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PROJECT FINAL REPORT

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[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

4.1 Final publishable summary report

4.1.1 Executive summary (< 1 page)

The MorphElle project aims to address the CO2-emissions and external noise targets outlined in Flightpath 2050 and the recently unveiled Strategic Research and Innovation Agenda (SRIA) outlined CO2-emissions and external noise targets. by exploring the potential multi-functional benefits afforded by active compliant systems technologies applied to the inlet and cowl (collectively known as “nacelle”) of an aircraft propulsion system.

Based on market analysis and projection techniques, a Y2025+ medium range reference aircraft is defined. Based on the derived dimensions, solutions for shape variable (morphing) nacelle components are developed taking into account structural, aerodynamic, and operational constraints. The best solution was identified in a formal down-selection process and developed in more detail.

The result is a morphing nacelle inlet lip, that is capable of changing its contour during flight. Most notably, it is able to change the lip bluntness (more round / more pointed) as well as the diameter of the inlet tip. This enables the nacelle to modify its shape for different flight conditions such as take-off and cruise. Notably, due to the deformation principle and the chosen materials, the system also features integrated lightning-strike protection and de-icing capabilities.

The concept is based on a series of pneumatically actuated tubes that are draped over a support structure, that is structurally similar to a conventional nacelle inlet lip. On top of the tubes, a strong, yet deformable skin material is placed. It is composed of an elastomeric skin that is reinforce using metal wire meshes and a flexible sandwich core. The main properties of this skin are a high in-plane tension stiffness and a low circumferential shear stiffness.

In order to define the target shapes for the morphing process as well as evaluate the potential benefits, a parametric CFD model has been created. Additionally, the impact on the perceived ground noise was calculated using aero-acoustic models. Based on the target shapes, the developed concept has been investigated and optimized by means of highly parametric multi-scale FEM simulations.

In parallel a hardware technology demonstrator was designed, built and tested. This test rig shows the general morphing capability of the concept. It is reduced in complexity in order to keep with in time and resource constraints but still illustrates all important aspects very well. The achieved contours in the test match those in the corresponding FEM simulations.

Finally, the overall estimated mass and aerodynamic performance are evaluated in order to produce first estimations of the potential benefits of such a morphing inlet lip. Due to preliminary nature of this study, the resulting range of possible benefits is still relatively large but the technology shows significant potential. The influence on the external noise was smaller than anticipated. Promising system modifications to ameliorate this have been proposed. The aerodynamic benefits were more promising: in the best case, a MTOW reduction of 1,8% and a block fuel reduction of 5% compared to the reference aircraft could be achieved. The exact quantification is up for future investigations.

4.1.2 project context and main objectives

The objectives declared by the Advisory Council for Aeronautics Research in Europe (ACARE) Vision 2020 [22] with 80% and 50% reduction in nitrous oxide (NOx) and carbon dioxide (CO2) emissions, respectively, have been adopted by the European Union (EU) research community at large for over a decade now, the EU with its so-called "Flightpath 2050" agenda [23] stipulates a reduction of 90% in NOx, and of 75% in CO2 emissions. All quoted values are relative to the capabilities of typical aircraft in-service during year 2000. The ACARE Vision 2020 and EU Flightpath 2050 goals are not unique. As presented in Figure 1, from an international perspective one can compare and contrast the EU objectives to those espoused by International Air Transport Association [24], International Civil Aviation Organization [25] and the US National Aeronautics and Space Administration [26].

Contribution of Propulsion Systems in the Future

After expending a collective effort spanning mid-2011 until mid-2012 ACARE unveiled a new Strategic Research and Innovation Agenda [27]. The assorted targets for CO2-emissions as originally defined in Vision 2020, AGAPE 2020 [28] and SRIA 2020 were categorized into airframe, propulsion and power, Air Traffic Management (ATM) and airline operations. The SRIA goals have been re-calibrated to reflect the achievements assessed by the AGAPE report and a new medium-term goal for entry-into-service (EIS) year 2035 which is a significant point for aircraft fleet renewal has been defined

