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PROJECT FINAL REPORT

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Project acronym: NOVEMOR

Project title: Novel Air Vehicle Configurations: from Fluttering Wings to Morphing Flight

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Executive Summary

In **NOVEMOR**, two lines of work were followed: 1) study of morphing concepts and their application to a reference regional jet model; 2) study of an innovative joined-wing (JW) configuration and the application of morphing mechanism to it. Several morphing concepts and mechanisms were proposed in WP2, including: morphing wingtip (for both control optimization and fuel consumption minimization), morphing camber (leading edge (LE) and trailing edge (TE)), telescopic wing, sweep and planform morphing. Some numerical tools were especially developed for designing and analysing the devised morphing concepts, including those developed in WP3. DLR developed a 3D topology optimization tool that was used to design a morphing wingtip (applied to the regional reference aircraft) which was tested in wind tunnel at UBRIS (in WP5). Morphing camber devices (LE and TE) were proposed by POLIMI in WP2 resulting from the employment of the design tools developed in WP3 (PHORMA and SPHERA, and were tested in wind tunnel facilities at POLIMI (in WP5). IST proposed in WP2 a telescopic wing concept which was applied to a small conventional RPV (Remotely Piloted Vehicle); the concept functionality and feasibility were demonstrated in flight, although it was not possible to prove experimentally the benefits of the telescopic wing for the RPV model. A few planform and sweep morphing concepts (outboard wing sweep, dihedral changes, telescopic rear wing and morphing vertical tail) were analysed and applied to a small joined-wing concept by UBRIS; despite the benefits found from this exercise, it was deemed too complex to implement these changes in-flight. UBRIS developed in WP2 also a 0-v honeycomb structure, a chiral structure and a variable rotating spars concepts to illustrate how changes in chord, length, camber, twist and stiffness can be achieved; the numerical computations performed closely to the functionality tests conducted in wind tunnel (in WP5).

Central to NOVEMOR project was the definition of a complete aircraft model to be used as a benchmark for evaluating potential benefits of the morphing concept developed within the consortium. EMB defined in WP3 a regional transport aircraft reporting weight and balance calculations, aerodynamic results, flight envelope, flying qualities, performance analyses and engine performance. EMB explore the possibilities of introducing a morphing wingtip and morphing TE devices. Both concepts provide computational benefits in terms of block of fuel burned for a typical mission profile (a maximum saving in 80 kg was reached by combining both morphing concepts), being the morphing trailing concept the one that provides the highest aerodynamic benefit. KTH enhanced the computational aircraft design framework CEASIOM with: 1) the capability of defining morphing lifting surfaces; and 2) the CPACS parameterization tool. The KTH extensions to the CEASIOM were applied to design a winglet for the reference model and optimizing it for cruise conditions. POLIMI developed enabling tools (PHORMA and SPHERA) to study compliant camber morphing devices allowing aero-structural shape optimization of these devices (these tools were applied in WP2 to design the camber morphing mechanisms). IST developed a performance based Multidisciplinary Design Optimization (MDO) framework for conceptual design which incorporates in an optimization environment the goals of analysing morphing solutions and novel configurations in WP3. The IST tool was used for the Weights and Energy Balance in WP4 and was applied to optimize a morphing wingtip on the reference aircraft and on the JW RPV model. UBRIS worked with KTH on the aerodynamic design methodology for the JW aircraft and reference aircraft winglet (approach later used in WP4).

WP4 represents the effort put into quantification of the benefits and penalties of the morphing concepts and the JW configuration. TE morphing seems to have the greater potential for reducing fuel consumption in all flight segments although requiring structural reinforcement, while LE morphing is indicated for low speed flight without requiring significant changes in the load bearing capability of the structure. The JW configuration seems promising when considering wing design only, due to the increased aspect ratio and related benefits, but when considering a more global approach, involving the weight penalties due to decreased root chord, the aerodynamic benefits are surpassed by trim drag penalties.

The presence of a wingtip in the reference model was tested in wind tunnel at CSIR (in WP5) and it was proved to be beneficial in aerodynamic terms by increasing the lift-to-drag ratio. The LE and TE morphing devices were also tested at CSIR transonic wind tunnel (in WP5) with contradictory results: 1) the subsonic morphed LE results in an increase in the stall angle of attack of at least 1°; 2) the lift-to-drag ratio CFD predictions for the morphed TE were not observed in the experimental results. A rigid and a flexible reduced scale JW models were designed, manufactured and tested in WP5. Good flight qualities were observed for both, although aft wing buckling was verified on the flexible model.

In WP6, EMB performed a benefit evaluation of the morphing concepts proposed and EMB foresees the morphing devices as a promising technology that can and will provide benefits to ACARE main goals. However, the employment of the morphing devices, at the regional aviation, might occur in a second moment due to the following peculiarities: 1) it is not possible to rely entirely on the morphing devices to satisfy the demanded aircraft field performance (High-lift devices are still necessary); 2) regional jet wings are relatively small, which brings difficulties to have any kind of mixed solution: conventional high-lift devices and morphing devices.

Description of Work

Context and Objectives

Air transport is increasingly becoming more accessible to a greater number of people who can afford travelling by air, both inside and outside Europe, for leisure and business purposes. This is evidenced by the fact that last year the European air transport system moved more than 1 billion passengers and 14 million metric tonnes of freight through its airports, whilst handling more than 12 million movements over the same period. Despite the effects of 9/11, SARS and the IRAQ war, the sector forecasts that over the next decade, both passenger and freight traffic is expected to increase at an average of 4 to 5% p.a., with freight being expected to increase slightly more - both significantly above global GDP growth. In air transport terms, this implies a doubling of traffic about every 16 years. It is evident that environmental requirements, such as noise impact and emissions, will play a dominant role in future transport aircraft development, becoming a driving force for aircraft design. This is the main reason for which ACARE, in the Strategic Research Agenda, established the so-called *greening aircraft* as the first objective of future research activities related to Aeronautics. The adoption of this kind of global requirement has two main consequences: firstly, the greening level becomes one of the criteria for which a new aircraft has to be judged or selected; and secondly, the ***aircraft configuration*** itself must be defined to fulfil the greening requirements. Since other design targets, such as economic and technical factors, must be satisfied, new design criteria arising from the greening requirements must be taken into account right from the beginning of the design cycle.

Looking at actual transport aircraft it is very easy to identify many similarities in shape and configurations of different airplanes, even if during the last decades great technological improvements have been reached, for example concerning engine emissions and noise reduction, high-lift device configurations and advanced materials. One of the reasons is related to the fact that configuration and performance of commercial aircraft, especially fixed-wing aircraft, have been optimized within a limited range of conditions, especially cruise conditions, in terms of speed and altitude. Outside this range, aircraft behaviour is less than optimal.

Concurrently, technological developments in materials and computer sciences have evolved to the point where their synergistic combination has culminated in a new field of multi-disciplinary research in adaptation. Advances in material sciences provide a comprehensive and theoretical framework for implementing multi-functionality into materials, and the development of high-speed digital computers has permitted the transformation of that framework into methodologies for practical design and production. Adaptive structures represent a new approach or design philosophy that integrates the actions of sensors, actuators and control circuit elements into a single system that can respond adaptively to environmental changes in a useful manner. These integrated systems possess a functionality that adds significant value to materials, technologies or end-products, which in turn enables system performance enhancements that are not possible with traditional conventional approaches.

The aim of the **NOVEMOR** (**NO**vel Air **VE**hicle Configurations: From Fluttering Wings to **MOR**phing Flight) research project is to **investigate novel air vehicle configurations** with new lifting concepts and **morphing wing solutions** to enable cost-effective air transportation. A multidisciplinary analysis and design optimization environment developed in an earlier EU Project (SIMSAC) will be used and improved to include analysis of novel configurations, such as the joined-wing concept for improved lift, and morphing wing solutions to tailor the wing for optimum lift and manoeuvring capabilities. The design and development of the proposed solutions will be performed an integral part of the aircraft conceptual design, rather than just as an add-on later in the design cycle, thus enabling innovative aircraft designs to be made through the use of morphing structures technologies. Such concepts will enable improved aircraft efficiencies, aerodynamic performance, reduced structural loads and lighter weight structures, leading to overall lower fuel consumption and therefore improvement on the greening level of the aircraft.

The NOVEMOR project will be focused on the following primary objectives:

1. Design and evaluation of a new aircraft concept, the joined-wing configuration, including structural, aerodynamic and aeroelastic scaling simulations and analysis, and multidisciplinary design optimization techniques. This configuration will be evaluated against a reference aircraft.
2. Morphing wing solutions (span and camber strategies and wing-tip devices) will be proposed to enhance lift capabilities and manoeuvring. These will be considered early in the design process, right from the beginning of aircraft design cycle, included in the conceptual design.
3. Design, test and evaluate the joined wing configuration and some of the more promising adaptive/morphing concepts and mechanisms as part of a conceptual design environment, capable of augmenting performance characteristics in terms of drag reduction, loads reduction, weight and noise impact reduction;
4. To evaluate the overall benefits of these new proposed concepts in terms of reducing operational cost.

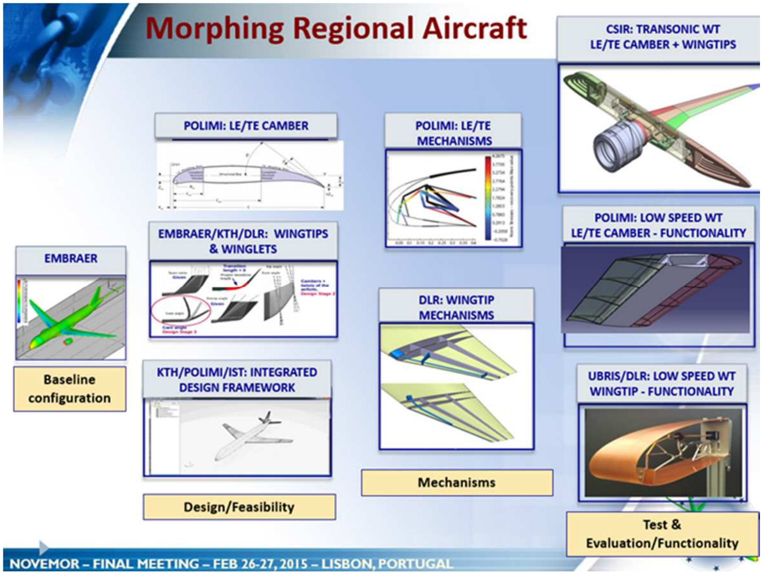
Partners

	Organization Name	Acronym	Scientific Team Leader	Country
1	Instituto Superior Técnico (Coordinator)	IST	Suleman, Prof. Afzal	PT
2	Politecnico di Milano	POLIMI	Ricci, Prof. Sergio,	IT
3	University of Liverpool (Terminated)	ULIV	Cooper, Prof. Jonathan	UK
4	Kungliga Tekniska Högskolan	KTH	Rizzi, Prof. Arthur	SWE
5	Deutsches Zentrum für Luft- und Raumfahrt	DLR	Monner, Dr-Ing Hans Peter	DE
6	Centre for Scientific and Industrial Research	CSIR	Gerryts, Dr. Beeuwen	SA
7	EMBRAER S.A.	EMB	Negrão, Dr. José Ricardo	BRA
8	University of Bristol	UBRIS	Cooper, Prof. Jonathan	UK

Description of Work

The project is split into two parallel lines of work which are complementary:

1. The study of morphing concepts and their application to a Reference Aircraft Model of a regional transport aircraft provided by the industrial partner EMBRAER (Figure 1).
2. The study of morphing concepts and their application to novel configurations, particularly the joined wing configuration (Figure 2).



Morphing Regional Aircraft

EMBRAER

Baseline configuration

POLIMI: LE/TE CAMBER

EMBRAER/KTH/DLR: WINGTIPS & WINGLETS

KTH/POLIMI/IST: INTEGRATED DESIGN FRAMEWORK

Design/Feasibility

POLIMI: LE/TE MECHANISMS

DLR: WINGTIP MECHANISMS

Mechanisms

CSIR: TRANSONIC WT LE/TE CAMBER + WINGTIPS

POLIMI: LOW SPEED WT LE/TE CAMBER - FUNCTIONALITY

UBRIS/DLR: LOW SPEED WT WINGTIP - FUNCTIONALITY

Test & Evaluation/Functionality

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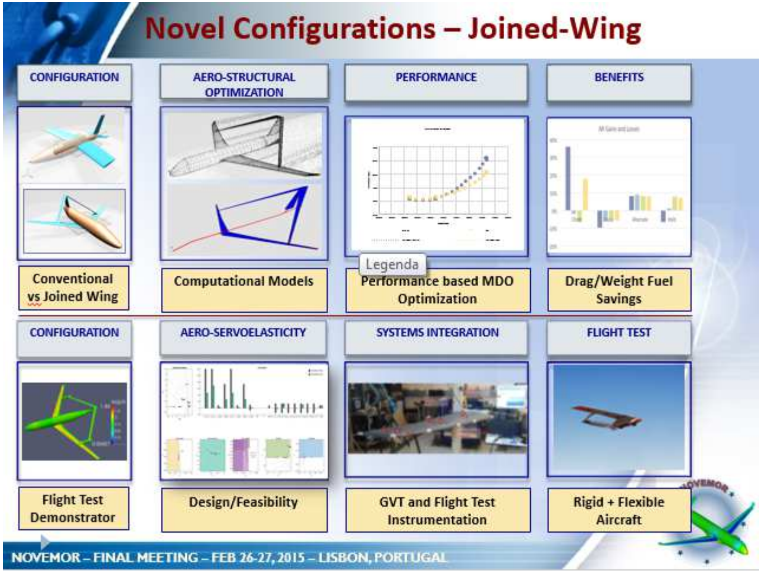
Figure 1. 1st line of research – Morphing of Conventional Aircraft.



Novel Configurations – Joined-Wing

CONFIGURATION

Conventional vs Joined Wing

AERO-STRUCTURAL OPTIMIZATION

Computational Models

PERFORMANCE

Legenda

Performance based MDO Optimization

BENEFITS

Drag/Weight Fuel Savings

CONFIGURATION

Flight Test Demonstrator

AERO-SERVOELASTICITY

Design/Feasibility

SYSTEMS INTEGRATION

GVT and Flight Test Instrumentation

FLIGHT TEST

Rigid + Flexible Aircraft

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Figure 2. 2nd line of research – Morphing of Novel Configurations Aircraft.

A short description of each Work Package (WP) objectives follows:

- **WP1- Project Management, Dissemination and Exploitation (Leader: IST)**
    - To secure the prompt initiation and smooth running of the project activities and the timely production of all deliverables, to the EC as well as to the partners, within the budget, and according to the EC rules.

- **WP2- Design of Morphing Concepts and Mechanisms (Leader: DLR)**
    - To develop and assess new concepts for adaptive wing camber and twist.
    - To develop and assess new concepts for adaptive wingtip and winglet.
    - To develop and assess new concepts for variable planform and sweep wings.
    - To identify and discuss the implementation issues of the proposed morphing concepts.
- **WP3- Novel Configuration, Simulation and Analysis (Leader: KTH)**
    - Enhance the CEASIOM software suite with:
        - Parameterized geometrical representations for morphing aircraft, suitable for conceptual design and mesh generation for CFD and CSM;
        - Techniques for the automatic generation of structural and aerodynamic models;
        - Optimization procedures for the design of compliant mechanisms;
        - Aeroelastic analysis tools adapted for morphing configurations;
        - Flight-dynamic stability analysis of flexible and morphing configurations and apply these enhanced tools;
        - Setup of a complete aircraft reference model, e.g. the Clean-Sky-type configuration, to serve as the critical benchmark, against which the proposed configurations will be evaluated in terms of efficiency gained in increased performance, reduced weight, costs etc.
- **WP4- System Analysis and Integration (Leader: UBRIS)**
    - Evaluation of aeroservoelastic stability across the entire flight envelope for morphing systems including all failure and payload cases.
    - Definition of aerodynamic performance gains (drag, flight handling qualities, control effectiveness, etc.).
    - Definition of an approach to determine the energy balance of the implementation of a particular morphing concept compared to conventional control surfaces.
    - Definition of an approach to determine the weight balance of the implementation of a particular morphing concept.
    - Definition of an approach to assess the systems integration and avionics issues of implementing morphing concepts.
    - Definition of an approach to assess the trade-offs between the above issues in order to determine a ranking for various morphing concepts.
- **WP5- Wind Tunnel and Flight Demonstrators for Validation of Morphing Concepts and Joined Wing Configuration (Leader: POLIMI)**
    - Build upon WP2 and WP3, the goal of WP5 is to develop physical models for validation of the proposed solutions and validation of the simulation results.
    - To manufacture WT and flight test wings with the proposed morphing solutions. It is noted that only the most promising morphing solutions will be tested in the WT and in flight.
    - To support WP6 with experimental data for the benefit analysis and also provide validation results to the numerical tools developed in WP3.
    - Experimental validation of adaptive/morphing wing planform, camber.
    - Design, manufacture and wind tunnel testing of a half wing equipped with fixed morphed geometries based on morphing solutions identified in WP2 and WP3.
    - Design, manufacture and transonic wind tunnel testing of a half wing equipped with a continuous active camber device based on compliant mechanisms designed in WP2 and WP3.
    - Flight test on the IST RPV for aircraft with planform change.
    - Quantification on each morphing concept in the flight performance of the aircraft.
    - Airworthiness of joined wing concept with flight tests.
- **WP6- Benefit Evaluation in Terms of Impact on Lift, Drag, Weight and Aeroelastic Response (Leader: EMB)**
    - Benefits assessment for the different adaptive/active concepts studied.
    - To evaluate potential weight saving (including aspects related to concept installation and systems) for the different adaptive/active concepts studied.
    - Analysis for the reference test case of weight saving related to the active camber concept.
    - To evaluate aeroservoelastic response (flutter margins, loads alleviation, aerodynamic stability derivatives, and structural vibrations) for the different adaptive/morphing concepts studied.
    - Trade-off between drag reduction, aeroelastic stability and loads alleviation.
    - Aeroelastic analysis of reference case implementing the morphing concepts.

- The trade-off between the effect on drag reduction, aeroelastic stability and external noise will be evaluated.
- Benefits assessment for different adaptive/morphing concepts studied when applied to Reference Aircraft.

Main S&T Results/foregrounds (WP Summaries)

WP1 - Project Management, Dissemination and Exploitation

All the deliverables were uploaded to the EU platform. The documentation regarding the management (Project Manual (IST), Dissemination Plan (UBRIS), Technology Implementation Plan (EMB), Internet Page (IST) Progress Reports (IST), Consortium and Grant Agreements) within the partners is available to them through the website at www.novemor.eu. The periodic meetings between the partners have also been performed. In the kick-off, 6th month, 12th month, 18th month, 24th moth and final meetings the partners have presented their work and discussed the action items to the following period of the project. All presentations and meeting minutes are available to the partners in the website. Besides the periodic meeting also web conferences took place whenever deemed necessary.

