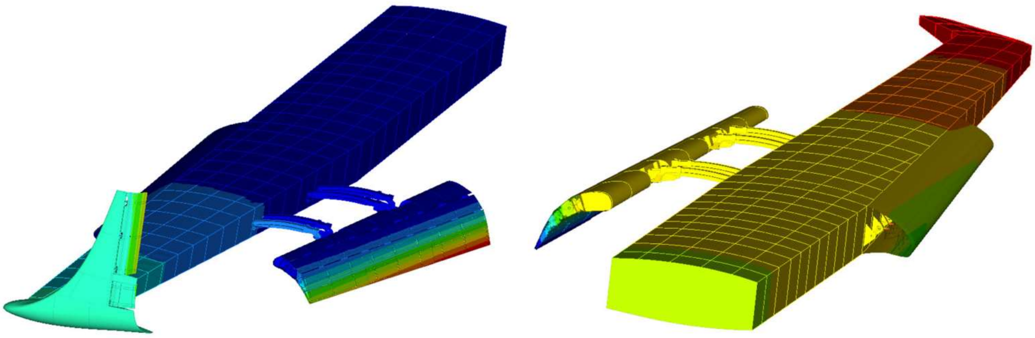

Figure 12: General views of the deployed mechanisms for the morphing wing model

4.1 Wing including the winglet

The global model of the full wing including the winglet is illustrated in Figure 13. It is inserted in the CAD of the aircraft. The other components of the wing are visible, like classical slats and flaps (in yellow), plus a schematic view of engine nacelle and fuselage.

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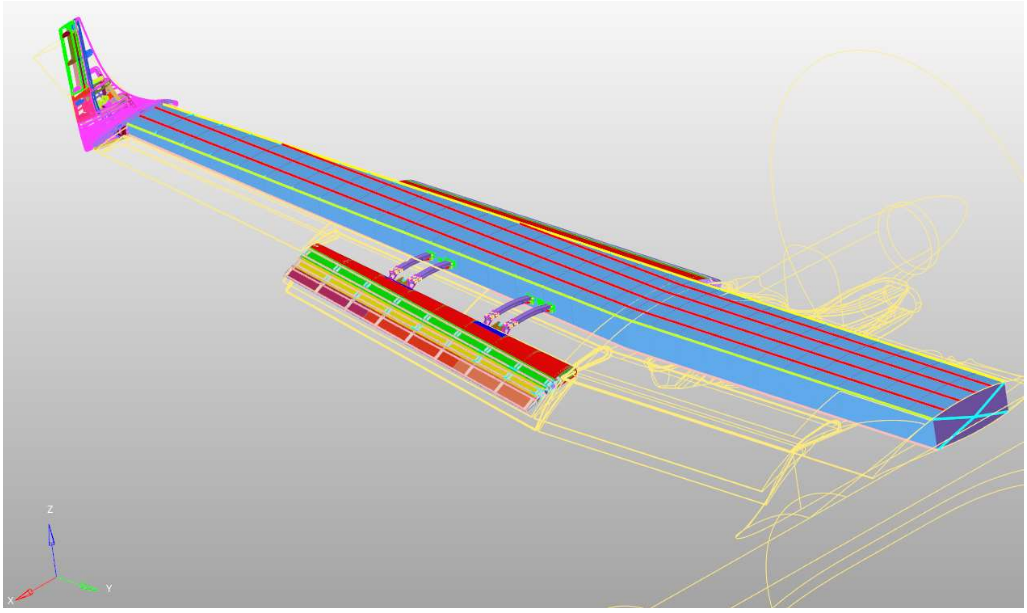

Figure 13: Global view of the full wing model with the winglet

In Figure 14, we illustrate the motion and the deformation of the components of the wing, as a validation of the full MBS-FEM model. The loads and actuations applied to the wing and its components are an aerodynamic pressure on the wing and on the morphing flap, and assigned movements of the droop nose mechanism (deflection), of the morphing flap (deflection) and of the winglet (rotation of the aileron).