Converting these energy efficiencies into an array of constituent contributions that are expected to realize a total 60% reduction in fuel burn and CO2 per passenger.km for target EIS of 2035, SRIA 2035 stipulates contributions of 25% propulsion and power, 25% from airframe, 7% from improved ATM and 3% from operational efficiency. If one extends beyond in order to consider a plausible strategy for Flightpath 2050, according to SRIA 2050 a possible breakdown for the total 75% reduction in CO2 emissions would be 68% from advanced propulsion systems and airframe, and, the remaining 7% from improvements through ATM and operations. Examining the potential for airframes this reduction in fuel burn and CO2 needs to have associated with it the adoption of innovative and high-risk aircraft morphologies (configurations), including novel materials, and, component technologies like flow control devices and various adaptive [morphing] systems applied to lifting surfaces only. SRIA 2050 does not partition contributions between airframe and propulsion, and, published studies indicate growing evidence that the improvement due to airframe will not be better than around 25% [29][30][31], which means this shortfall needs to be recovered by some other means: if one focuses on propulsion and power systems the target becomes something like 43% in this respect, which is synonymous with the overall CO2 reduction objective stated in SRIA 2020.

Potential of adaptive nacelle techniques

Serious consideration has not been hitherto given to the potential multi-functional benefits afforded by Active Compliant Systems technologies applied to the inlet and cowl (collectively known as "nacelle"). Targeting a service entry year of 2025+, the MorphElle Project aims to address this aspect, and thus, would constitute a body of investigative work that will serve to complement encouraging efforts expended in other projects. This project will undertake the task of designing an adaptive nacelle concept suited to advanced propulsion ideas and shall qualify numerical experimental work by performing tests on a mechanical test rig. Finally, potential benefits and risks will be produced and an initial roadmap for resolving the most important issues for implementation shall be communicated. The MorphElle Consortium benefits from a Joint Technical Advisory Committee (JTAC) comprising 10 members: SAFRAN Aircelle, MTU, Airbus, EADS, Alenia Aermacchi, Rolls-Royce Deutschland, ONERA, DLR and CNRS – FEMTO-ST Besançon. The MorphElle Project has the vision of investigating ground-breaking technologies to provide a means of physical shape change such that adaptive compliant nacelle systems make a noticeable contribution in reaching the emissions and noise reduction targets beyond year 2025.

Technical Objectives

The global objectives of the MorphElle Project is to utilise ground-breaking adaptive structures technologies applied to the nacelle in order to bring about a dual set of reductions: CO_2-emissions and perceived noise of future propulsion systems. A breakdown of the targets is itemised as:

- The **CO_2-emission reduction target of 3-5%** is to be accomplished through optimization of engine performance and reduction in both installed nacelle and general airframe drag according to **designated point design**, and more importantly, **during off-design operating points**. Compatibility of the adaptive technologies to be examined in this project will be established according to UHOPR and UHBPR solutions produced for past and current ongoing projects like FP5 EEFAE, FP6 VITAL, FP6 NEWAC, FP7 DREAM, FP7 LEMCOTEC, FP7 E-BREAK and the proposed FP7 ENOVAL.
- A target **engine noise reduction of 2.0 EPNdB on fan noise source** will allow the possibility of achieving a cumulative reduction of over 11.0 EPNdB (including the achievements of SILENCER, VITAL, DREAM and OPENAIR and ENOVAL), thereby allowing for fulfilment of ACARE Vision 2020/SRIA 2020.

The MorphElle Project fuel burn and noise objectives are targeted via a two-pronged approach. The first involves consideration of geometric design variables whereupon a pre-design study of different alternatives for integrating multiple instances of Single Degree-of-Freedom (S-DoF) and Multiple-Degrees-of-Freedom (M-DoF) technologies will be conducted for purposes of evaluation and subsequent matching with adaptive systems candidates.

Multi-disciplinary numerical experimentation utilising quasi-analytical and variable fidelity methods for aerodynamics, aero-acoustics, structures, actuators and engine performance analyses will constitute the basis for evaluating the extent of functional sensitivity (strong, moderate or weak) against four objectives. The four objectives will include: (1) Aerodynamics; (2) Aero-acoustics; (3) Engine Performance; and, (4) Ancillary Functions.