Regarding the dissemination of the project results so far several proceedings have been and will be presented in conferences. A NOVEMOR special session was held place in Aachen, Germany, at the 4th EASN Association International Workshop on Flight Physics & Aircraft Design.

WP2 – Design of Morphing Concepts and Mechanisms

Introduction

Central to the NOVEMOR project is the investigation into the benefits and relevance of morphing technology in aircraft. The underlying premise behind morphing is that the aircraft can adapt its shape to best suit the prevailing conditions, thereby operating at a higher efficiency over the full range of flight conditions in its mission profile. In what is a multidisciplinary and highly cross-coupled field, the way in which the aircraft structure enables and delivers morphing is also critical, and assessment can only be made with from an integrated systems point of view. Thus the design of the morphing structural subsystem and its constituent mechanisms are critical and it is important to develop appropriate tools for the design of this new class of structure.

Work Package (WP) 2 involved significant efforts by the four work package partners (DLR, POLIMI, UBRIS and IST) in devising morphing concepts and mechanisms, and developing the software tools used for their designs. Budgeted for 36 person months, this work package was divided into four areas (deliverables):

- Morphing wingtips (D2.1);
- Morphing camber (D2.2);
- Variable planform and sweep (D2.3);
- Implementation issues (D2.4);

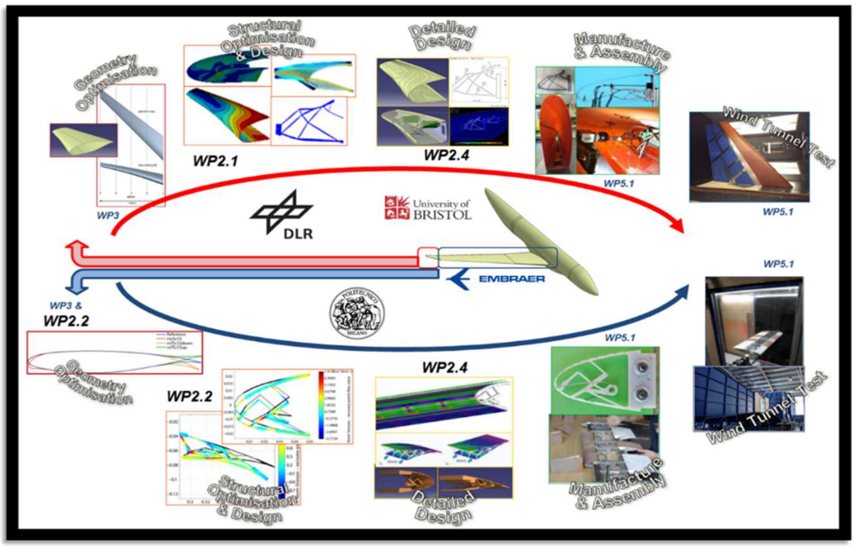


Figure 3. Workflow schematic comparing the design of the morphing wingtip and the wing with morphing camber in WP2.

The first three subsections involved conceptual development, with morphing wingtips (D2.1) and morphing wing camber (D2.2) applied to the reference aircraft by Embraer (defined in WP3), and variable planform and sweep (D2.3) applied to a remotely piloted vehicle (RPV). D2.4 was dedicated to conducting detailed design and analysis for the ensuing wind tunnel and flight tests of WP5.

WP2 played a critical role in the NOVEMOR project as it was a prerequisite for the experimental work in WP5, with the success and effectiveness of the wind tunnel and flight tests made possible by the careful design and planning in this work package. Furthermore, the assessments of morphing conducted in WP6 required the detailed design information completed in this work package, as well as the projection of the usefulness of the design tools into the future as TRLs evolve. Overall, the work in this work package was successfully completed, with the four deliverables met and the four milestones achieved. Key developments were made to the software design tools and substantial knowledge into the design, analysis, performance and manufacture considerations of morphing structures and mechanisms was generated in this work package.

Morphing Wingtips and Morphing Camber

The reference wing of the Embraer regional jetliner was divided into the wing and wingtip regions; the design of a droop-nose morphing wingtip was conducted by DLR and supported by UBRIS in the experimental stage, whilst the design of morphing leading and trailing edge devices in the wing was performed by POLIMI. In this manner, various design tools and methodologies could be explored and assessed simultaneously, thereby increasing the knowledge pool. It should be noted that both approaches (i.e. DLR droop nose morphing wingtip and POLIMI variable camber wing) featured smoothly varying and continuous morphing, being more than just shape change in general. This type of morphing has added benefits to the general morphing benefits aforementioned, such as flow laminarisation and reduced airframe noise. Smoothly morphing implies the design of flexible or compliant devices, and as such, both approaches feature compliant mechanisms in the structural design. The schematic of the parallel effort between these two approaches in Fig. 3 shows similarities between the two approaches in terms of the overall workflow. However, the tools developed and used, manufacturing methods and testing aims are largely different, and this parallel effort forms the scope for further collaborative work.

DLR - Droop-Nose Adaptive Morphing Wingtip (AMWT)

The DLR contribution to WP2 included the structural optimization, design and analysis of the droop-nose adaptive morphing wingtip, leading up to the manufacture and wind tunnel test of a full scale model at the UBRIS (WP5). The AMWT featured a target droop deflection of 2° as specified by Embraer. Anticipated benefits included drag reduction and aeroelastic benefits, such as the mitigation of the loss of aileron efficiency with increasing dynamic pressure. The geometry was highly 3D with 32° sweep, 9° average dihedral, double curvature and streamwise morphing targets and this made the design challenging. A seamless composite skin made from an optimized layup of HexPly 913® prepreg plies was used for the droop-nose device. This skin was driven and supported by compliant mechanisms at an integral stringer, and the compliant mechanisms were driven by electrical linear stepper motor actuators. The key new aspects of research contributed to the field include i) the 3D wing skin design, ii) the design of the compliant mechanisms which notably were fabricated from superelastic nickel-titanium alloy to handle extremely high strains (>2.5%); and iii) the development of the 3DSkinOpt software tool, and the continuum-based topology optimization method to handle multifunctional compliant mechanisms with shape control objectives.

Figure 4. DLR benchtop droop-nose demonstrator designed, built and used as an intermediary step for the final morphing wingtip wind tunnel model.

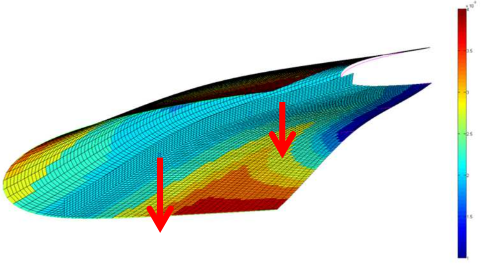


Figure 5. Final thickness distribution of the GFRP composite leading edge skin for the DLR morphing wingtip obtained from the 3DSkinOpt tool.

A sequential 2-step design chain was employed, whereby the skin was first designed via the 3DSkinOpt tool and then compliant mechanism was designed using continuum-based topology optimization. Fig. 4 depicts a benchtop demonstrator built to put the design chain into practice as an intermediary learning step for the final wind tunnel design. In this process, the results of the skin optimization formed the working boundary conditions for the compliant mechanism. The 3DSkinOpt tool optimizes the thickness distribution around the leading edge structure such that the deformations due to the actuator and external forces match as closely as possible to the pre-specified target shapes, thus creating a structure with tailored stiffness. This tool follows the concept of that of the previous EU project SADE, however for NOVEMOR it was entirely redeveloped for 3D designs. The variation in thickness is achieved by appropriate stacking of prepreg plies with optimized geometries. The optimization basis is the Nelder-Mead Simplex method. The software tool is automated and iterative and involves multiple FEA calls for different flight load cases and droop configurations, thereby accounting for stiffness and flexibility functions in the design. The resultant 3D layup is shown in Fig. 5.

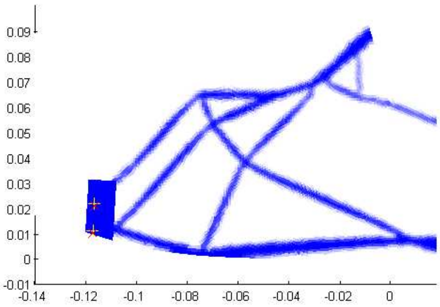


Figure 6. Final topology optimization result of the morphing wingtip compliant mechanism.

The compliant mechanism design was conducted using continuum gradient-based topology optimization, with the SIMP material model and the method of moving asymptotes as the mathematical optimizer. This topology optimization method essentially allows the user to start from a “blank canvas” and obtain the layout of the material in the structure which best achieves the objective. A shape control formulation was used whereby the displacements at the stringer (i.e. where the compliant mechanisms are attached to the skin) are used as targets and the output displacements of the compliant mechanism are required to move to these points. A stiffness objective function is also included to ensure the compliant mechanism is stiff enough to transfer the actuation force onto the skin and also to resist external forces. The resulting topology in the droop configuration is shown in Fig. 6.

POLIMI - Morphing Camber Devices

The conceptual design of morphing leading and trailing edge devices for the Embraer reference aircraft was performed by POLIMI in WP2. It was envisaged that these devices can alter the camber of the wing across the span thereby tailoring the aerodynamic load distribution, thus resulting in higher overall efficiency across the aircraft's mission. The contribution of POLIMI to WP2 mainly centred upon the development of tools for the design of morphing structures based on compliant mechanisms. The work in WP2 built up from past experience in other EU projects with continued tool development and the application to leading and trailing edge morphing devices of the Embraer reference aircraft as conceptual design. In addition, the morphing tools were applied to the design of a small scale model for the wind tunnel tests in WP5. An overview of the approach is presented below.

The general approach is based on geometry parameterization via the Class/Shape function Transformation (CST) method by Kulfan coupled to a two-level multiphysics optimization procedure. This two-level optimization approach dedicated to morphing aircraft design, uses the tools PHORMA (Parametrical sHapes for aerOdinamic and stRuctural Modelling of Aircrafts) and SPHERA (Synthesis of comPliant mecHanisms for EngineeRing Applications) in each level respectively. In the first level via PHORMA, the best deformed aerofoil shape is determined as the most efficient aerodynamic shape while concurrently limits the requested energy to deform the aerofoil skin. In the second optimization level via SPHERA, the best internal structural configuration is obtained using a load path representation topology optimization tool based on genetic algorithms that synthesizes a compliant structure able to adapt itself for matching the optimal shape coming out from the first level. At the core of PHORMA is the ability to parameterize geometries via the CST method (extended to morphing aerofoil design by POLIMI) and due to its analytical basis, it allows for the fast computation of the derivatives of various geometrical features, such as length and curvature of the upper and lower aerofoil surfaces, aerofoil area, surface slope etc. This efficient computation of sensitivities makes it highly suitable for use in shape optimization. Such geometrical features are strictly related to the structural properties of the morphing skins, with changes in length and curvature correlating to axial and bending stresses in the skin. The availability of length and curvature variations of the aerofoil's upper and lower surfaces can then be used as explicit constraint functions in the shape optimization procedure.

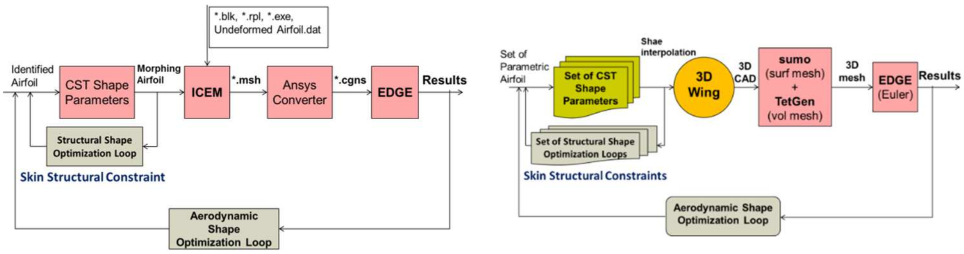


Figure 7. 2D (left) and 3D (right) aero-structural shape optimization framework for morphing camber devices.

The framework shown in Fig. 7 includes features for the generation of CAD, CFD, FEM and load paths models and contains techniques for the coupling between the different models. The parametric shapes can be combined and directly used to produce corresponding mesh, to perform structural and fluid analyses and to provide a fast interface to commercial software. The most important parts have been implemented as objects and classes interacting each other by means of the Object—Oriented Programming (OOP). The OOP concept allows for independent development of each component and an easy interface with any other application which can take advantage of its capabilities.

Variable Planform and Sweep

Various strategies have been devised for making changes to the wing planform area and the sweep angle. UBRIS initially perform several planform change to a small Joined Wing RPV model to enhance flight performance. IST developed a bend-twist morphing concept and a telescopic wing concept. UBRIS was involved in the development of a zero Poisson's ratio (0-v) honeycomb structure, a chiral morphing concept, and a variable stiffness rotating spars concept.

UBRIS - Gross Morphing Geometry Changes for Joined Wing Aircraft

An investigation into the use of global morphing to alter the shape of a baseline 5m span Joined Wing UAV (see Fig. 8) was performed. Four different global morphing strategies were considered over a typical flight mission that all involved gross deformation of the Joined Wing configuration planform: Outboard Sweep, Dihedral Changes, Telescopic Rear Wing and Morphing Vertical Tail, as seen in Figure 9.

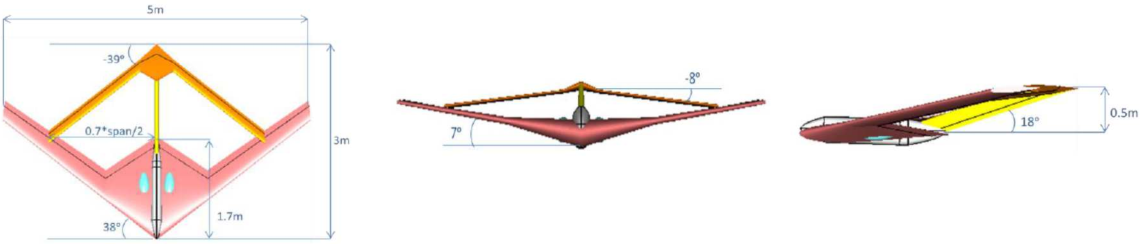
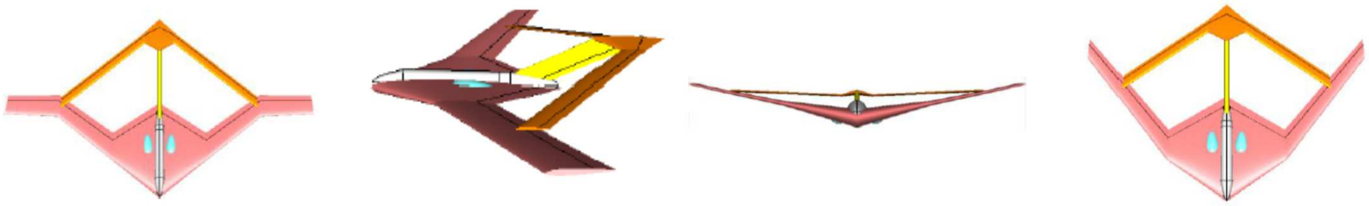


Figure 8. Baseline Joined Wing Aircraft.



a - Outboard Wing Sweep b - Morphing Vertical Tail c - Dihedral Increase in Front Wing d - Telescopic Rear Wing

Figure 9. Morphing Concepts Considered.

The effect of the morphing approaches was considered on the performance, stability and control, and aeroelastic behaviour of the UAV. It was found that a Morphing Vertical Tail solution, accompanied by changes in the main and rear wing sweep angles, gave the biggest overall performance improvement. Sample results illustrated in the form of spider plots are shown in Fig. 10. Unfortunately, it was considered that this was far too complicated a morphing strategy to implement using currently available structural technologies.

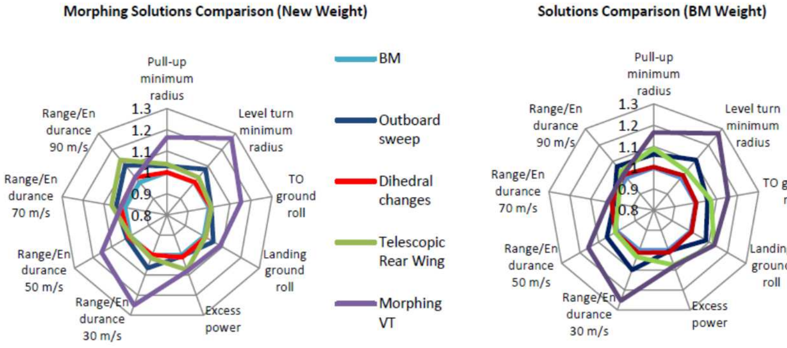


Figure 10. Spider Plots Showing Comparison between the Different Morphing Approaches.

IST-Assessment of a bend-twist morphing concept for the JW RPV configuration

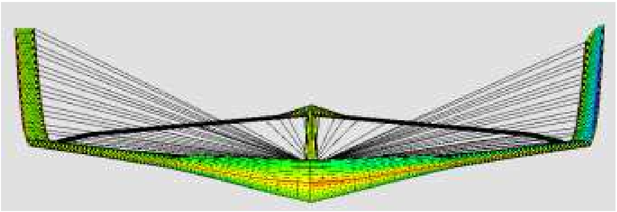


Figure 11. Bend-Twist morphing concept.

It is known that the Joined-Wing (JW) RPV (Remotely Piloted Vehicle) would benefit from lateral stability increase at low speeds, due to the absence of significant lifting vertical surface. As means to tackle this issue, a bend-twist morphing concept was analysed. This concept assumed the capability of bending and twisting the outboard part of the front wing of the JW RPV. The purpose of the study was to determine if the concept would improve control authority through roll moment coefficient and yaw moment coefficient maximization. While yaw moment coefficient was greatly improved in the configuration presented above, the roll authority is significantly reduced. This fact added to the difficulty of implementing such significant bending rendered the concept not useful.

IST-Telescopic Wing Development and Testing

IST efforts on Variable Planform Devices were dedicated also to the development and testing of a morphing wing with telescopic capability in a RPV. The telescopic concept adopted was fairly simple:

- Each half wing is composed of a fixed wing and a moving wing. This minimizes the number of moving parts and also the number of transitions between wings exposed to the flow, therefore minimizing drag penalties in these region;
- The moving wing slides in and out of the fixed wing;
- The moving wing is supported in the conformal spars of the fixed wing “wing-box“, the movement is achieved by overcoming friction;
- The chord of the moving wing is 80% of the fixed wing chord. This dimension is related to the thickness of the aerofoils of the fixed and moving wing;

- Actuation is based on pulleys, threaded belts and an actuator spar.
- Symmetric actuation for the two sides of the aircraft. Telescoping for roll control was discarded.