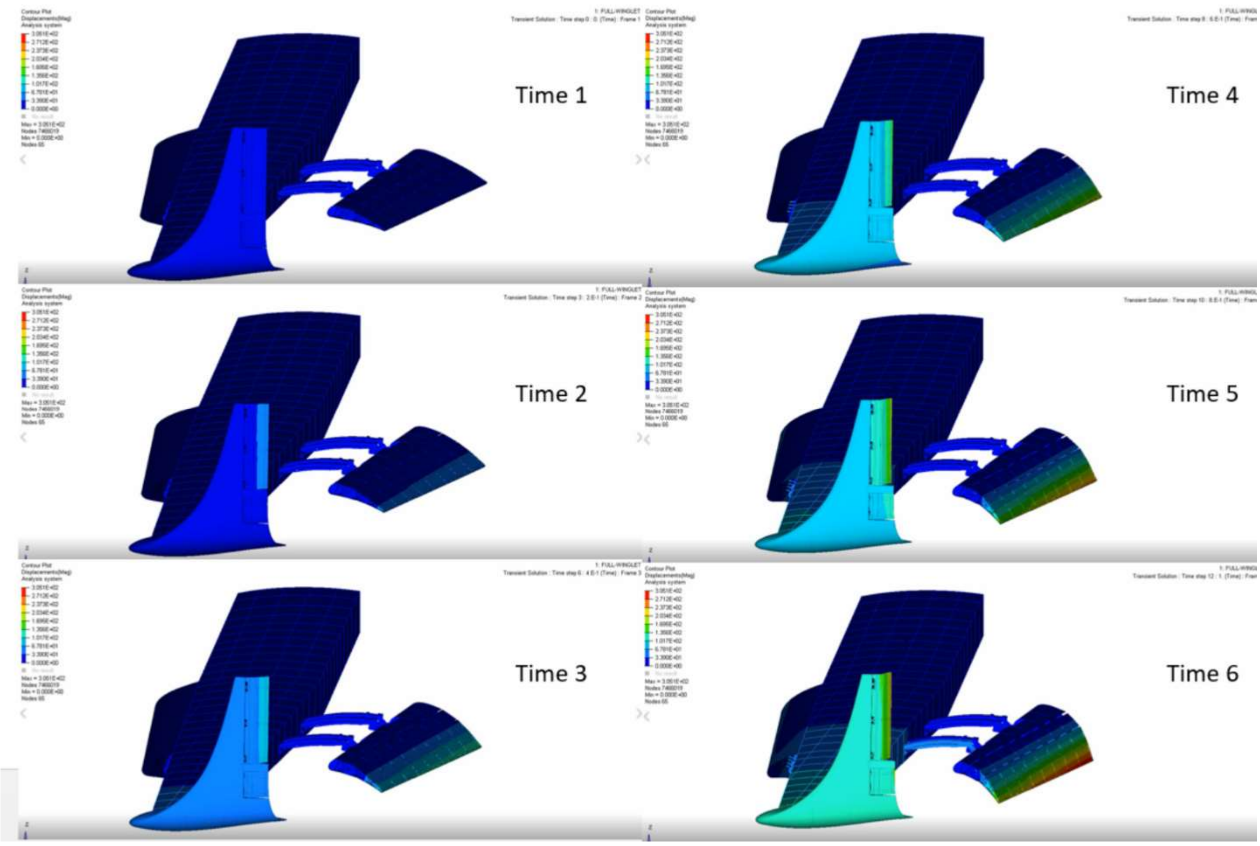

Figure 14: Motion and deformation of the full wing including the winglet

DOI: 10.13009/EUCASS2022-3586

4.2 Wing including the wingtip

In Figure 15, we illustrate the model including the wingtip, assembled in the wing with the droop nose and the morphing flap. As done for the winglet, the motion and the deformation of the components of the wing are checked, as a validation of the full MBS-FEM model (Figure 16). The loads and actuations applied to the wing and its components are an aerodynamic pressure on the wing and on the morphing flap, and assigned movements of the droop nose mechanism (deflection) and of the morphing flap (deflection).