The aerodynamics related studies will involve considerations given to:

- Avoidance of separated flows via active inlet lip and cowl contouring
- Manipulation of cowl contours, slenderness and inlet airfoils to promote increased laminar flow
- Suppression of compressibility effects through active cowl contouring and variable contraction ratio
- Reduction of spillage drag through active inlet area ratio system

The aero-acoustics related studies will involve considerations given to:

- Active [negative] scarfing control
- Choice of novel compliant material and topological definition that will serve as acoustic lining as well
- Inlet lip geometry manipulation for low-speed operations
- Alteration of inlet slenderness and internal contouring

- Active closure rate of fan plume

The engine performance related studies will involve considerations given to:

- Flow straightening to reduce distortion through inlet slenderness and internal contouring
- Internal contouring to maximize inlet pressure recovery
- Upper lip augmentation to improve windmill condition
- Avoid surge during operation via internal contouring and lower inlet lip alteration
- Improved performance at angle of attack and sideslip through variable internal lip contraction
- Customized inlet radial tailoring for cross-wind performance
- Inlet face planar tilt to align according to freestream

The ancillary related studies will involve considerations given to:

- Shield against FOD through lower inlet lip augmentation and inlet slenderness
- Active de-icing/expulsion of ice accretion via inlet aerofoil manipulation and exterior nacelle contouring
- Examine additional degrees of freedom w.r.t. accessories mounted inside nacelle and thrust reverser options

Approaching the problem initially from a non-hierarchic perspective, a coherent and rational method allows one to address questions like how many DoF would be of interest and what combinations of DoF would generate a best and balanced design outcome for a given objective function target and level of technical risk.

Once these influential geometric design variables have been identified, and leading candidates for S-DoF and M-DoF strategies have been devised an integrated adaptive nacelle concept shall be procured using the multi-disciplinary numerical experimentation techniques discussed earlier.

Finally, as a means of producing evidence to support initial feasibility and emerging practicality of various component technologies associated with materials and actuation considered in the MorphElle Project, a scaled adaptive nacelle test rig will be undertaken. The mechanical test rig artefact shall represent the forward underside portion of a selected state-of-the-art baseline concept.

4.1.3 main S&T results and foregrounds

Requirements, Standards and Initial Exploration

For the introduction of morphing nacelle technology into the commercial air transport market, the twin-engine wide-body aircraft market segment was considered most promising since medium-to-long application is expected to particularly benefit from improved efficiency and the resulting cascade effects of propulsion system and aircraft design. In order to reflect in-service year 2000 systems an Airbus A330-300 [1] type aircraft was selected.

As the year 2000 reference power plant system the General Electric CF6, type CF6-80E1A2 [2], powering the for the A330-300 was chosen. The power plant features a 2-spool boosted direct drive turbofan architecture, and, a short duct separate flow nacelle design.

For the definition of the year 2025+ projected technology reference (R2025+) system, an appropriate set of Aircraft Top-Level Requirements (ATLeRs) was established based on forecasted market grow rates and seat movements per region using References 4-11. The accordingly identified best and balanced payload-range capability for the year 2025+ reference system features 340 PAX including baggage at 4800nm range as can be seen in Figure 1.