Studies on the merit of the concept application in small aircraft and the effect of scaling up were performed early in the project. The concept seemed very promising in terms of drag reduction for small scale aircraft, for which even with 20% increase in aircraft weight the benefits in drag reduction would compensate, with a telescopic capability of increasing the span in 70% and wing area in 56%.

The methodology for the assessment of the benefits was based in flight simulation with a 3 degrees of freedom model, dedicated only to the longitudinal movement analysis. This methodology was based on optimal control determination for a multi-objective function minimization which included trajectory and altitude tracking and consumption minimization and was the basis for the methodology adapted in the morphing concepts benefits assessment in WP4.

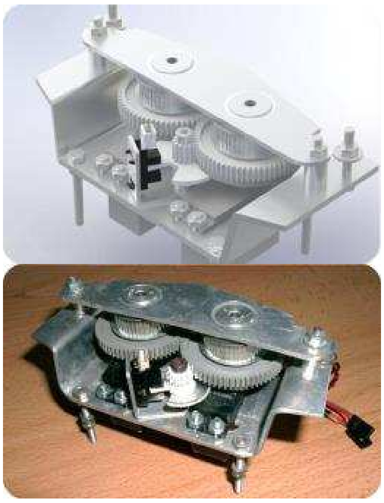


Figure 12. Actuation mechanism for the telescopic wing.

Since the half-span of the RPV equipped with the telescopic wing varies from 1m to 1.7m, it represents a case of morphing telescopic wing demanding severe requirements in terms of functionality of the concept, due to the high deformations involved, the transmission of forces from the moving wing to the fixed wing and also the possibility of instabilities occurring during flight due to the free play between the moving wing and the fixed wing, which increases as the wing extends.

Static loading structural tests were performed and actuation energy was measured with and without loading in ground. Actuation was shown to be possible with high levels of deformation and actuation energy was deemed very acceptable at this small scale.

Figure 13. Telescopic wing of the RPV aircraft during landing.

Flight tests were performed with this RPV as to prove the concept functionality during flight. Several successful span variations in levelled flight where tested. Although measurements were taken in flight, the absence of an autopilot prevented that suitable quasi static situations were obtained during the flights. Therefore it was not possible to quantify the benefits or penalties of the different configurations.

In a qualitative and sensitive assessment, it can be stated that manoeuvrability is significantly altered with span variation, as expected. The span and area increase reduce the landing speed very perceptibly, also as expected. Fig. 12 shows the actuation mechanism for the telescoping action and Fig. 13 shows camera screenshots of the RPV during landing.

For commercial aircraft, the benefits from this concept would be reduced due to two main factors: the variation of wing span and area would never be as significant as in a RPV; and the actuation energy becomes significant as the scale of the aircraft increases relative to the RPV dimensions. Nevertheless, some exploration of this concept applied to the reference aircraft without wingtip shown that aerodynamic benefits could be obtained for high CL operation (above 0.65), possibly during hold, for a wing extension of 3m on each side.

UBRIS - Honeycomb Trailing Edge Concept

Honeycomb core structures coupled to flexible face sheets have been proposed for morphing aircraft applications; however the cores have inhibited the envelope for morphing due to inherently high in-plane stiffness properties. The performance benefits associated with morphing would be lost due to the additional mass of morphing mechanisms and the batteries storing their energy requirements.

Adaption of the cellular structure of the honeycomb to give one plane high-strain/low-stiffness properties relative to the two other planes would be an avenue worth exploring for one-direction, one-dimensional, morphing applications. Beyond this, developing a core that has no Poisson ratio effects in morphing (i.e. a zero Poisson's ratio structure) would not only remove the additional load

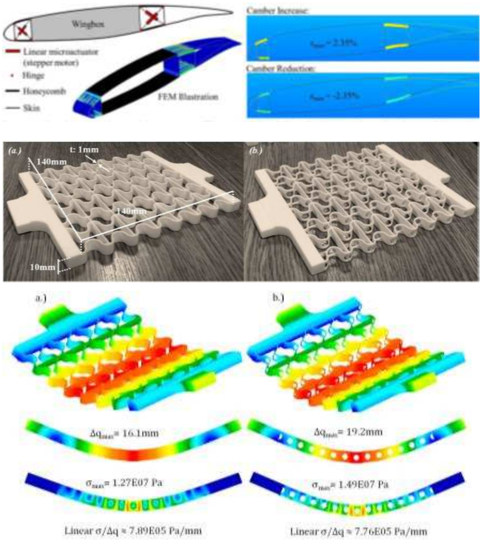


Figure 14. 0-*v* honeycomb concept for camber and chord morphing.

requirements associated with non-morphing direction secondary displacements but would make the use of a one-directional morphing honeycomb more practical in use.

The 0-v honeycomb structure with curved members is shown in Fig. 14. In morphing wing applications, the concept can be applied to the upper and lower skins. Camber can be varied if differential actuation across the honeycomb segments is input whilst chord extension is possible with uniform actuation input over the honeycomb segments. Detailed finite element analyses were conducted to determine the structural performance under transverse loading in elongated and stowed configurations.

UBRIS - Chiral Morphing Concept

The proposed design features a chiral structure (Fig. 15) mapped within the winglet's aerofoil based on a modified geometry layout of a periodic chiral structure where the circular nodes are replaced by regular hexagons for manufacturing reasons. The twist of the wingtip was designed to be controlled by rotating one of the chiral nodes in the structure.

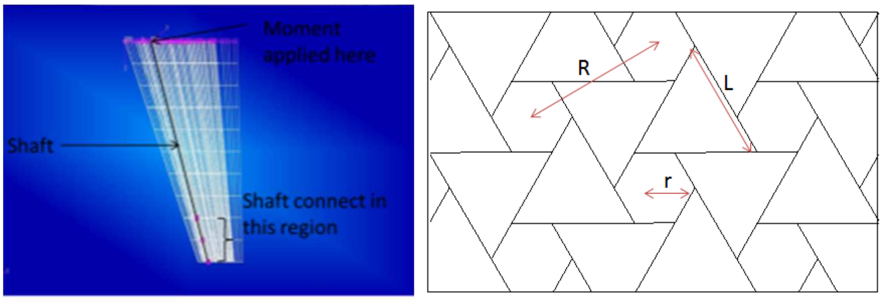


Figure 15. Chiral structure concept for twist morphing.

A Genetic Algorithm based optimizer was used to optimize the chiral structure to achieve the largest change in rolling moment for a given actuator sizing. The internal structure of the chiral tip was parameterized in terms of the chiral parameters r and R as well as the locations of the front and rear spars. The thickness of the chiral hexagonal elements, the ligaments and skin were set to the minimum printing thickness of 1mm.

UBRIS - Variable Stiffness Rotating Spars Concept

The final morphing concept tested at UBRIS consisted of the design and manufacture of an adaptive stiffness rotating spar based actuated wing tip in order to control wingtip twist and bending. This approach had not been attempted before on a swept aerodynamic surface or at such high dynamic pressures. The resulting deformations were then validated via comparison with NASTRAN based aeroelastic computations and comparison with the other morphing concepts.

Implementation Issues

The tools mentioned in the above three sections were applied for the design of morphing devices for the reference aircraft and for a RPV as mentioned. Detailed designs were obtained from those generated by the software tools following a number of post-processing steps and detailed CAD constructions and finite element analyses.

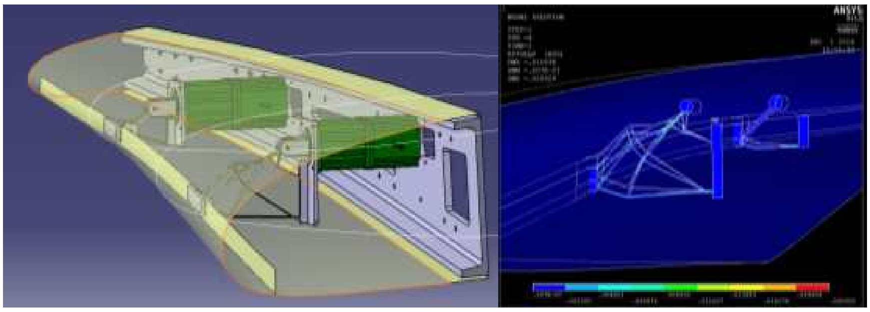


Figure 16. CAD final assembly (left) and detailed FEA simulation (right) of the droop-nose morphing wingtip.

Morphing Wingtip

Postprocessing was required to convert the skin and topology optimization results into manufacturable parts. For the skin design, a postprocessing software tool was also generated which inspected the final thickness distribution (based on the FEA mesh) and converted the edges of the different thickness regions into smooth contours. These were then exported into a CAD program to create the plybook, wherein the stacking sequence of the 32 layers (0°, ±45°, and 90° orientations) was preset (also used in the FEA calculations). The topology optimization results were also postprocessed by converting the geometries into a parametric CAD model which would subsequently be used for wire electric discharge machining (EDM). This allowed for precise fine tuning of the compliant mechanism features, in particular the thickness of the different members in the topology. The skin and compliant mechanism models were then combined into a high fidelity FEA model with shell elements. This model was then used for aeroelastic computations conducted by UBRIS. The results were promising and allowed for continuation into the wind tunnel testing stage. Fig. 16 shows the final CAD assembly of the leading edge and a snapshot of the detailed FEA results.

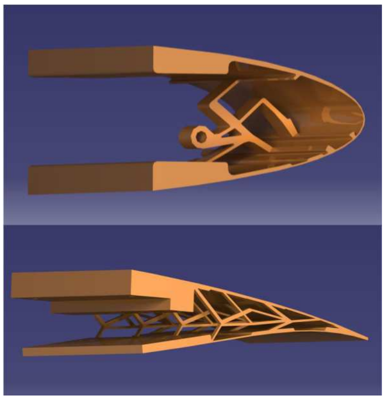


Figure 17. CAD models of the leading and trailing edge wing camber morphing devices for manufacture.

Morphing Camber

Postprocessing was required for the manufacture of the compliant devices and was performed with Stereolithography (SLA) and selective laser sintering (SLS) manufacturing techniques in mind. Fig. 17 shows the CAD models of the final leading and trailing edge devices. Detailed FEA was also conducted for the purpose of comparison with the wind tunnel test results, as shown in Fig. 18.

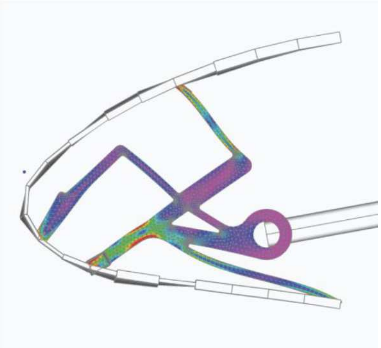


Figure 18. Detailed FEA of the final leading edge wing camber morphing device.

Variable Planform and Sweep

Telescopic Wing

The telescopic wing requires lubrication for actuation forces reduction. This could be an issue if implementation in a commercial aircraft was to be made due to the direct exposure of the lubricated surface of the moving wing to the flow. Its benefits are related to span and area increase. As the extension is performed at the tip, the moving wing interferes with the placement of ailerons, and these reduce significantly the chord of the moving wing, limiting the benefits. In the RPV, these issues where tackled by implementing spoilers in the lower surface of the fixed wing, thus reducing the aerodynamic efficiency and authority of the roll control surfaces. A possible solution could be implementing morphing camber for roll control.

When retracted, the moving wing is a structure occupying an important volume inside the wing that is usually used for other purposes, like structural support for aileron actuation systems.

The predictable higher actuation forces for a telescopic wing in a transport aircraft would further require more volume inside the wing for actuation and would possibly require structural reinforcement in the wing structure towards the tip, otherwise lighter.

UBRIS 0-v honeycomb, chiral structures and rotating spars concepts

A wind tunnel model wing featuring the 0-v honeycomb concept was constructed using additive layer manufacturing to create the wing using 6 controllable trailing edge segments as shown in Fig. 19. The scaling of the wing was based upon a 150% version of the outer wing section (beyond the join) of the baseline NOVEMOR joined wing UAV as shown in Fig. 19. Each trailing edge segment was actuated independently using micro-linear actuators, which enabled the angle of the trailing edge to be varied and also to change the local chord.

Chiral structures have been commonly made from plastics using rapid prototyping manufacturing methods and even machined from solid metal. The rapid prototyping approach has been chosen for the proposed demonstrator as shown in Fig. 16. One of the advantages of using the rapid prototyping is that the design and manufacture can be simplified by using the same material for the skin and the demonstrator can be printed as one piece. The model was made from polyamide printed using selective laser sintering. The material has a Young's modulus of 1650MPa and a tensile strength of 48MPa. The minimum wall thickness that can be printed is 1 mm.

A rotating spar wingtip was designed via structural optimization resulting in the wing design shown in Fig. 19. The outside skin of the wing was covered in solarfilm in order to provide an aerodynamic surface. The spars were controlled via two geared stepper motors, being able to rotate the spars through 90 degrees in approximately 0.5 second.

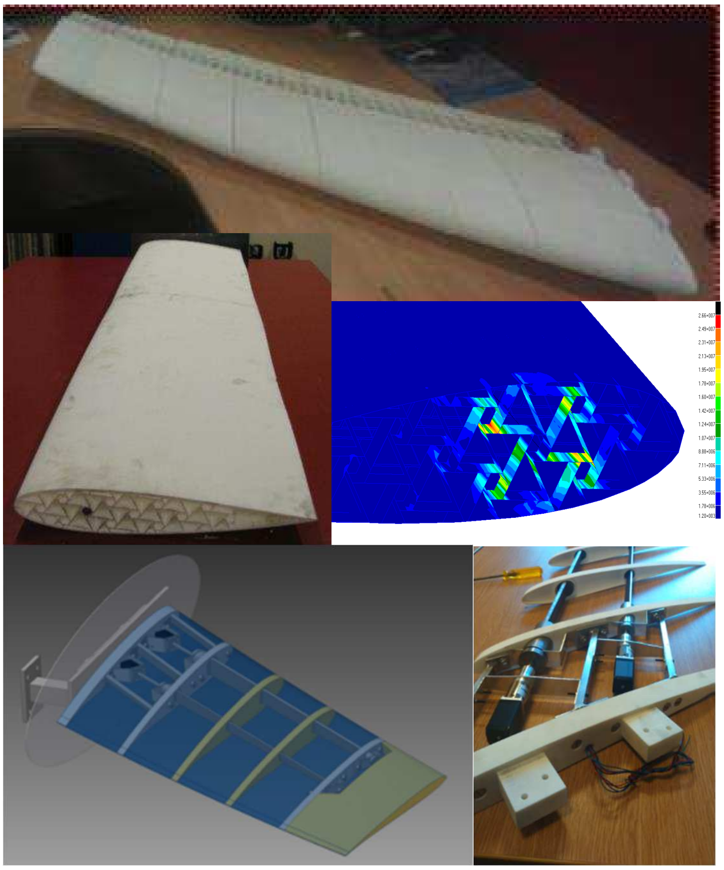


Figure 19. Implementation of the 0-v honeycomb, chiral morphing structure and rotating spars concepts.

Concluding Remarks

Morphing Wingtip

Significant developments were made to the design tools for droop-nose morphing devices. A skin optimization tool was redeveloped for 3D considerations and the continuum-based topology optimization method was developed to handle shape-control problems with the consideration of stiffness and flexibility functions. The tools mentioned were developed keeping in mind manufacturing issues. The results of the tools in the AMWT design were promising and showed that the targets specified by Embraer could be attained within acceptable tolerance. As such, the results were postprocessed for the manufacturing and testing stages. Further developments can be made to the tools to improve the design of these types of morphing structures in future work.

Morphing Leading Edge and Trailing Edge Devices

The multiphysics aero-structural framework developed by POLIMI featuring the routines PHORMA and SPHERA has proven to be a highly useful tool for the design of morphing structures. Designs resulting from the optimization routines were manufacturable and a scaled wind tunnel model was fabricated from an SLA 3D printing method. Future work involves the consideration of aircraft certifiable materials and for full scale design

Telescopic Wing

It was not possible to prove experimentally the telescopic wing concept benefits for the RPV. The concept feasibility and functionality on the other hand do not present any significant challenge for a non-optimized implementation. Lower limits on wing weight increase after implementation were not quantified.

Regarding concept implementation in transport aircraft, the relatively low extent of the wing geometry change possible, not enough for significant aerodynamic benefits, does not seem to compensate the increase in complexity required for such changes.

UBRIS Morphing Concepts

The 0-v honeycomb, chiral structures and variable stiffness rotating spars concepts illustrate how changes in chord length, camber, twist and stiffness can be achieved. Results from numerical and experimental work match closely and the proof-of-concept has been demonstrated. Whilst currently at low TRLs, continued development and down selecting of the most useful techniques/concepts will see the TRLs rise and generate significant research contributions as part of the process.

WP3- Novel Configuration, Simulation and Analysis

Introduction

The development of tools capable of analysing morphing concepts and novel configurations was on the basis of WP3, as well as the definition of a reference aircraft to be used as a benchmark in order to evaluate the potential benefits that morphing devices and an innovation joined-wing configuration can bring in terms of global performances.

Work Package (WP) 3 involved significant efforts by the four work package partners (KTH, IST, POLIMI, EMB and UBRIS) in: developing computational frameworks enabled in the capabilities of analysing both morphing concepts and novel configurations; defining a reference aircraft model to be used as baseline to apply the morphing concepts studied in WP2. Budgeted for 54 person months, this work package was divided into five areas:

- Reference Aircraft Model (D3.1a); and collection of morphing strategies for reference aircraft (D3.1a);
- Computational design framework for a fully parametric virtual aircraft with morphing surfaces (D3.2);
- Multidisciplinary design and analysis optimization framework (D3.3);
- Conceptual design framework for aeroelastic modeling and optimization of morphing aircraft (D3.4).

The developed simulation approaches and models in WP3 have been used in the following WPs 4 and 5 for the development of different adaptive/morphing concepts. A simulation model of a complete aircraft has been supplied by UBRIS and POLIMI to all partners. The concepts investigated in WPs 3 to 6 have been scaled up and implemented numerically on the reference aircraft, based on the models developed in WP2. Comparative simulations have been performed in WP6, to assess the potential of the concepts on performance, noise, aeroelastic stability, for an efficient short/medium range transport aircraft.

Reference Model Definition

EMBRAER worked on the definition and development of the Reference Aircraft Model, concluding it with a report on the model assessment of different disciplines (D3.1). The definition of the reference model was developed using proprietary tools from EMBRAER since the required tasks demanded the adoption of higher fidelity than is available within CEASIOM software, the analysis tool available to the consortium. The reference model is shown in Figure 20 and the design specifications are presented in Table 1.