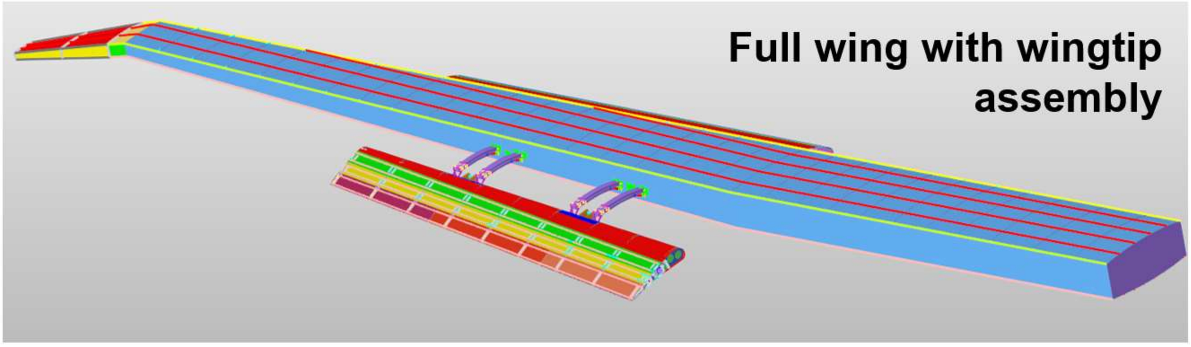

Figure 15: Wingtip mounted on the wing

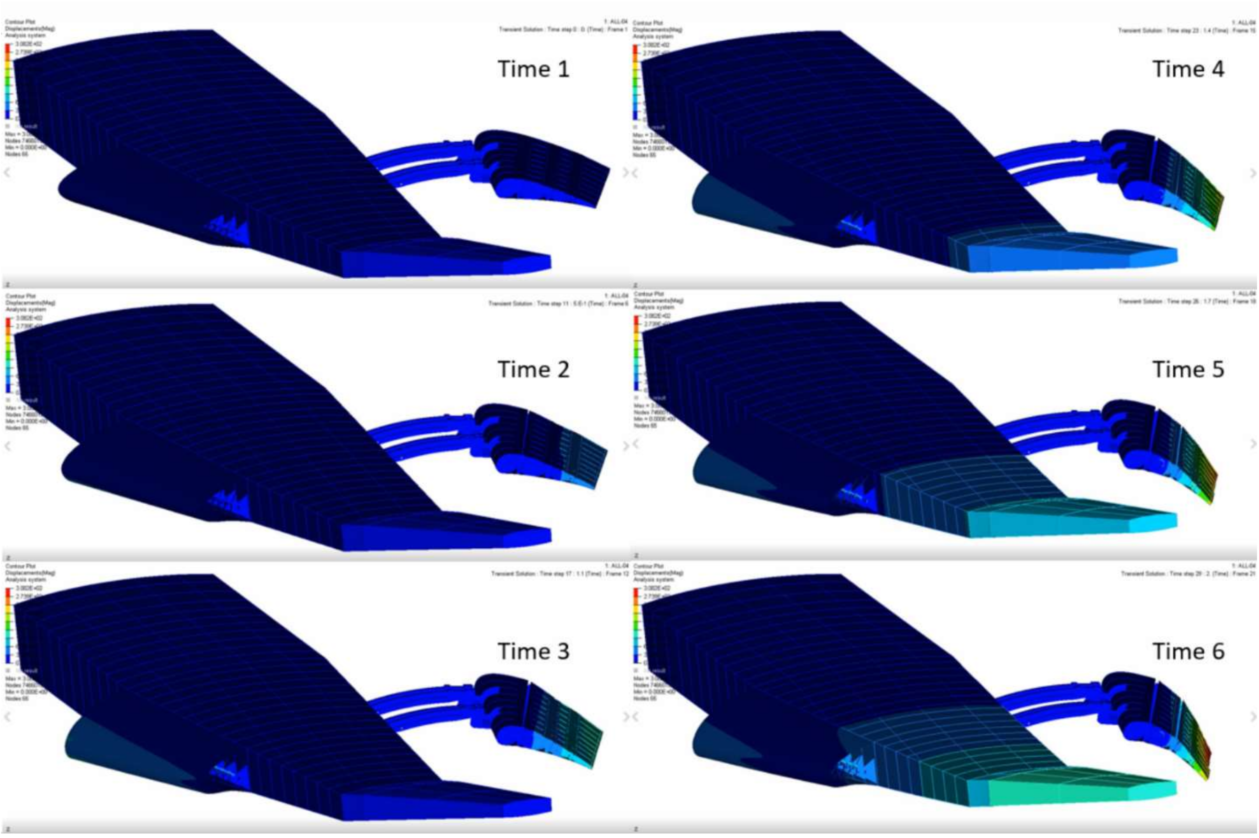

Figure 16: Motion and deformation of the full wing including the wingtip

5. Conclusion

This paper presented the results of the DEMMOW project (CleanSky 2, n°755621). The goal of the project was to develop a high fidelity integrated non-linear MBS-FEM model of a morphing wing, including several structural components (composite box, morphing winglet, wingtip, droop nose and adaptive trailing edge), with kinematic joints and actuators. Here, the separate components of the morphing wing were first modelled and then mounted on the

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wingbox to create the model of the full wing, either including a winglet or a wingtip. Multi-body dynamics modelling of the mechanical system was addressed with SAMCEF software. The finite element method extended to multi-body systems including flexibility and non-linearities related to large displacements and rotations, and to morphing parts that can include compliant structures and non-linear materials, leading to a flexible wing concept, was used. The models of the full wings were validated by assigning pressures and motions to the movable parts. Next steps will be to use the models as companions of physical tests for the validation of the new morphing wing design.

Acknowledgements

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References

[1] Rudolph P. 1996. High lift systems on commercial subsonic airliners, NASA Report CR-1996-4746.
[2] Di Matteo N. 2012. Optimal design and numerical analysis of morphing flap structures”, PhD Thesis. Cranfield University.