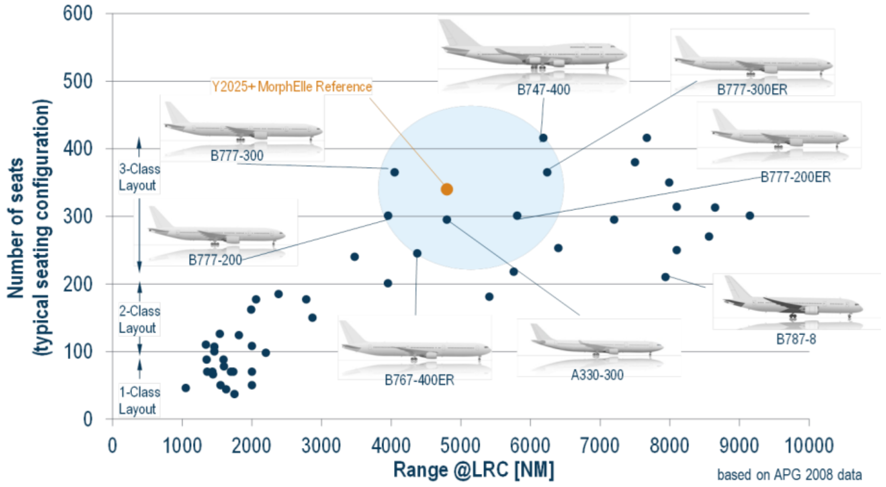

Figure 1: Payload-range capacity of year 2025+ reference aircraft

The R2025+ aircraft features both advanced airframe aerodynamic and structural, as well as power plant system technology according to the targeted Entry-into-Service. The R2025+ propulsion system features a 2-spool boosted geared turbofan architecture, and, a short duct separate flow nacelle design. The power plant design features a Bypass Ratio of 18, and, 20% reduction in Thrust Specific Fuel Consumption (TSFC) during cruise compared to the Y2000 power plant. A comparative synopsis of basic properties of all three reference power plant systems is given in Table 1.

Table 1: Comparative synopsis of Y2000, Y2010 and Y2025+ reference propulsion systems

	Y2000 Reference	**Y2025+ Reference**
Architecture	2-spool, direct-drive turbofan	2-spool, geared turbofan
Stage Configuration	1-4-14-B-2-5	1-G-3-9-B-2-4
Nacelle Configuration	Short Duct Separate Flow	Short Duct Separate Flow
Fan Diameter	2.438 m	3.300 m
Engine Bypass Ratio	5	18
Cruise Spec. Fuel Consumption*	base	–20 %

Both reference aircraft systems were mapping through an integrated aircraft sizing and performance model based on in-house methods and expertise using the commercial software Pacelab APD3.0 [3]. Propulsion performance was computed using the gas turbine simulation software GasTurb11™ [4]. The reference system definition included basic nacelle shaping and dimensions (acc. to [5][6]), as well as, performance evaluation at flow path sizing (i.e. top-of climb), typical cruise and take-off conditions for all three reference power plant systems. The developed models for aircraft and power plant sizing and performance were validated against published data [1][2][7]. The R2025+ system served as a baseline for adaptive nacelle system-level assessment and technology benchmarking in MorphElle Task 3.4. Therefore, appropriate evaluation procedures including meaningful figures of merit, as well as, a consistent thrust/drag book-keeping scheme [8] were introduced. As a comprehensive information basis, two volumes of reference system definition reports (Vol. I & II) were issued to the MorphElle consortium.

Initial Multi-Disciplinary Numerical Experimentation

Evaluation of morphing structure concepts based on pneumatics and cellular configurations

As a part of WP1 and WP2 several concepts involving combinations of pneumatic actuation and cellular structures configurations have been evaluated for the structural morphing of the inlet during the reporting period M1-M12. The starting baseline technology that has been adopted as inspiration was the “smart stick” actuator concept, that biomimics the deformation mechanism of the spider leg [13] (rigid modules put in angular deformation by inflatable tubes under differential pressure). Smart stick-inspired prototypes have been produced and modelled with Finite Element approaches to verify the design envelope and feasibility of using within a morphing aeroengine nacelle configuration (Figure 2).

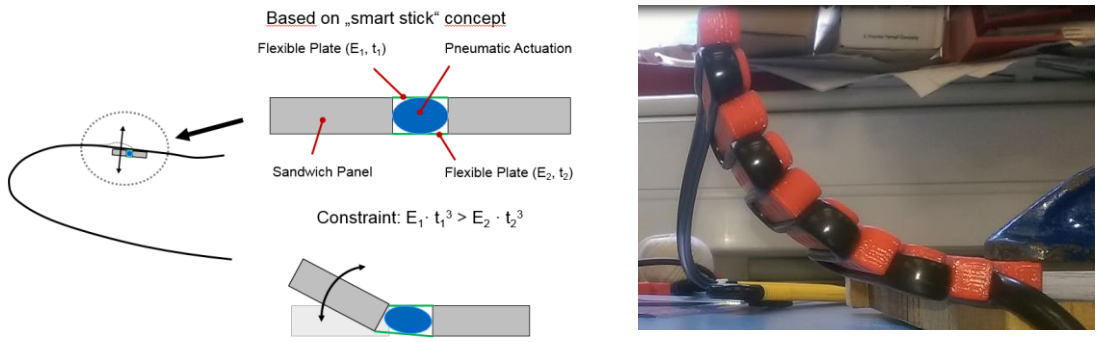

Figure 2: Smart-stick concept for the morphing of the nacelle lip, and prototype developed for the feasibility study