The Reference Aircraft Model report included:

1. Weight and balance calculations including details of the various loading sequences;

2. Aerodynamics results details in the wing design. Discussion about issues around the separated flow regions, the wingtip design, etc. An interesting set of results showed the improvement that can be obtained in Mach-related drag rise for the different wingtip designs.
3. Flight envelope analysis including details on the design speeds, load diagram, etc;
4. Flying qualities: 6 DOF analysis using an aerodynamic database was performed. At this stage only static flying qualities were considered. Static margin was determined for various conditions, horizontal tail deflection estimation, steady heading sideslip and some static lateral flying qualities.
5. Performance analysis was done by evaluating take-off, landing, climb and cruise flight phases performances. Several trade-off studies were conducted for each phase such as altitude and payload variations.
6. Propulsion: An engine deck and in-house propulsion code was used to generate engine performance tables required to predict aircraft performance under different conditions. These included take-off, climb, payload vs performance, block fuel block time, etc.
7. Morphing: Additional work on analysing the wingtip and trailing edge morphing concepts. Several studies to assess performance of wingtip and trailing edge morphing concepts were done and compared with the reference model results. The wingtip cant, sweep and twist angles and leading edge were considered in the analyses. Wingtip angles were optimized for a typical mission profile of a regional jet.
8. CEASIOM: The reference model was implemented in CEASIOM framework and the obtained results were evaluated with those obtained by EMBRAER tools.

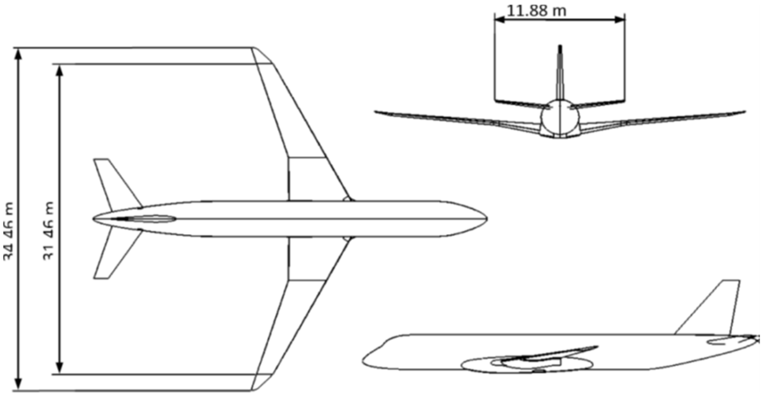
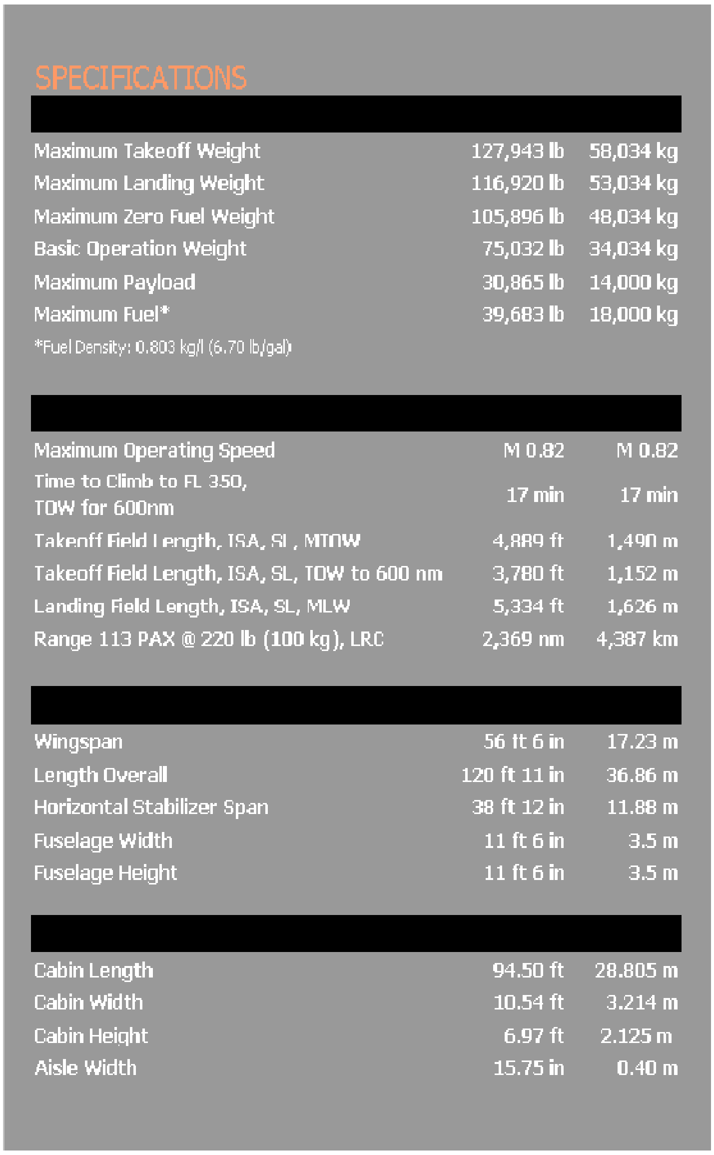


Figure 20. The Reference Model (with a wingtip).

Table 1. EMB9MOR characteristic chart.



SPECIFICATIONS

Maximum Takeoff Weight	127,943 lb	58,034 kg
Maximum Landing Weight	116,920 lb	53,034 kg
Maximum Zero Fuel Weight	105,896 lb	48,034 kg
Basic Operation Weight	75,032 lb	34,034 kg
Maximum Payload	30,865 lb	14,000 kg
Maximum Fuel*	39,683 lb	18,000 kg
*Fuel Density: 0.803 kg/l (6.70 lb/gal)		
Maximum Operating Speed	M 0.82	M 0.82
Time to Climb to FL 350, TOW for 600nm	17 min	17 min
Takeoff Field Length, ISA, SL, MTOW	4,889 ft	1,490 m
Takeoff Field Length, ISA, SL, TOW to 600 nm	3,780 ft	1,152 m
Landing Field Length, ISA, SL, MLW	5,334 ft	1,626 m
Range 113 PAX @ 220 lb (100 kg), LRC	2,369 nm	4,387 km
Wingspan	56 ft 6 in	17.23 m
Length Overall	120 ft 11 in	36.86 m
Horizontal Stabilizer Span	38 ft 12 in	11.88 m
Fuselage Width	11 ft 6 in	3.5 m
Fuselage Height	11 ft 6 in	3.5 m
Cabin Length	94.50 ft	28.805 m
Cabin Width	10.54 ft	3.214 m
Cabin Height	6.97 ft	2.125 m
Aisle Width	15.75 in	0.40 m

Computational Frameworks

KTH, POLIMI – CEASIOM and NeoCASS

The CEASIOM (Computerized Environment for Aircraft Synthesis and Integrated Optimisation Methods) is a framework developed in the scope of the EU FP6 Project SimSAC (Simulating Aircraft Stability And Control Characteristics for Use in Conceptual Design) for conceptual aircraft design that integrates discipline-specific tools like: CAD & mesh generation, CFD, stability and control analysis; all for the purpose of early preliminary design. The CEASIOM framework offers possible ways to increase the concurrency and agility of the classical conceptual-preliminary process. NeoCASS is a module of CEASIOM developed by POLIMI responsible for structural and aeroelastic analysis of the designed configurations.

KTH - CPACs framework for Multidisciplinary Design

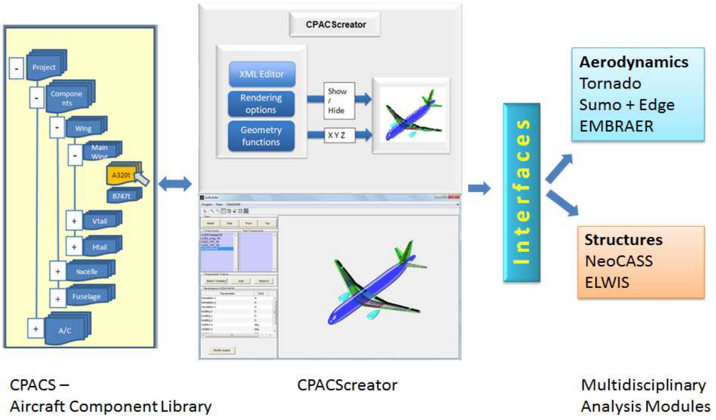


Figure 21. The toolchain/framework is built with object-oriented modeling so that via interfaces the heterogeneous modules can be linked in the framework.

KTH has worked on extending the computational design framework CEASIOM to define a fully parametric virtual aircraft with morphing lifting surfaces including wingtip parameterization for Computational Fluid Dynamics (CFD) and Computational Structural Modelling (CSM). The parameterization tool is CPACS from DLR, which is available for CFD and CSM analysis. KTH developed a CPACScreator to enhance CEASIOM as a CPACS model visual editor and generator. In Fig. 21, it is shown possible interfaces for multidisciplinary optimization using the CPACScreator. This software and the corresponding report (D.3.2) were delivered to the project consortium. The computational design framework CEASIOM was enhanced within the NOVEMOR project with:

- parameterized geometrical representations for morphing aircraft, suitable for conceptual design and mesh generation for CFD and CSM;
- techniques for automatic generation of meshes for structural and aerodynamic models;
- optimization procedures for the design of compliant mechanisms;
- aero-elastic analysis tools adapted for morphing configurations;
- flight-dynamic stability analysis of flexible and morphing configurations.

POLIMI - Develop Lo/Hi Fidelity Aero-Structural Models for Morphing Surfaces

The POLIMI's contribution to WP3 activity has been mainly focused on the development of design tools suitable for the multi fidelity analysis of morphing devices to be applied to the Reference Aircraft. The morphing concept taken into consideration is the so called Active Camber obtained by the continuous deflection of Leading and Trailing edge conformable control surfaces. Aiming at this top level target, POLIMI further develop the in-house procedure based on a two level optimization approach and implemented in two different modules, called PHORMA and SPHERA. The first one is used to define the best aerodynamic shape able to guarantee an optimal performance of the morphing devices taking into account from the beginning the constraints due to the counteractive role of the skin. The second one, using the optimal aeroshape as a target input, design the optimal compliant internal structure able to match the desired external shape when actuated. The development and application of PHORMA has been mainly carried out in WP3 and is summarized in the following.

The Parametric Framework PHORMA

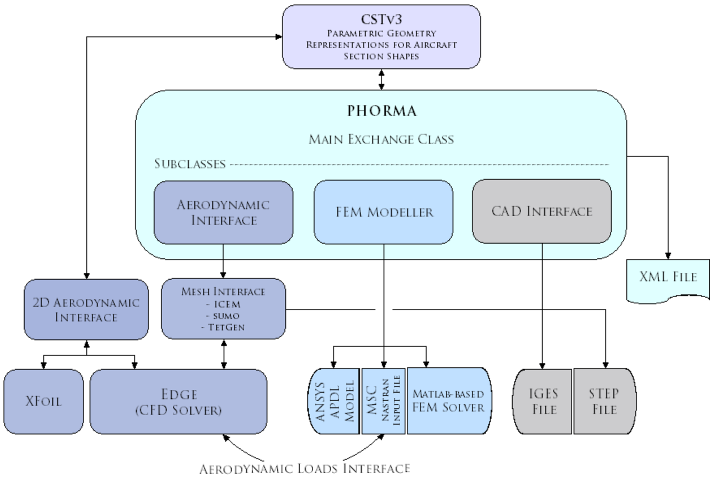


Figure 22. The framework PHORMA.

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.

One of the problem in analysing 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 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 aerofoils, a 2D morphing shape optimization able to introduce the shape changes under all the design requirements and a 3D propagation to the full wing.

2D and 3D CFD modelling

Aerodynamic loads can be computed by a specific code embedded into the CST tool able to automatically produce a 2D structured mesh around the aerofoils and to perform Navier-Stokes computations. The automatic generation of the structured mesh around the parameterized aerofoil 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 aerofoil shape used to produce the load path model.

While the optimal morphing mechanisms is computed at first on the 2D aerofoil, 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.

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 quadrilateral element, the code includes Finite Volume Beam element.

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 aerofoil skins. For this purpose, a tool based on the Radial Basis Function (RBF) 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 aerofoils and using it as aeroelastic interface, aerodynamic loads are distributed along the beam nodes and reduced to lumped forces.

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 aerofoil skins, in the second one an aerodynamic optimization is performed starting from physically realizable aerofoils. In the 2D shape optimization, the process is applied to each aerofoil shape extracted from the reference CAD model. After the structural shape optimization, PHORMA automatically produce the mesh of both clean and morphing aerofoils, in order to perform as many 2D high–fidelity aerodynamic shape optimizations as the number of identified sections are. Combining the different optimal aerofoil shapes coming out from the 2D shape optimizations represented in Fig. 23, 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 aerofoils previously subjected to the skin constraints via a number of structural shape optimizations equal to the number of identified sections. The

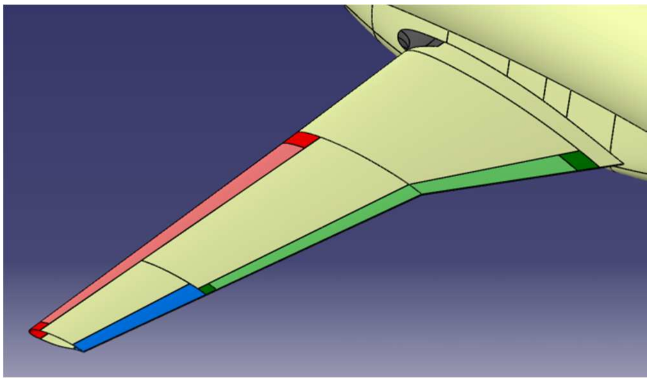


Figure 23. The different LE and TE morphing configurations investigated.

aerodynamic shape optimization directly produce the final 3D morphing model. Figure 23 shows the configuration of LE and TE morphing control surfaces investigated and applied to the Reference Aircraft.

IST - Model multidisciplinary design optimization of morphing mechanisms

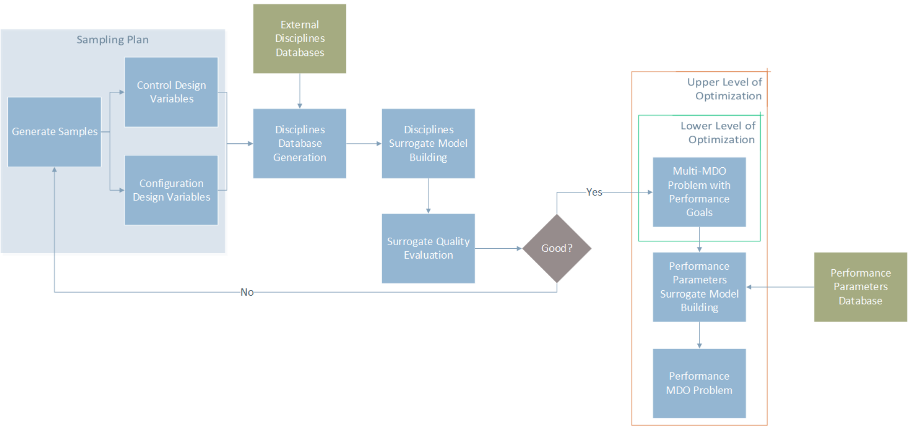


Figure 24. MDO architecture.

IST developed a performance based Multidisciplinary Design Optimization (MDO) framework in the scope of WP3 for preliminary aircraft design, which has the capabilities of analysing the two main objectives of NOVEMOR project: morphing solutions and novel configurations. The MDO framework includes the main aircraft disciplines in an optimization environment. Several modules were either built or adapted from existing in-house codes for this tool: Geometry; Aerodynamic; Structures; Propulsion; Fluid-Structure Interaction; Payload and Fuel Distribution; Performance; and Optimization. This MDO framework was defined since the early development stages to be the most versatile and modular possible, allowing for the introduction of different software (since they are accessible by either command line or dll. file).

A two-level MDO architecture (see Fig. 24) was specially designed to incorporate the two devised goals of NOVEMOR project (morphing solutions and novel configurations). In the first (lower) level, multi MDO problems can be defined, one for each performance goal. At this level, the available controls in the aircraft can be set as design variables to be determined such that they minimize or maximize a given performance target. A mission design tool is available at this level of optimization, where a mission profile can be followed. This option was used to performance the weight and energy balance in the WP4 (D4.2) since it enables the user with the capability of defining the morphing strategy for a given aircraft configuration and for the entire flight operation. The second (upper) level consists in optimizing the aircraft configuration for a weighted objective function (which can be customized by the user and may include different performance goals) while at the same respecting the imposed requirements (also can be defined by the user and different performance targets can be used).

The MDO architecture was planned to allow the employment of surrogate model instead of real analysis models to reduce the computation effort required to conduct a performance based MDO of an aircraft. Databases are required to generate the surrogate models, which on one hand represent a considerable increase on the computation time and on the other hand allows the employment of already available databases. High fidelity data and experimental data can be included in these databases in order to improve the quality of the optimization results.

Computational Studies

EMB – Morphing Wingtip

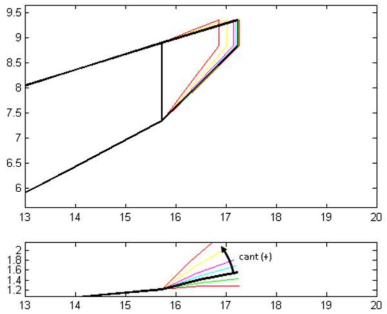


Figure 25. Cant Definition.

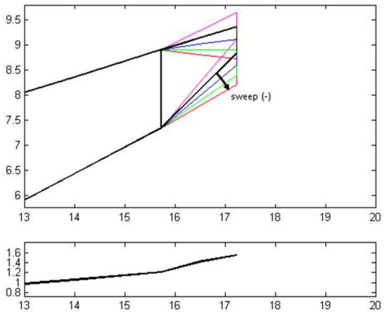


Figure 26. Sweep Definition.

A morphing study is performed over the aircraft configuration with the wingtip. In order to accomplish such task, different deflections for the cant angle and the toe angle were analysed. For each of the considered evaluated proposals an aerodynamic databank was created. The information about the aerodynamic database is necessary in order to evaluate the block fuel consumption for a mission of 600 nautical miles. In the present moment of the study, the additional weight caused by morphing actuators or mechanisms responsible to change the wingtip configuration, are not being taken into account. Performance data was calculated considering the same weights of the reference model.

It was considered deflections on the cant from -10 to 30 degrees and on the toe angle from -15 to 5 degrees. The angles are relative to the wingtip, which is taken as the reference geometry and the variations are shown in Fig. 25 and Fig. 26. From this study a maximum benefit of 35kg in fuel block was reached (see Fig. 27). A benefit of the adoption of morphing devices can be attributed to an extension of the payload x range chart. Considering a certain mission that carries the maximum allowable payload, the capability to reduce the fuel consumption can increase the mission range.