[3] Geier S., et al. 2016. Experimental and finite element analyses of multifunctional skins for morphing wing applications. In: Sensors and Smart Structures technologies for Civil, Mechanical and Aerospace Systems 2016, Proceedings of SPIE, vol. 9803 980328-1.
[4] Santer M. and Pellegrino S. "Topological optimisation of compliant adaptive wing structure", *AIAA Journal*, 47(3): 523-534.
[5] Schorsch O. et al. 2015. Polymer based morphing skin for adaptive wings. *7th ECCOMAS Thematic Conference on Smart Structures and Materials*. Eds. Araujo, Aurelio, Mota Soares.
[6] Ursache N. et al. 2008. Technology integration for active poly-morphing winglets development. *ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, October 28-30, 2008, Ellicott City, Maryland, USA.
[7] Xi F. 2014. Advancements in aircraft morphing technology. International Innovation, July 2014.
[8] Kota S. 2016. Twistable wings take flight – replacing traditional flaps with bendable bits will reduce noise and save fuel. IEEE Spectrum, vol. 53(9), September 2016.
[9] Barbarino S., et al. 2011. A review of morphing aircraft. Journal of Intelligent Material Systems and Structures, 22: 823-877.
[10] Cardona A. and Géradin M. 2001. Flexible Multibody Dynamics: A Finite Element Approach, Wiley.
[11] Bruyneel M. and Granville D. 2007. Mechatronic analysis of a flexible mechanism using SAMCEF: application to robotics, *5th NAFEMS Nordic Seminar – FEA Modelling and Numerical Simulation: Advances and Practical Applications*, Copenhagen, Denmark, 24th – 25th October 2007.
[12] Bruyneel M., Granville D. Pasquet Ph. and Gabellini E. 2008. Discussion on the modelling fidelity levels in flexible system dynamics, *8th World Congress on Computational Mechanics – WCCM8*, June 30 – July 5, 2008, Venice, Italy.