Another concept that that has been evaluated is the rotating tube concept inspired to chiral structures, to provide the creation of an internal circumferential shape change to the inner part of the nacelle inlet (Figure 2). The concept has been evaluated though linear and nonlinear FE modelling, showing that the actuation authority of the system is not sufficient to provide the shape change necessary for the change in pressure recovery required from the CFD simulations.

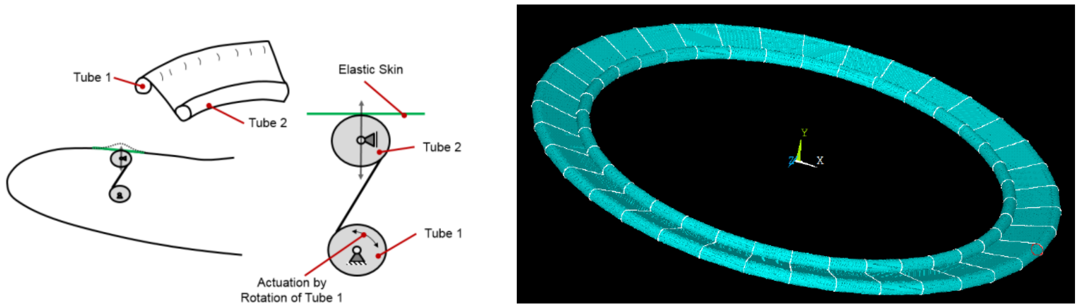

Figure 3: Rotating chiral cylinders deformation mechanism and its annular configuration

Another concept explored within the project is the variable thickness honeycomb through pneumatics actuation (Figure 3). In this design a honeycomb structure embedded by a flexible inflatable tube within a porous material matrix is able to provide a shape change in thickness of an airfoil, and therefore is able in principle to change the thickness of an inlet cross section. The concept has been explored using analytical, Finite Element and experimental tests on small-scale prototypes, showing a significant promise in terms of thickness change of an airfoil. One of the most interesting aspects (the pneumatic actuation provided to a cellular core for an acoustic liner) has then been considered as a potential solution for the morphing nacelle configuration.