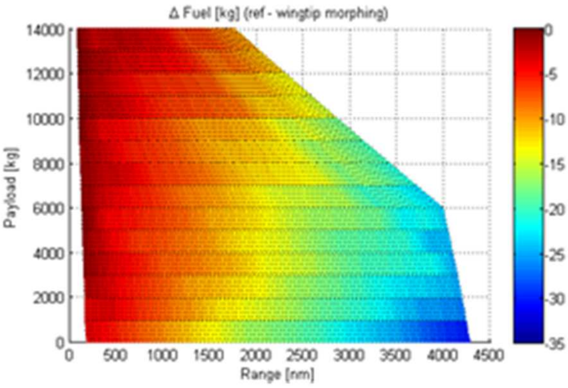


Figure 27. Fuel reduction with wingtip morphing.

EMB – Morphing Trailing Edge

In this section, it is shown some initial results obtained with the morphing concept for the trailing edge devices, mTE. It was considered two different approaches: (1) deflection angles; (2) elastic analysis.

For the first approach, in order to perform small deflections of the morphing trailing edge, few profiles were deflected in their rear portion. It was decided to modify those profiles that were located in the wing spanwise region that ranges from y=4.0 [m] up to y=10.0 [m]. A small region situated before and after the above mentioned y coordinates were considered as transition regions. Figure 28 illustrates the transition region along the wing span.

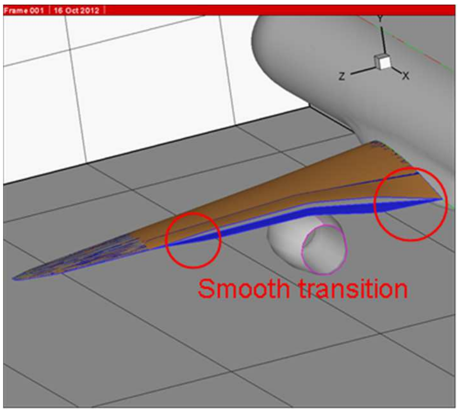


Figure 28. Trailing edge morphing transition.

The numerical simulations were performed for a wide range of CL and Mach similarly to the conditions evaluated for the morphing wingtip. In the present case the profile deflections were able to deflect from -12° up to +12°. Fig. 29 and Fig. 30 show the optimum trailing edge deflection and the respective reduction on drag. The morphing of the trailing edge, mTE, provided a gain of 3.7 drag counts which implies in a certain amount of fuel reduction for some flight conditions as shown in Fig. 31.

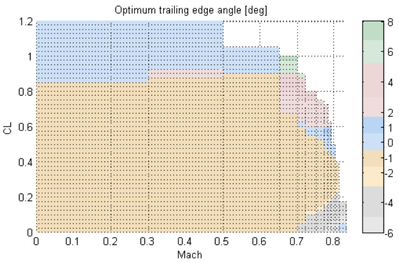


Figure 29. Optimum trailing edge deflection.

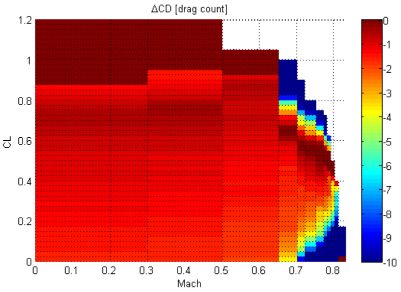


Figure 30. Drag reduction due to the morphing of the trailing edge.

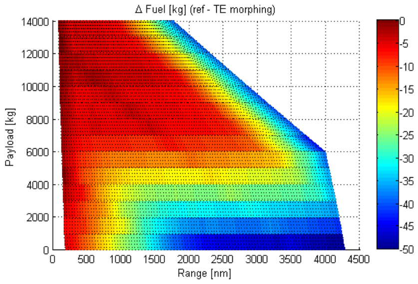


Figure 31. Fuel reduction considering the trailing edge morphing.

The combination of the morphing devices for the trailing edge and the wingtip can provide a reduction of 8.6 drag counts. In Fig. 32 it is possible to observe the effect of both morphing devices for the entire payload versus range diagram.

The initial created database considered the aircraft wing as rigid aerodynamic component. In the second approach, the wing was considered as a flexible component. Fig. 33 shows the deflection and torsion of the wing due to the flexibility.

Analyses were performed for a vast range of Mach number and CL coefficient considering both a rigid and flexible wing. Fig. 34 shows a summary of the difference between both approaches. It can be observed that the wing loses performance when the elastic effect is considered. This is a consequence of not designing the wing as a flexible component. In some situations it is possible to achieve up to 10 drag counts. On the other hand, it is possible to see an opportunity to use the trailing edge morphing devices to recover part of this loss.

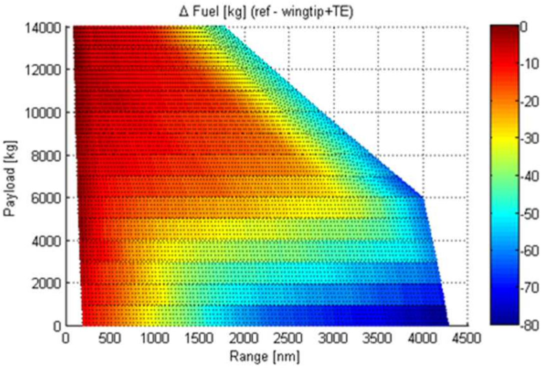


Figure 32. Fuel reduction considering the wingtip and trailing edge morphing.

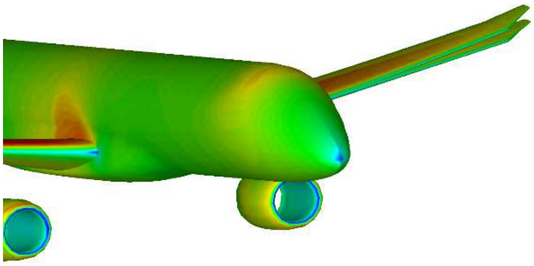


Figure 33. Wing deflection and torsion due to the elastic effects.

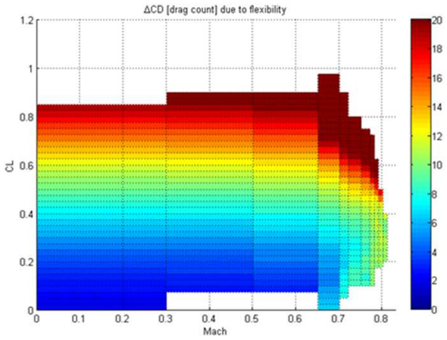


Figure 34. Effect of flexibility on the drag coefficient. (Baseline flexible - Baseline rigid).

IST – Morphing Wingtip

The performance based MDO framework developed by IST was applied to assess the benefits of introducing morphing devices on conventional (Reference Aircraft) and unconventional aircraft (Joined-Wing RPV) configurations. The first problems consists in evaluating the benefits (in terms of fuel consumption) of introducing a morphing wingtip in the reference model defined by EMBRAER in WP3 (D3.1). The wingtip parameters (span, wingtip chord, cant, toe and sweep in Fig. 35) were first optimized such that they maximizes the range and then the angles of toe, cant and sweep were optimized for fuel consumption minimization for climb and hold conditions. No significant benefits were achieved by enabling the wingtip with morphing capabilities since less than 1% reduction in fuel consumption was obtained (for both climb and hold). This benefit is deemed insignificant and most probably, the inclusion of the added weight due to the morphing actuation mechanism (only the wingtip structure with the spar and caps were considered for the calculations) may lead to a smaller gain or even a decrease in efficiency. In the second problem, a morphing wingtip concept was purposed to improve the poor lateral-directional stability of the small JW PRV and the results were discussed in the previous WP summary (WP2).

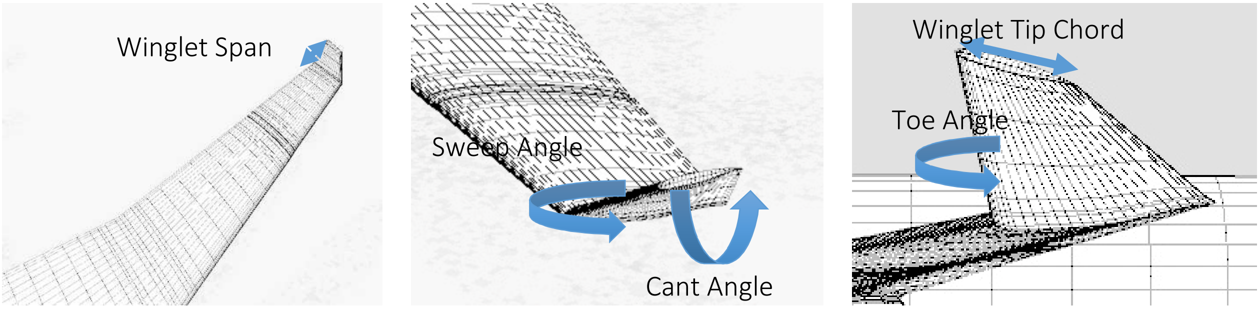


Figure 35. Wingtip morphing concept.

KTH - Winglet Design of Regional Jet Aircraft

The original reference wing has a winglet with cant angle 12 degrees, or, the folded angle 7 degrees since the wing has a 5 degrees dihedral. It shows that for cruise condition the reference wing (7 degrees folded angle) has the minimum inviscid drag (Fig. 36). The enhancements performed by KTH to the CEASIOM software were tested on the reference model and a morphing winglet was optimized for cruise condition achieving an 8% reduction on the inviscid drag.

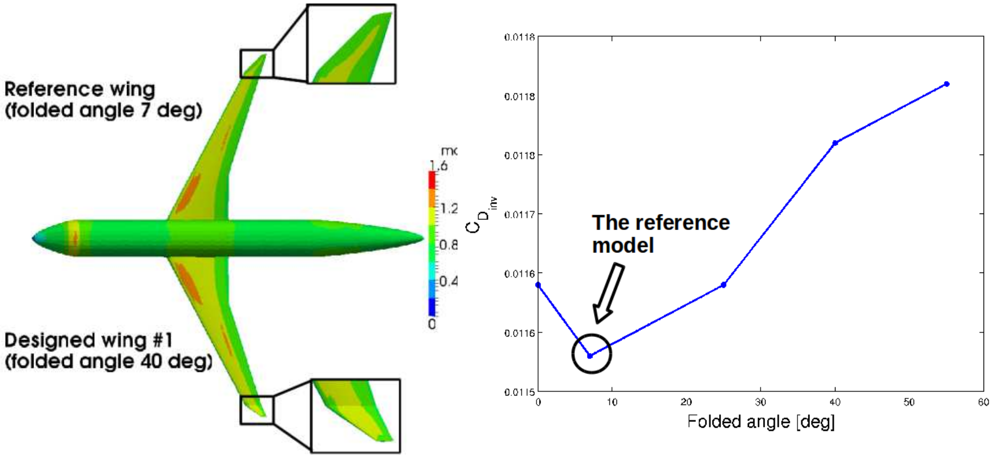


Figure 36. Euler solutions for the reference model with different winglet cant angles at Mach 0.78 and CL =0.47: Mach contours (left); and inviscid drag coefficients CDinv (right).

KTH and UBRIS – Joined-Wing Regional Jet Aircraft Studies

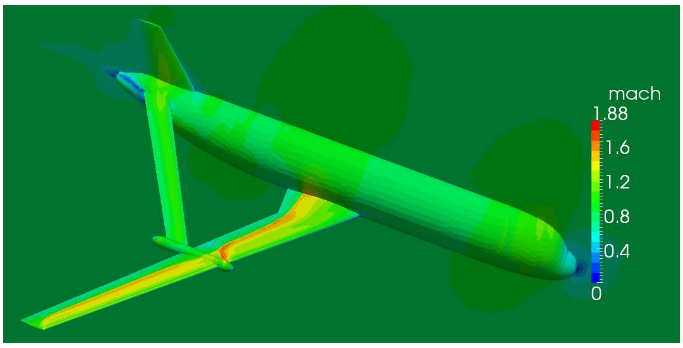


Figure 37. Euler solution for the joined wing configuration using Edge.

A joined-wing configuration was designed by UBRIS and modelled in CPACS by KTH. The parametric model was then lofted in sumo and finally a mesh was generated in sumo and tetgen. Euler solutions can then were carried out on this grid with the Edge flow solver. Typical results are shown in Fig. 37. Note the shock patterns associated with the wing joins around the store tanks. These shocks increase the wave drag, and must be minimized.

Concluding Remarks

EMB defined a complete aircraft model of a regional jet which was defined as the baseline model to study the application of morphing concepts. EMB studied a morphing wingtip and a trailing edge morphing concept, both providing gains in terms of drag counts and fuel consumption. However, EMB found that if a flexible aircraft was used instead there will be aerodynamic penalties when compared to the rigid aircraft, although, the morphing trailing edge seems a promising solution to mitigate these losses.

The enabling tools to study morphing concepts were successfully developed and tested in the concepts studied within NOVEMOR project and used in WP2 (to study morphing concepts), WP4 (to perform an overall assessment of the morphing benefits) and WP5 (the most promising concepts were tested in WT). KTH enhanced the computational design framework CEASIOM with: 1) the capability of defining morphing lifting surfaces; 2) and the CPACS parametrization tool. The KTH extensions to the CEASIOM were applied to design a winglet for the reference model and optimizing it for cruise condition. POLIMI developed enabling tools (PHORMA and SPHERA) to study compliant camber morphing devices allowing aero-structural shape optimization of these devices. POLIMI methodology was applied to design the morphing leading edge and trailing edge concepts developed in WP2 and tested in WT in WP5.

IST developed a performance based Multidisciplinary Design Optimization (MDO) framework for conceptual design which incorporates in an optimization environment the goals of analysing morphing solutions and novel configurations. The IST tool was used for the Weights and Energy Balance in WP4 and was applied to optimize a morphing wingtip on the reference aircraft and on the JW RPV model. UBRIS worked with KTH on the aerodynamic design methodology for the JW aircraft and reference aircraft winglet. This approach was later used on WP4 studies.

WP4- System Analysis and Integration

Introduction

The morphing mechanisms and concepts developed in WP2 have been applied to the aircraft configurations developed in WP3. Some of these have also been considered for wind tunnel testing for both low speed and transonic tests, and also for the flight testing of a joined wing UAV, in WP5.

All WP4 partners (UBRIS, IST and POLIMI) contributed to the tasks in the WP4, with much greater information being given in the two deliverables reporting this work:

- Aero-servo-elastic performance quantification and analysis of morphing concepts (D4.1);
- Weight and energy balance; overall assessment (D4.2).

Aeroservoelastic Analysis

This task dealt with the stability, flight mechanics and aerodynamic performance of all the concepts applied to the various configurations considered in the NOVEMOR project (regional jet aircraft and joined wing aircraft). Flutter stability was determined using the industrial standard FE / DLM based coupled analysis and it was found that for all of the concepts considered, there were no cases of a flutter instability. The flight handling qualities of the various concepts was considered using the relevant package in the NeoCASS software. The aerodynamic performance was determined using the inverse aerodynamic approach that was used throughout WP3 and WP4 to determine the optimal aerodynamic shape that was required throughout the flight envelope.

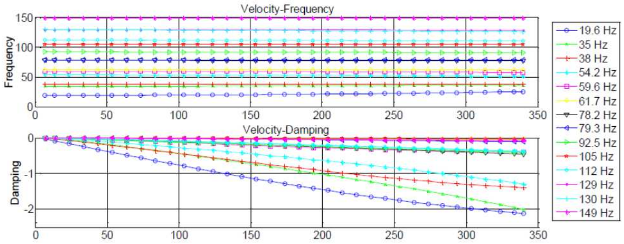


Figure 38. Sample vg and vω plots for Joined Wing Aircraft.

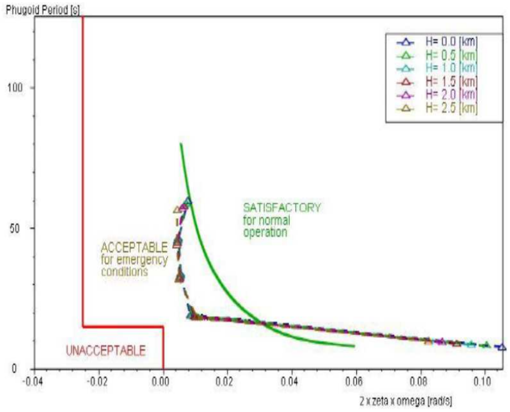


Figure 39. Phugoid Plot for Sample Joined Wing Configuration.

There were no flutter stability / divergence issues found within the desired flight envelope for the range of concepts considered (leading edge and trailing edge morphing, adaptive stiffness morphing). Similarly, there were also no flight mechanics (i.e. flight handling qualities) issues resulting from application of except for some of the grosser planform deformations considered for one of the joined wing RPV configurations.

Weight and Energy Balance

This task dealt with the methodology for evaluation of morphing concepts and novel configurations. In the morphing concepts analysis, the approach is essentially determining the allowable weight penalty due to morphing implementation before this implementation causes penalty in fuel consumption instead of benefit. In the Joined Wing configuration analysis, two approaches were followed: 1) the concept is initially optimized for a configuration with fixed span and lifting area as the sum of main and aft wing surfaces (same as the reference aircraft main wing span and area) of the main wing using performance based optimization in order to determine the benefits relatively to the reference aircraft configuration for a specific mission. 2) Parametric studies were performed allowing this time the main wing span to vary while the lifting area of the main wing is kept constant (same as reference aircraft). For both Joined Wing analysis approaches, the fuel consumption comparison with the reference aircraft was used as metrics for the configuration merit.

The methodology behind all the analysis described are based on the calculation of aerodynamic, structural, mass and inertia and propulsion databases which are used to build surrogate models in order to optimize the controls (including morphing surfaces/concepts) for a set of flight conditions.

Once this configuration databases are calculated, performance parameters are calculated for an aircraft configuration (e.g. fuel consumption), for a specific mission or a set of missions.

The optimal configuration is then determined through an optimization process based on the performance parameters obtained, either inserted in the objective or constraint functions calculation, thus reducing the multidisciplinary optimization complexity to a set of performance goals.

The morphing Leading Edge (mLE) concept was shown to be beneficial when the aircraft is operating at high angles of attack. Its aerodynamic benefits come from aligning the LE of the actuated wing segments with the flow without significant changes in the lift distribution. There is an exchange between reduction of local Angle of Attack (AOA) and increase in local camber.

The morphing Trailing Edge (mTE) concept shown aerodynamic improvement in all the levelled flight mission segments. The physics behind the improvement may be due to a reduction in operational AOA, leading to the alignment of the fuselage with the flow and consequent reduction in fuselage drag or a change in lift distribution and reduction of wing induced drag or a combination of both.

The calculations performed allow to estimate the consumption as a function of Take Off Weight (TOW) for the reference and morphing aircrafts and, by doing so, calculate the difference between the morphing aircrafts and the reference aircraft TOW for the same consumption. This difference was designated here as the Allowable TO Weight Increase (AWI) and provides an estimate of how much weight one can add to the aircraft with morphing concepts implementation before benefits turn into penalties.

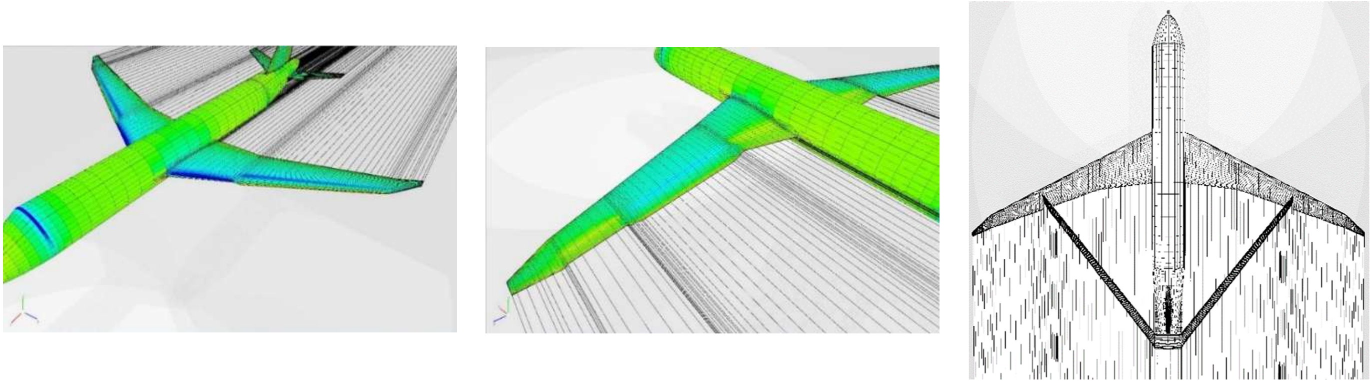


Figure 40. Leading edge (left) and trailing edge (centre) morphing concepts and Joined Wing configuration (right).

The AWI was show to increase with TOW for the mLE concept, while it decreases with TOW for the mTE concept. For low TOW, any increase in weight due to mLE implantation will cause consumption increase. For high TOW, benefits occur if the weight increase is lower than 276Kg. The mTE has much higher AWI, which remain high at higher TOW. For a TOW of 56ton, the AWI is about 982Kg. This values would be reduced significantly if cruise benefits are excluded.

The first approach on the Joined Wing concept, based on constant lifting area and span, resulted in an optimal configuration that has shown that the lift load is concentrated in the main wing, and its geometry has the highest aspect ratio possible and lowest area. As a result, the AOA is excessively high in cruise and hold, although benefits are obtained in cruise and penalties in hold. The benefits in cruise are disregarded due to the existence of shock at cruise speed, which is not predicted using the low/medium fidelity aerodynamic tools used. Furthermore, a structural weight penalty of nearly 4tons was predicted.

In the second approach, parametric studies were performed showing that the smallest aft wing chord/area is the most promising in terms of aerodynamic drag and that increasing the wing span is beneficial in hold and alternate segments. In cruise, as the increase in main wing span is followed by an increase in the aft wing area (joint is at constant 70% span), the benefits of span increase become penalties.

The Joined Wing configuration chosen in the second approach was the one showing lower drag penalty in cruise. For this configuration, the influence of the trim drag was studied and also the influence of CGx position on static stability. The trim drag was shown to be lower with the CGx position moving towards the aft wing, at the expense of a lower static margin.

The overall fuel consumption of the Joined Wing configuration with the CG position equal to the reference aircraft has shown penalty for higher TOW and a small benefit for the lowest. This benefit is turn into penalty due to the high structural weight penalty calculated of 2.8tons for the Joined Wing configuration.

A comparison between low and high fidelity calculation for lift and drag shown that the method used for drag calculation underpredicts the drag. Therefore, the benefits calculated would reduce its significance if higher fidelity tools would have been used. Nevertheless, the relative potential for drag reduction of the different concepts is believed to be correctly assessed.

System Integration, avionics and telemetry

The instrumentation system required for the flight and ground tests of the reduced scaled aeroelastically tuned JW PV model were discussed in WP4, although presented in WP5 D5.4. Aiming to observe and quantify the non-linear aeroelastic response, several sensors were employed on the wing model:

- Strain gauges: to measure bending strain;
- Accelerometers: for ground test phase to measure the modal response;
- Optical cameras: to measure displacements.

Data acquisition is divided into two scenarios: 1) ground based testing allows the use of larger, lab based equipment with higher sampling rates and resolutions; 2) a miniaturized system was designed for flight testing that has lower sampling rates but is smaller, it has on-board logging and is capable of passing a real-time feed to the ground at a reduced frequency.

Concluding Remarks

WP4 of the NOVEMOR project has strived to evaluate the various morphing concepts that have been considered on two types of configuration:

- a regional jet with trailing edge and leading edge devices and also a wingtip device;
- a joined wing RPV configuration with a number of different performance morphing devices and also gross planform morphing changes.

A further consideration of the joined wing design was the conceptual design of commercial jet aircraft using this configuration.

The main findings from this WP are:

- The configuration of the original reference regional jet aircraft was such that any added wingtips had little effectiveness regardless of the amount or type of morphing that was applied. Analysis was performed using an inverse aerodynamic design approach to determine the optimum aerodynamic shape for each configuration.
- An approach to include morphing devices into the aerodynamics and structural design process, including jig shape design, was developed. It was shown that the combination of both camber and variable stiffness morphing provides the most effective way of obtaining the optimal aerodynamic shape throughout the flight envelope. It was shown that for an aircraft design for a particular range, the use of morphing was beneficial for missions much shorter than the design range. The effect of uncertainty on the structures and aerodynamics used throughout the design process was also considered, and the uncertainty in the aerodynamic parameters was found to have a significant effect upon the structural design robustness.
- A range of different morphing concepts were applied to the baseline joined wing RPV model, including the wing tip and the front wing. It was shown that leading edge morphing of the front wing was most beneficial.

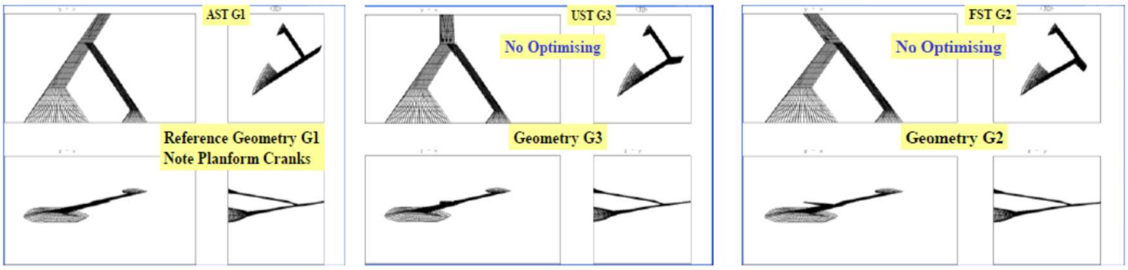


Figure 41. Sweep Morphing Concepts Applied to Baseline Joined Wing Wingtip.

- The conceptual design of a joined wing regional jet aircraft was investigated and it was shown that such a design merits serious consideration if much larger aspect ratios are considered than previously investigated.

Figure 42. Joined Wing Regional Jet Designs Considered in this Study.

- A range of different planform morphing concepts were considered to the baseline RPV joined wing design. It was shown that it is possible to develop a joined wing design with very good characteristics, however the concepts considered were thought to be of much practical application.
- A number of performance morphing concepts were applied to the wing tip of the baseline joined wing aircraft. It was shown that the application of a number of different morphing approaches to the outer wing had very little effect on this baseline configuration, particularly for roll control, and that leading edge / trailing morphing applied to the forward wing was the most effective, along with a variable twist device applied to the wing tip.
- A buckling alleviation component was developed that has the potential to be used to alleviate the onset of nonlinear buckling of the rear wing which has proved to be a critical component of joined wing design. Initial studies have proved very encouraging.
- The overall benefits of the mLE and mTE concepts application to a regional commercial aircraft have shown to be limited and most probably overestimated. Nevertheless, the relative potential of the two concepts was evaluated.
- The mLE concept has shown greater potential for benefits in high CL flight conditions, namely Hold stage. These benefits were calculated to be 2.1% in a 56tons TOW aircraft performing the typical mission of the reference regional aircraft considered in the NOVEMOR project. The concept virtually does not alter the lift distribution and therefore does no incur in structural weight penalty.

- The AWI of the mLE concept increases as the TOW increases. Thus, implementing the concept would require substitution of the existing LE devices in order not to penalize consumption in lower TOW missions.
- The mTE concept has shown potential benefits in all CL flight conditions. Benefits calculated range from 4.5% to 6.5% for different TOW, increasing as TOW increases. When disregarding cruise condition gains, benefits range from 1.7% to 4.3%. This concept incurs in weight penalty since it alters the lift distribution on the wing in order to reduce induced drag. The resulting increase of Root Bending Moment causes a structural weight penalty calculated to be of 218Kg, with corresponding reduction in range or payload.

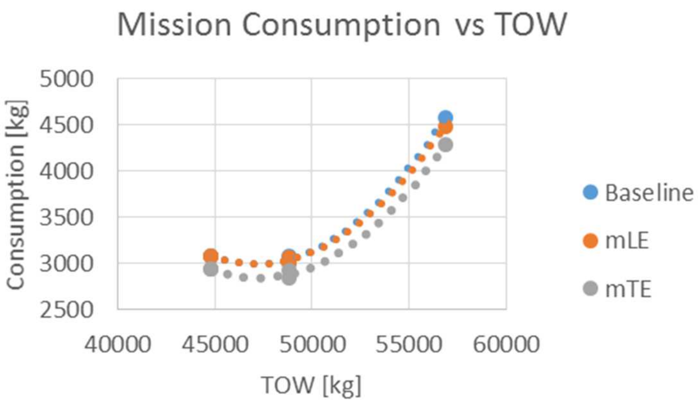


Figure 43. Consumption as a function of Mission Take-Off Wright for the reference and morphed aircraft.

- The AWI of the mTE concept decreases as TOW increases. Nevertheless, the calculated AWI is high enough for high TOWs to accommodate the structural weight penalty of 218Kg and some more weight coming from mechanism implementation.
- Even though the mTE benefits are shown to be higher and occurring in all regions of the flight envelope, its implementation conflicts with lift requirements for Take Off as these are not foreseen to be able to substitute the conventional flap systems.
- From the Joined Wing configurations analysis and optimization, it was not shown that this configuration could bring significant benefits in the future, mainly due to the high structural weight penalty caused by the reduction in root chord of the main wing as the Aspect Ratio of the wing is increased. Different degrees of freedom for the configuration optimization, both aerodynamic and structural, may change this conclusion.

WP5- Wind Tunnel and Flight Demonstrators for Validation of Morphing Concepts and Joined Wing Configuration

Introduction

The main goal of this WP was the WT and flight testing of developed concepts on physical platforms: subsonic and transonic WT models and aeroelastically scaled joined-wing RPV

Validation testing is a critical component when developing new aircraft technology. No matter how novel a new concept may appear, this is not proven useful until a qualified test campaign have been successfully completed. This is even truer when dealing with concepts that exploit new morphing solutions of the airframe to achieve performance benefit. The multidisciplinary character of the morphing airframe makes it very difficult to develop simulation models that are sufficiently accurate and efficient for design purposes. Aerodynamic analysis always poses a significant challenge, but even the development of an accurate structural model of a real airframe can be a very involved and time-consuming process. Another problem related to the multidisciplinary character is related to the fact that the improvement of some performance metric can be accompanied by a loss of performance in another metric, since it is very difficult to consider all possible correlated effects during the design process. Ultimately, this calls for careful validation testing under realistic conditions in order to investigate if a concept is feasible or not.

The purpose of this effort is to validate the adaptive/morphing concepts developed in WP2, using wind tunnel testing and especially to support partners decisions for rejection or further development of the different concepts. Thus, the principal objectives of this WP have been:

1. Experimental validation (functionality test) of the adaptive morphing Leading Edge, Trailing Edge and Wing tip developed by DLR, POLIMI, UBRIS and IST in WP2 and 3.
2. Experimental validation of the LE and TE morphing shapes developed by EMBRAER and POLIMI by means of dedicated WT transonic test carried out at CSIR.
3. Experimental flight test validation of real-time (in-flight) joined-wing aeroelastically scaled RPV to assess airworthiness and to validate the aeroelastic response on dynamically scaled joined-wing aircraft.

In the following the main outcomes of these activities are highlighted.

Wind Tunnel Tests

UBRIS – Functionality tests

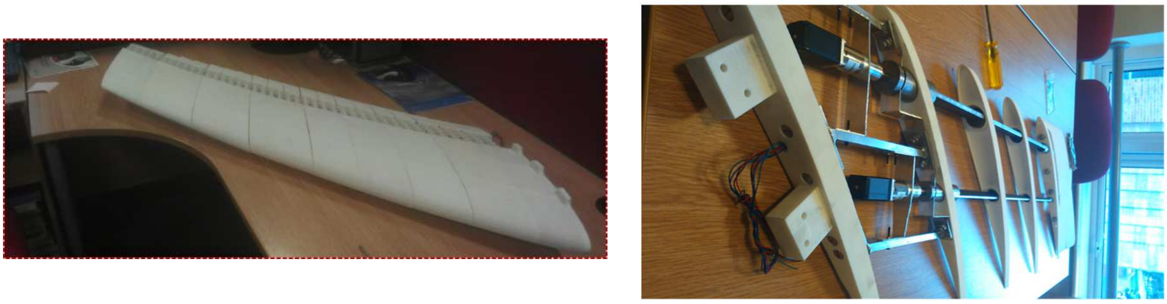
Four sets of low speed wind tunnel tests were performed at the University of Bristol as part of the NOVEMOR research project. The tests were performed in the 7 feet (2.1m) x 5 feet (1.5m) wind tunnel at UBRIS, see Fig. 44, which has a top speed of 60 m/s. Each of the sets of wind tunnel tests was focused upon a different morphing concept applied to a wing-tip, which are described in much greater detail in NOVEMOR deliverables D2.4 and D4.1, with a greater explanation of the wind tunnel test matrix and results shown in deliverable D5.1. The concepts considered were:

- Droop-Nose Adaptive Morphing Wingtip
- Honeycomb Trailing Edge Concept
- Chiral Wing Tip Concept
- Variable Stiffness Rotating Spars

For the first three of these concepts, this was the first time that a prototype had been designed, manufactured and wind tunnel tested. Although the rotating spars approach had been implemented in previous work, the concept was included here in order to compare the variable stiffness methodology with the other concepts; it had not been previously applied to a swept wing at such a high dynamic pressure.

The drooping morphing leading edge concept was applied to a full scale model of a wing tip of the reference regional jet aircraft, whereas the other three concepts were applied to a half size model of the wing tip of the joined wing UAV that was flight tested as part of the NOVEMOR project and described in deliverable D5.4.

Wind Tunnel model of Wingtip with droop nose. Wind tunnel model based on chiral structure



Wing equipped with honeycomb trailing edge. Rotating spar wing structure.

Figure 44. UBRIS wind tunnel models.

The key outcome from these tests was the experimental demonstration of the feasibility of using these morphing concepts (Fig. 44). Further work is required to continue developing these morphing concepts.

CSIR – Transonic Wind Tunnel Tests

The work package 5.2 focused on the transonic wind tunnel test of the wing body configuration representing a high speed regional transport aircraft, called Reference Aircraft, developed by EMBRAER in WP3. In particular, the performances in the baseline configuration and in one equipped with morphing LE and TE have been evaluated to validate the CFD results. More in details, the objectives of the tests are to characterize the global forces and moments of the half model reference and morphed configurations for the wing only. The test was executed in accordance with the test specification.

A full boundary layer simulation exercise was conducted, investigating the effect of different trip locations and total pressures (Reynolds number sweeps). Laminar to turbulent trip locations were applied at 5%, 20%, 35% of the chord and also without dots for natural tripping.

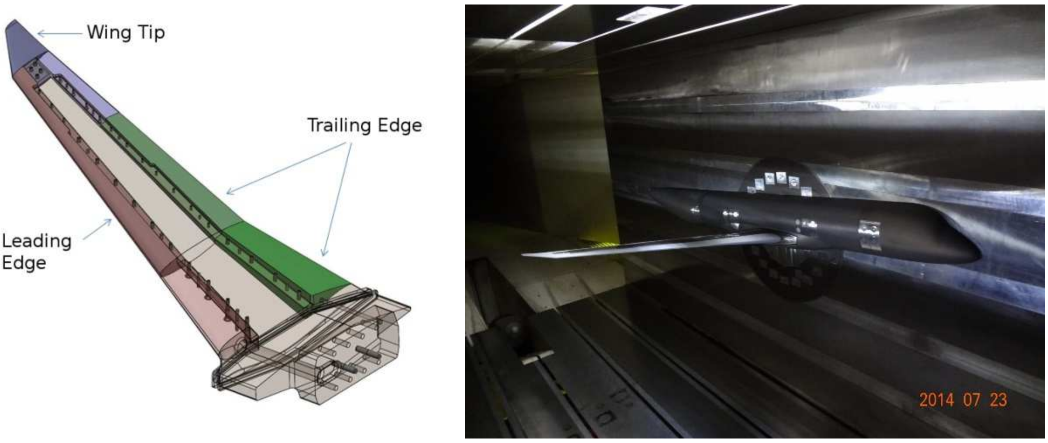


Figure 45. Modular wing model configuration: baseline LE and TE can be substituted by the morphing ones (left); overview of the full model during the test (right).

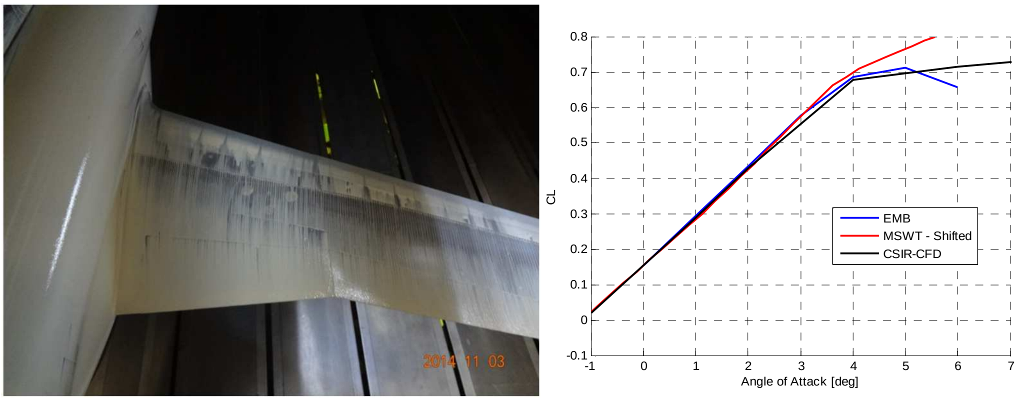


Figure 46. Flow visualization (left) and one of the numerical vs. experimental correlation result (right).

Finally, different visualizations have been performed to help interpret the global force and moment trends and to check if the trips were performing their function of tripping the flow.

POLIMI – Functionality Tests

The work package 5.3 focused on the functionality test performed at POLIMI on a small scale (1:10) wing model to validate the functionality of morphing devices under realistic aerodynamic loads. For this reason not special aerodynamic indices have been measured, such as aerodynamic forces by means of a dedicated wind tunnel balance. The POLIMI's tools PHORMA and SPHERA have been used for the design of morphing mechanisms. Starting from the morphing configuration already developed in WP3 for the Reference Aircraft. Unfortunately, due to the small scale of the model, it is impossible to simply scale down the already available solution for the full scale aircraft. For this reason, a complete new optimization was requested for the redesign of the morphing devices. In the process of transferring optimal solutions into physical models, many issues emerged during the design of realistic geometries compatible not only with desired kinematic and structural performance, but also with manufacturing limitations. In this regard, near prohibitive challenges were posed by the small scale of the wind tunnel test chamber for such morphing devices, in the individuation of production technologies that could cope with extremely complex compliant mechanism layouts and their deformation requirements.

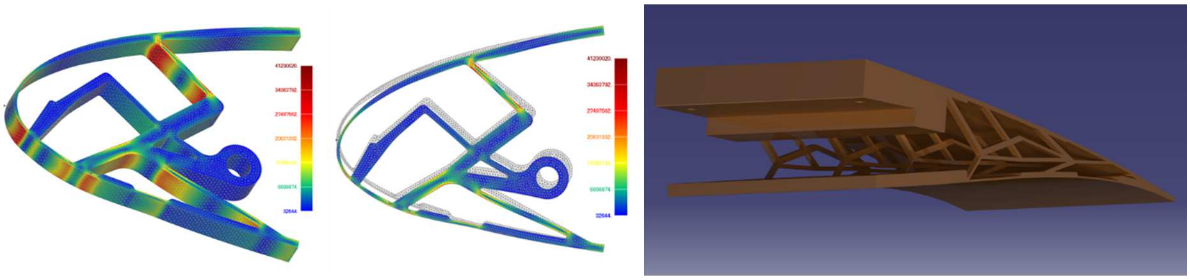


Figure 47. Simulation model of the morphing LE based on a compliant structures (left); CAD model of the compliant TE ready for 3D printing (right).

3D printing solutions were deemed the most appropriate thanks to their capabilities in terms of complex shape reproduction and material flexibility for the limited scale of the models. After some failed attempts, PolyJet Modelling and Stereolithography gave satisfactory results, demonstrating the feasibility of compliant mechanism concept also for wind tunnel testing.

The final WT demonstrated a high correspondence between the simulation models and the real behaviour of morphing devices in terms of both capability of reproduce the target shape and values of the actuation forces.

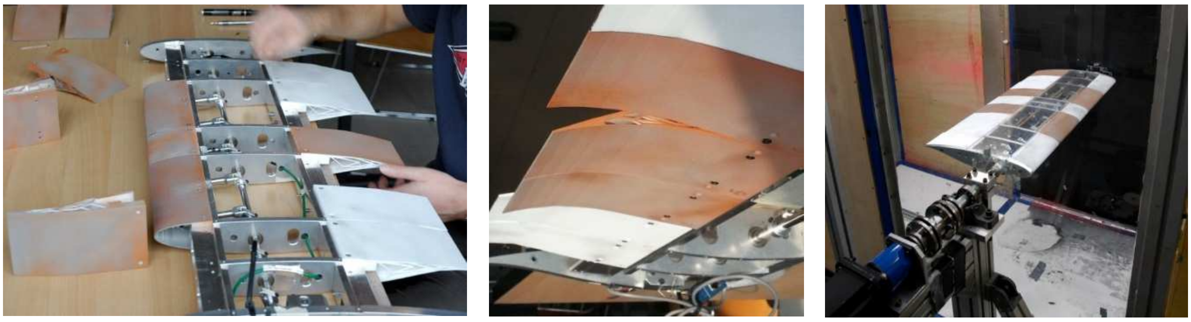


Figure 47. Wing model assembly (left); deformed TE (centre); wing model during WT test (right).

Flight Tests

IST – Flight Tests

A reduced scale Joined-Wing (JW) aircraft was designed and manufactured to demonstrate the airworthiness of this novel configuration and to capture the nonlinear aeroelastic response of the aft-wing. To accomplish this task, several important design issues were addressed: 1) distribution of mass (weights & balance); 2) available payload volume; 3) instrumentation integration; 4) stability; 5) electromagnetic interference; 6) control surfaces location and effectiveness; 7) engines integration; 8) materials selection; and 9) internal structural design.

An unconventional structural layout composed of tailored aluminium spars and non-load bearing aerodynamic panels was used to ensure manufacturability and flightworthiness of the reduced scale JW model. The booms and fuselage were built using carbon and glass monocoque construction. Many of the internal components were fabricated using rapid prototyping (Stereo Lithography and fused decomposition methods). Various machined parts were built using a combination of manual work and CNC machines. The mass properties of the structural components were measured and used to update/tune the FE models.

Prior to the flight tests, several ground tests were conducted to measure the static and dynamic response of the aeroelastically tuned JW model. The FE models were updated with the data collected from these tests using optimizing software. In addition, other important tests were conducted to check flightworthiness of the configuration: 1) Bifilar Pendulum Tests; 2) autopilot tuning; 3) system calibration; 4) installed thrust testing; 5) EMF/RF test; 6) HIL simulation; 7) launcher test; and 8) safety tests.

Two models were flown: 1) a rigid model; and 2) a flexible model. The rigid model flights served as a stepping stone to flights using the flexible structure. They are seen as a low risk to develop and validate safe flying characteristics, tuning autopilot, determine achievable loading conditions during flight, train pilots and ground crew and supply data to dry run post processing tools and methodologies. The flexible model flight tests were conducted with the aim of prove the flightworthiness of the flexible JW concept and to investigate the aeroelastic response of the aft wing in both linear and non-linear regimes.

Good flight qualities were observed in rigid and flexible model flight tests, controllability was ensured. The expected non-linear aft wing buckling was observed in the flexible flight test.

Concluding Remarks

Experimental tests were conducted in wind tunnel to validate the morphing concepts developed in WP2 and WP3: morphing leading edge; morphing trailing edge; and morphing wingtip. A functionality test of a full scale morphing wingtip with a droop nose topologically optimized by DLR in WP2 for the regional airliner was successfully conducted in subsonic wind tunnel at UBRIS. The functionality of morphing concepts developed by UBRIS in WP2 (Honeycomb Trailing Edge Concept; Chiral Wing Tip Concept; and Variable Stiffness Rotating Spars) applied to the JW RPV model were also tested in the same wind tunnel.

The presence of a wingtip in the reference model wing was tested in wind tunnel at CSIR and it was proved to be beneficial in aerodynamic terms by increasing the lift-to-drag ratio which was an expected result. The leading edge and trailing edge morphing devices were also tested at CSIR transonic wind tunnel with contradictory results: 1) the subsonic morphed leading edge results in an increase in the stall angle of attack of at least 1 degree; 2) the lift-to-drag ratio CFD predictions for the morphed trailing edge were not observed in the experimental results.

At POLIMI wind tunnel a reduced scale morphing leading edge device and a morphing trailing edge device were tested. Good agreement between simulation and experimental models was observed in terms of both capability of reproduce the target shape and values of the actuation forces.

A reduced scale JW model was designed, manufactured and tested in ground and flight. It was observed non-linear aft-wing buckling on the aeroelastically tuned JW model.

WP6- Benefit Evaluation in Terms of Impact on Lift, Drag, Weight and Aeroelastic Response

Introduction

The working scope defined in WP6 was covered on its totality. In order to assess the benefits of the morphing devices numerical and experimental approaches were employed. The conducted investigations were focused in evaluating the decrease in the drag coefficient, the improvement in the lift coefficient, the weight increase or decrease and the aeroelastic behaviour to define the overall benefits.

In the first moment the assessment of the benefits have just considered the aerodynamic point of view. Thereafter, subsequent analyses, from different technologies, were performed in order to evaluate if a benefit could still be found. It is worth mentioning that it is not an easy task to define the level of fidelity and details that each analysis must consider. Certainly each performed analysis, in the present project, could not get into the tiny details up to component level for each analysed system. Nevertheless, rather than certificating a specific morphing configuration most of the project objectives lie on a more general feasibility assessment wherein different morphing proposals are evaluated.

Aerodynamic Benefits (Lift and Drag)

The aerodynamic analyses for the reference aircraft and the evaluated morphing devices were performed in accordance with the adopted strategy defined at the beginning of the project. The definition of the mathematical and numerical formulations considered the need to have the most adequate approach to capture the pertinent physical phenomena at the subsonic and transonic regime. Indeed, as expected the transonic regime has demanded the use of high-fidelity tools to capture the non-linearity of the flow.

The obtained numerical results for the trailing edge morphing devices could not be validated with the wind tunnel results. It was not possible to observe the numerical morphing benefits reproduced at the wind tunnel. Nevertheless, the work performed on both numerical and experimental sides has shown how challenging is to measure and validate small differences for the aerodynamic coefficient. This experience has provided important lessons that address the following issues:

a) the need to adopt numerical approaches that consider higher order schemes to ensure that the small measured differences are indeed present;
b) wind tunnel balance with the capacity to measure the small differences in the lift and drag coefficients.

Another important conclusion from the aerodynamic and performance assessment of the morphing devices lies on the fact that the design process must consider the use of such technology since the earlier design phases.

Weight Savings

For those aircrafts that do not belong to non-conventional category the weight estimation is a consolidated process due to the vast database from aviation history. However, for aircrafts that employ new technologies such as the morphing devices this is not an easy task due to the lack of available data in the literature. In terms of weight it was decided to perform the assessment considering two methods. The first one is called method P0 and it considered the combination of the morphing devices with the high-lift devices. It was performed an energetic analysis to considered the maximum allowable weight that would still imply in benefits in performance. The second method, named method P1, considered the substitution of the high-lift devices by the morphing devices. This method established two metrics: the weight per length for the leading edge and the weight per area for the trailing edge.

The performed study of the NOVEMOR project about the weight benefits does not allow a conclusive position about this issue. The results from the method P0 seem optimistic whilst those from the method P1 are not conclusive due to the dispersion. The weight assessment is not simple because it implies in evaluation of the configuration at the component level or the use of consolidated database which is not available for the morphing technology. Thereby, in order to have any sort of weight assessment about the morphing device it is necessary to employ a detailed analysis about the structural solution, mechanisms and the actuators.

Aeroelastic Response

The aeroelastic results have not shown any type of degradation in the flutter velocity provoked by the adoption of the morphing devices. A multi-fidelity analysis has been performed with the FEM model.

POLIMI developed an aeroelastic model of the reference aircraft to analyse the aeroelastic behaviour of the reference model and in particularly to assess the effect of morphing leading edge (mLE) and morphing trailing edge (mTE) devices in the aeroelastic behaviour of the reference regional aircraft. The analyses were conducted in PyPAD (Python module for Preliminary Aircraft Design) framework developed by POLIMI. This framework includes a Panel Code to model the aerodynamics and for the aircraft structure a complete FE model is built (including ribs, spars, skin and stringers in the wings as well as accounting for movable parts such as the mLE and mTE devices).

The effect of deflecting the morphing leading and trailing edge devices was evaluated in terms of trim solutions and load distributions. The morphing deflection were considered both rigid and flexible. The Mach number were considered in the calculations: 0.3, 0.5 and 0.7.

The first results suggest that the effect of the morphing on the stability derivatives and on the trim solutions is clearly influenced by the aeroelastic behaviour of the model which effect increases as Cmy/Morp increases.

By evaluating the C_P distributions, a clear difference between the solution with morphing deformation and the one without for Mach 0.3 is observed, although the difference between rigid and aeroelastic solutions is small. When the Mach increases the difference between rigid and aeroelastic solutions increases (worth remembering that also the trim solutions are different) especially in the outboard part of the wing, where the deformations are larger.

The changes in C_P distributions also affect the internal loads on the aircraft and in particularly on the wings. The morphing effect is visible in the torque moment for the Mach 0.3 case: the lift moves back along the chord, increasing his arm from the shear centre. This behaviour increase in importance by increasing the Mach number. Also by increasing the Mach number the differences on shear and bending moments increase: globally the loads are lower when the aeroelastic effects are considered, but the shear at the root increases when the morphing is activated. This because the angle of attack required to trim the aircraft is lower when the aircraft is morphed and the outboard part of the wing, due to twist in the airfoils and to elastic deformation has a negative incidence.

Concluding Remarks

EMB foresees the morphing devices as a promising technology that can and will provide benefits to ACARE main goals. However, the employment of the morphing devices, at the regional aviation, might occur in a second moment due to the following peculiarities:

- It is not possible to rely entirely on the morphing devices to satisfy the demanded aircraft field performance.
    - High-lift devices are still necessary.
- Regional jet wings are relatively small, which brings difficulties to have any kind of mixed solution: conventional high-lift devices and morphing devices.

Potential Impact

Tendencies and current aeronautic drives

Many factors are pushing the aeronautical technologies these days, pressuring for better aircraft performance. Especially, the aircraft direct operational cost, DOC, and the environmental legislation. The DOC is particularly influenced by the fuel cost and aircraft consumption, while the environment legislation imposes severe limitations to the CO2, NOx and noise emissions.

The discussions concerning the challenges to increase aircraft performance raise an interesting question: are there new technologies available nowadays to face and solve the emissions and the consumption problems?

At a first glance, it appears that the development and implementation of incremental new technologies would not be enough to respond to market needs in a reasonable timeframe.

Moreover, the current conventional aircraft design, based on a tubular fuselage cross section and two semi-wings, has reached such a technological development level, that it would be impossible to achieve the required evolution in terms of emissions and consumption reduction.

The figure below illustrates the situation where a negligible gain in performance is achieved for a certain investment on conventional aircraft configurations, while a significant performance step is obtained with the same investment on non-conventional configurations.

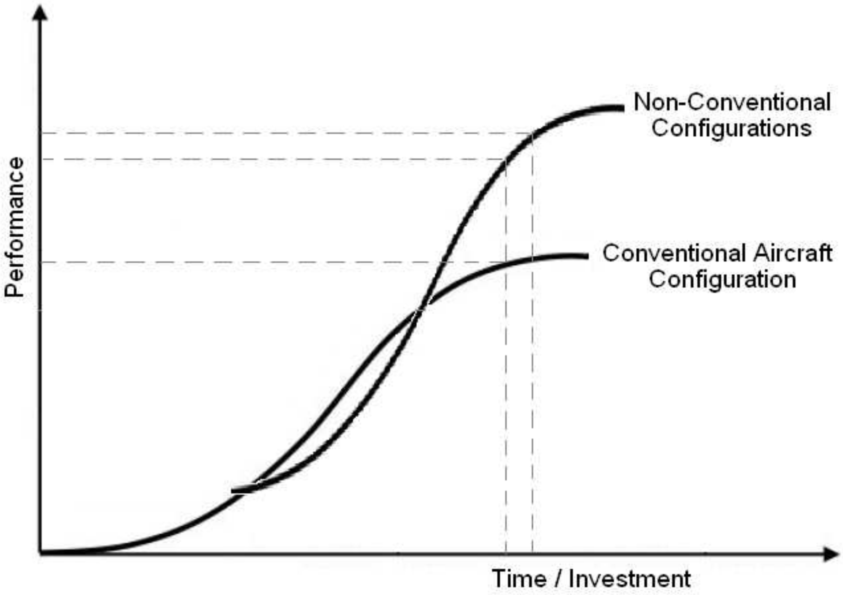


Figure 48 Technology evolution.

Another interesting aspect related to those curves displayed in Fig. 49, concerns the point where we are over the time line, i.e., in another words, how mature are currently the technologies associated with the non-conventional aircraft configurations?

The above reasoning infers that the study and the evaluation of alternatives aircraft configurations such as blended wing, body double tube cross section, high aspect ratio wing and others disruptive technologies aiming to address cost and environmental challenges are valid.

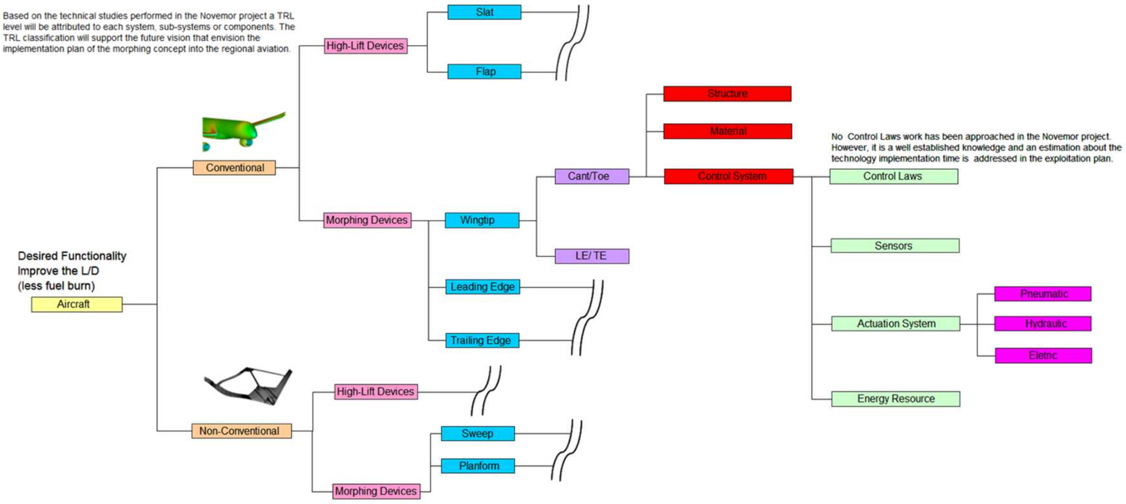
In this scenario, the NOVEMOR Consortium shares the conviction that the application of morphing structure solutions to the conventional tube and two semi-wings aircraft configuration might produce the expected step increase in performance. Moreover, morphing solutions would also be necessary and applicable to completely new and alternatives aircraft configurations.

Benefits exploitation for efficient short/mid-range transport aircraft

The studies performed during the NOVEMOR project have shown that the morphing devices are a promising technology that can help the achievement of the environmental goals expected by ACARE. Nevertheless, there is a long journey before this concept can be operational on the regional aviation. Some of the points are not intrinsically related with the technology concept itself, but with the liquid gains that can be obtained for the regional aviation. Probably, the morphing technology will emerge in the following sequence:

1. UAV
2. Business jet
3. Long-range aircraft
4. Regional aircraft

Figure 49 depicts a simple analysis wherein the wingtip morphing device is broken up to component level. The idea behind this exercise is to define the technological readiness level, TRL, for the morphing devices. In order to have any new technology implemented into the aircraft it is required that the entire system reaches TRL nine and if one single component does satisfy such requirement the technology is not available.

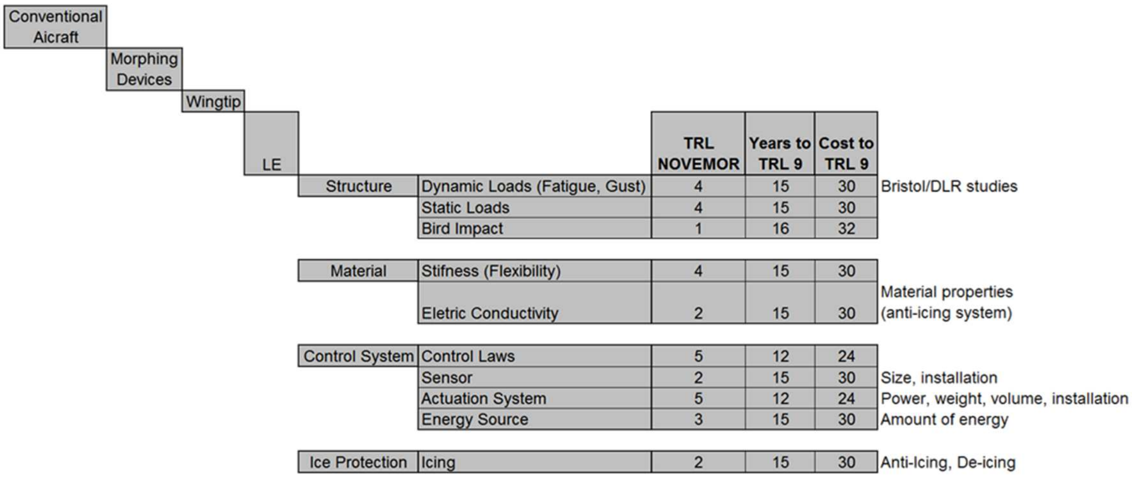


Based on the technical studies performed in the Novemor project a TRL level will be attributed to each system, sub-systems or components. The TRL classification will support the future vision that envision the implementation plan of the morphing concept into the regional aviation.

No Control Laws work has been approached in the Novemor project. However, it is a well established knowledge and an estimation about the technology implementation time is addressed in the exploitation plan.

Figure 49. Example of a simple exercise that goes from the system level up to some component level for one morphing device solution.

Figure 50 shows an example of the estimation exercise to define the TRL level for the wingtip morphing devices. The columns of the table shown in Figure 50 were filled based on the performed analyses conducted in the NOVEMOR project. It can be observed that the TRL varies as function of the considered analysis. Based on the overall analysis performed with the results of the NOVEMOR project it is expected to have TRL nine in approximately 15 years. There are some topics that are more evolved, but as mentioned before the entire system must have TRL nine. Thus, the most incipient topic will hold the entire development, unless efforts are directed to the topic with the lowest TRL in order to accelerate the maturity of the system.



Conventional Aicraft
Morphing Devices
Wingtip
LE

		TRL NOVEMOR	Years to TRL 9	Cost to TRL 9	
Structure	Dynamic Loads (Fatigue, Gust)	4	15	30	Bristol/DLR studies
	Static Loads	4	15	30	
	Bird Impact	1	16	32	
Material	Stifness (Flexibility)	4	15	30	
	Eletric Conductivity	2	15	30	Material properties (anti-icing system)
Control System	Control Laws	5	12	24	
	Sensor	2	15	30	Size, installation
	Actuation System	5	12	24	Power, weight, volume, installation
	Energy Source	3	15	30	Amount of energy
Ice Protection	Icing	2	15	30	Anti-Icing, De-icing

Figure 50. Expected time and investments to have morphing devices ready to be implemented in an aircraft.

NOVEMOR technology implementation process

The direct application of those most promised devices to commercial products are, however, not immediate. There is a considerable risk applying new technologies to commercial products based only on laboratories and representatives environment results. Additional development will be required to bring such morphing devices to a more mature level, reducing eventual risks, like system integration, scale problems, uncontrolled parameters on real operational environment and others issues.

Even that NOVEMOR project results push morphing devices to the TRL 5, additional investments are still needed to carry it to highest TRL as 8 or 9, before being ready to be implemented on commercial aircrafts.

This way, it is recommended for the NOVEMOR technology implementation plan to be deployed on two subsequent steps:

Morphing prototype flight test and demonstration project

A posteriori project shall be planned and executed aiming to apply the best solution proposed by NOVEMOR Project on an actual aircraft, for instance an EJ-170 aircraft. Two major results are expected from this task:

a) The technology should be tested and no further major development shall be required;

b) The performance and operation requirement issued from NOVEMOR Project should be validated and the aircraft operation as intended is demonstrated without significant design problems.

During this project, a cost model shall be developed showing:

a) Devices design and development costs;
b) Components acquisition and integration costs;
c) Maintenance and Direct Operational Costs impacts (DOC).

Other two important results are expected from the project:

a) A supplier and Intellectual Propriety (IP) consortium policy definition;
b) An aircraft certification plan shall be defined for commercial application.

Implementation of morphing technologies on commercial product

The process presented below, as proposed by Sarah Ganly, has been applied by different kinds of enterprise, showing an important margin of success in the implementation of new technologies on commercial products, and its deliverable to the market consumption. The implementation process is composed by the following tasks:

Defining goals

Examining in which aircraft the morphing devices improvements provide benefit on the company, defining a direct explanation of why installing this new system helps the company.

Researching

To conduct internal research that determines the means and methods to reach these goals. To determine:

- cost of various new technology systems and how the cost impacts the company;
- time and money saved by the new technology;
- amount of resources needed to implement the new technology;
- future of the system to be implemented on a short, medium and long term vision.

Analysing information

Allows appropriate decisions to be made when designing the plan:

- what aircraft use resources wisely and provide the company with the most value ;
- how to implement the new technology in regards to employee training and timing.

Deciding on a specific solution

Provides the basic foundation for figuring out the many details of the implementation plan provides the company with strategy and steps to install the new technology from beginning to finish, determining the training and other resources utilized. It provides specific details and step-by-step information on how the plan occurs.

Implementing

The new technology requires following through with the plan as it was designed. First, employees should be made aware of the steps of the implementation plan for the new technology system. Then the plan should be implemented according to the steps outlined in the detailed description of the plan.

Monitoring

The implementation allows for correction and adjustments to be made to the plan. It also allows the provision of feedback and show areas where the applicants require extra assistance.

Evaluating of the plan

Requires checking if specific goals have been met. It also allows for new strategies to be determined as well as poor strategies to be removed from the plan.

Dissemination

TEMPLATE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[1] (if available)	Is/Will open access[2] provided to this publication?
1	*Flight Dynamics and Control of a Vertical Tailless Aircraft*	*Brás M., Vale J., Lau F., and Suleman A. (IST)*	*Journal of Aeronautics and Aerospace Engineering*	*2:119*			*2013*		10.4172/2168-9792.1000119	yes
2	*Energy Efficiency Studies of a Morphing Unmanned Aircraft*	*Vale J., Lau F., and Suleman A. (IST)*	*Journal of Aeronautics and Aerospace Engineering*	*2:122*			*2013*		10.4172/2168-9792.1000122	yes
3										

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[1] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

[2] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

TEMPLATE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities	Main leader	Title	Date/Period	Place	Type of audience	Size of audience	Countries addressed
1	*MSc Thesis*	*Cardoso J.(IST)*	*Performance Evaluation of a Morphing Joined Wing Aircraft Configuration*	*October 2012*	*Lisbon, Portugal*			
2	*Conference*	*Falcão L., Gomes M. A., and Suleman A.(IST)*	*A Tool for the Automated Design of Multistable Composite Parts*	*8-11 October 2012*	*Delft, The Netherlands*			
3	*Conference*	*Vale J., Lau F., and Suleman A. (IST)*	*Static and Dynamic Analysis and Comparison of Fixed and Morphing Wing Equipped UAV Aircraft: Optimal Control Calculation and Energy Estimates Evaluation*	*8-11 October 2012*	*Delft, The Netherlands*			
4	*Conference*	*Dale A., Cooper J. E., and Mosquera A. (UBRIS)*	*Adaptive Camber-Morphing Wing using Zero-Poisson's ratio Honeycomb*	*8-11 October 2012*	*Delft, The Netherlands*			
5	*Workshop*	*Vale J., Lau F., and Suleman A. (IST)*	*Energy Balance Studies on Aircraft Morphing Technologies*	*22-24 October 2012*	*Lisbon, Portugal*			
6	*Workshop*	*Cardoso J., Suleman A. (IST), and Cooper J.E.(UBRIS)*	*Global Morphing of Joined Wing Aircraft*	*22-24 October 2012*	*Lisbon, Portugal*			
7	*MSc Thesis*	*Brás M.*	*Flight Dynamics and Control of a Vertical Tailless Aircraft*	*November 2012*	*Lisbon, Portugal*			

8	*Conference*	*Cardoso J., Suleman A. (IST), and Cooper J.E.(UBRIS)*	*Performance Evaluation of a Morphing Joined Wing Aircraft Configuration*	*8-11 April 2013*	*Boston, MA, USA*			
9	*Conference*	*Falcão L., Gomes A., and Suleman A.(IST)*	*Study of an Articulated Winglet Mechanism*	*8-11 April 2013*	*Boston, MA, USA*			
10	*Conference*	*Vale J., Lau F., and Suleman A. (IST)*	*Optimal Control and Energy Balance Evaluation of a Morphing Aircraft*	*8-11 April 2013*	*Boston, MA, USA*			
11	*Conference*	*Dale A. S., Cooper J. E., and Mosquera A. (UBRIS)*	*Adaptive Camber-Morphing Wing using 0-υ Honeycomb*	*8-11 April 2013*	*Boston, MA, USA*			
12	*Conference*	*De Gaspari A., and Ricci S. (POLIMI)*	*A Parametric Framework for the Design of Morphing Wings*	*24-26 June 2013*	*Torino, Italy*			
13	*Conference*	*Dale A. S., Cooper J. E., and Mosquera A. (UBRIS)*	*Adaptive Camber and Chord Morphing Wing with 0-υ Honeycomb Compared to Conventional Wing*	*24-26 June 2013*	*Bristol, UK*			
14	*Conference*	*De Gaspari A., and Ricci S. (POLIMI)*	*Active Camber Morphing Wings Based on Compliant Structures*	*9-12 September 2013*	*Naples, Italy*			
15	*MSc Thesis*	*Amândio L.*	*Stochastic Optimization in Aircraft Design*	*October 2013*	*Lisbon, Portugal*			
16	*MSc Thesis*	*Sousa F.*	*Topology Optimization of a Wing Structure: Studies on Morphing Compliant Edges*	*December 2013*	*Lisbon, Portugal*			
17	*Conference*	*De Gaspari A., Ricci S. (POLIMI), Antunes A., Odaguil F., and Lima G. (EMB)*	*Application of Active Camber Morphing*	*13-17 January 2014*	*National Harbor, MD, USA*			

			Concept to a Regional Aircraft					
18	*Conference*	*Afonso F., Vale J., Lau F., and Suleman A. (IST)*	*Multidisciplinary Performance Based Optimization of Morphing Aircraft*	*13-17 January 2014*	*National Harbor, MD, USA*			
19	*Conference*	*Dale A. S., Cooper J. E., and Mosquera A. (UBRIS)*	*Topology Optimization & Experimental Validation of 0-υ Honeycomb for Adaptive Morphing Wing*	*13-17 January 2014*	*National Harbor, MD, USA*			
20	*Conference*	*De Gaspari A., and Ricci S. (POLIMI)*	*Application of the Active Camber Morphing Concept Based on Compliant Structures to a Regional Aircraft*	*9 March 2014*	*San Diego, CA, USA*			
21	*Conference*	*Yang J., Nangia R. N., Cooper J. E., and Simpson J. A. (UBRIS)*	*Optimization of Morphing Wings for Improved Environmental Performance*	*12-14 March 2014*	*Brussels, Belgium*			
22	*Conference*	*Yang J., Nangia R. N., Cooper J. E., and Simpson J. A. (UBRIS)*	*Optimization Framework for Design of Morphing Wings Greener Aviation*	*16-20 June 2014*	*Atlanta, GA, USA*			
23	*Conference*	*Cooper J. E. (UBRIS)*	*Exploiting aeroelastic designs for improved aircraft performance (Keynote)*	*30 June – 2 July 2014*	*Porto, Portugal*			
24	*Conference*	*Cooper J. E. (UBRIS)*	*From Blue Skies to Clean Skies – How Structural Dynamics and Uncertainty Quantification can*	*7-12 July 2014*	*Le Mans, France*			

			Benefit Future Aircraft Designs (Keynote)					
25	*Conference*	*Suleman A., Vale J., Afonso F., Lau F. P. (IST), Ricci S., De Gaspari A., Riccobene L., Cavagna L. (POLIMI), Cooper J., Lambert L., Wales C., Cheung R., Nangia R. (UBRIS), Rizzi A., Zhang M. (KTH), Monner H.-P., de Kamp B. V., Vasista S. (DLR), Moreli, M. (CSIR), Parizi J., Odaguil F., Lima G., and Antunes A. (EMB)*	*Novel Air Vehicle Configurations: From Fluttering Wings to Morphing Flight*	*20-25 July 2014*	*Barcelona, Spain*			
26	*Conference*	*Yang J., Nangia R. N., Cooper J. E., and Simpson J. A. (UBRIS)*	*Morphing Wings Designs for Enhancing Performance of Aircraft*	*22-24 July 2014*	*Bristol, UK*			
27	*Conference*	*Afonso F., Vale J., Lau F., and Suleman A. (IST)*	*Multidisciplinary Performance Based Optimization of Aircraft*	*8-11 September 2014*	*Lisbon, Portugal*			
28	*Conference*	*Vale J., Afonso F., Lau F., and Suleman A.(IST)*	*Performance Based MDO of a Regional Transport Aircraft with a Joined Wing Configuration*	*8-11 September 2014*	*Lisbon, Portugal*			
29	*Conference*	*Amândio L., Marta A., Afonso F., Vale J., and Suleman A. (IST)*	*Stochastic Optimization in Aircraft Design*	*8-11 September 2014*	*Lisbon, Portugal*			
30	*Conference*	*Vale J., Afonso F., Lau F., and Suleman A. (IST)*	*Performance Based MDO of a morphing Joined-Wing aircraft concept*	*6-8 October 2014*	*The Hague, The Netherlands*			
31	*Conference*	*De Gaspari A., Ricci S., and Riccobene L. (POLIMI)*	*Design, Manufacturing and Wind Tunnel Validation of an Active Camber Morphing*	*6-8 October 2014*	*The Hague, The Netherlands*			

			Wing Based on Compliant Structures					
32	*Workshop Special Session*	*IST, POLIMI, KTH, UBRIS, DLR, CSIR, EMB*	*NOVEMOR Special Session*	*27-29 October 2014*	*Aachen, Germany*			
33	*Flyer*	*IST, POLIMI, KTH, UBRIS, DLR, CSIR, EMB*	*NOVEMOR: Design, Build, Test, and Fly*	*27-29 October 2014*	*Aachen, Germany*			
34	*Workshop, NOVEMOR Session*	*De Gaspari A., Ricci S. (POLIMI), Antunes A., Odaguil F., Lima G. (EMB), and Morelli M. (CSIR)*	*Application of Morphing Camber Concept to a Regional Aircraft*	*27-29 October 2014*	*Aachen, Germany*			
35	*Workshop, NOVEMOR Session*	*Cooper J.E., Cheung R., Wales C., Lambert L., Dale A., and Yang J. (UBRIS)*	*Design and Experimental Validation of Morphing Wings*	*27-29 October 2014*	*Aachen, Germany*			
36	*Workshop, NOVEMOR Session*	*Vale J., Afonso F., Lau F., Suleman A. (IST), Antunes A., Odaguil F., Lima G., Parizi J. (EMB), and Cooper J.E. (UBRIS)*	*Multidisciplinary design optimization of novel and morphing aircraft configurations: computational studies and experimental validation*	*27-29 October 2014*	*Aachen, Germany*			
37	*Workshop, NOVEMOR Session*	*Zhang M., Rizzi A. (KTH), and Nangia R. (UBRIS)*	*Geometry Modeling, Parametrization and Meshing of Conventional and Joined-Wing Aircraft*	*27-29 October 2014*	*Aachen, Germany*			
38	*Workshop, NOVEMOR Session*	*Vasista S., Monner H. P. (DLR), De Gaspari A., and Ricci S. (POLIMI)*	*Morphing Leading Edges for a Wing and Wingtip Based on Compliant Structures*	*27-29 October 2014*	*Aachen, Germany*			
39	*Symposium*	*De Gaspari A., Ricci S., and Travaglini L. (POLIMI)*	*Aeroelastic analysis of a regional aircraft with morphing wing using PyPAD framework*	*25-27 November 2014*	*Toulouse, France*			
40	*Conference*	*Vale J., Afonso F., Lau F., and Suleman A.(IST)*	*Performance Based MDO of a Joined-Wing*	*5-9 January 2015*	*Kissimmee, FL, USA*			

			Regional Transport Aircraft					
41	Conference	De Gaspari A., Ricci S., Travaglini L., Cavagna L. (POLIMI), Antunes A., Odaguil F., and Lima G. (EMB)	Active Camber Morphing Wings Based on Compliant Structures: an Aeroelastic Assessment	5-9 January 2015	Kissimmee, FL, USA			
42	Conference	Vasista S., Riemenschneider J., and Monner H. P. (DLR)	Design and Testing of a Compliant Mechanism-based Demonstrator for a Droop-Nose Morphing Device	5-9 January 2015	Kissimmee, FL, USA			
43	Conference	Yang J., Sartor P, Cooper J. E., and Nangia R. K. (UBRIS)	Morphing Wing Design for Fixed Wing Aircraft	5-9 January 2015	Kissimmee, FL, USA			
44	Conference	Wales C., Cheung R., and Cooper J. E. (UBRIS)	Chiral Morphing Wing Tip Design and Test	5-9 January 2015	Kissimmee, FL, USA			
45	Conference	Lambert L., Cooper J. E., and Nangia R. K. (UBRIS)	Buckling Alleviation for Joined WingAircraft	5-9 January 2015	Kissimmee, FL, USA			
46	PhD Thesis	Afonso F.	Performance Based Multidisciplinary Design Optimization of Energy Efficient and Novel Aircraft Configurations	February 2015 (Draft)	Lisbon, Portugal			

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