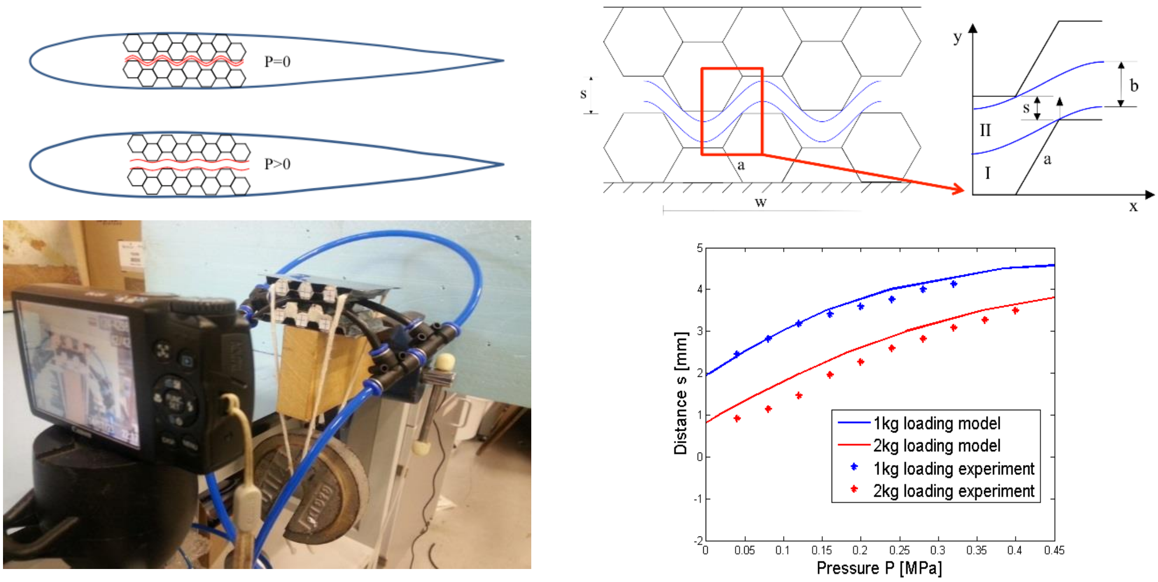

Figure 4: Morphing thickness airfoil concept for shape change of an inlet cross-section

It is worth noticing that the pneumatics and morphing concepts developed for the smart stick and morphing thickness airfoil could be used also for the morphing of other surfaces, like wingtips and wingbox systems. Two papers have been published to this regard ([14] and [15]), and they can be considered another MorphElle contribution to the morphing field.

Cellular skin designs

To make an effective morphing skin for a nacelle inlet new shear-type and membrane morphing cellular configurations have been explored using analytical, FE and also experimental tests. The skins however show promise more for blade-type or more conventional aerofoil configurations, and the metal shear mesh used in MorphElle has revealed to be the most appropriate choice for the morphing nacelle structures. The studies conducted on these new skins have however produced two journal papers ([16][17]), and they can be considered another contribution of the MorphElle project to the world of morphing structures.

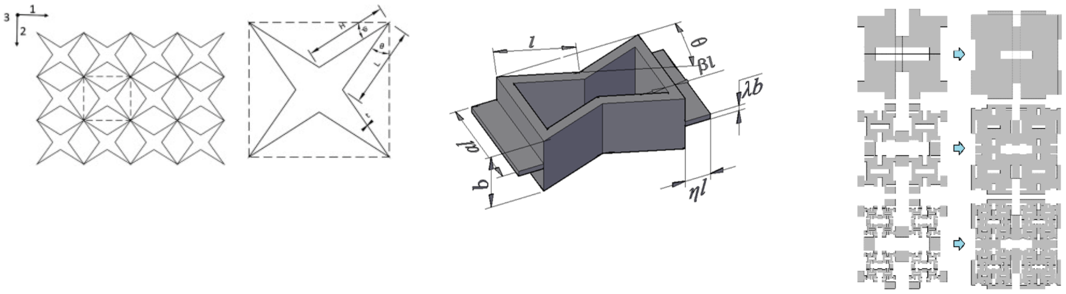

Figure 5: Designs of 2D morphing, bending and multiscale perforated cellular skins

Propulsion System Performance and Operations Axes

In order to allow for the consistent assessment of power plant performance characteristics and fuel efficiency at the relevant operating conditions integrated propulsion system conceptual sizing and performance models were prepared using GasTurb11™. Therefore, a comprehensive set of in-house developed heuristics for flow path design and operational tailoring [5] was incorporated in the simulation process. Model for basic intake characteristics such as pressure recovery and additive drag were developed based on References 18-21. The integrated power plant models were parameterised to facilitate a system-level assessment of nacelle shape morphing implications such as variations in intake pressure recovery, intake spillage drag, and, fan polytropic efficiency. Using the year 2025+ power plant system as a baseline, initial sensitivity studies for characteristic power plant properties were performed in flow path design and selected off-design operating conditions, in order to lay the ground for the identification of the improvement potentials for adaptive nacelle technologies. The obtained results were shared with the MorphElle project partners for information purposes.

Multi-disciplinary Interfacing and Test Campaign

Down-selection and Concept Freeze

Together with TUM, an overview of characterised technology concepts, so-called “concept cloud” was compiled based on the results obtained from MorphElle Concept Workshop organised by TUM on 10 July 2014. The concept cloud comprised 7 concept candidates for qualitative down-selection as shown in Figure 6.

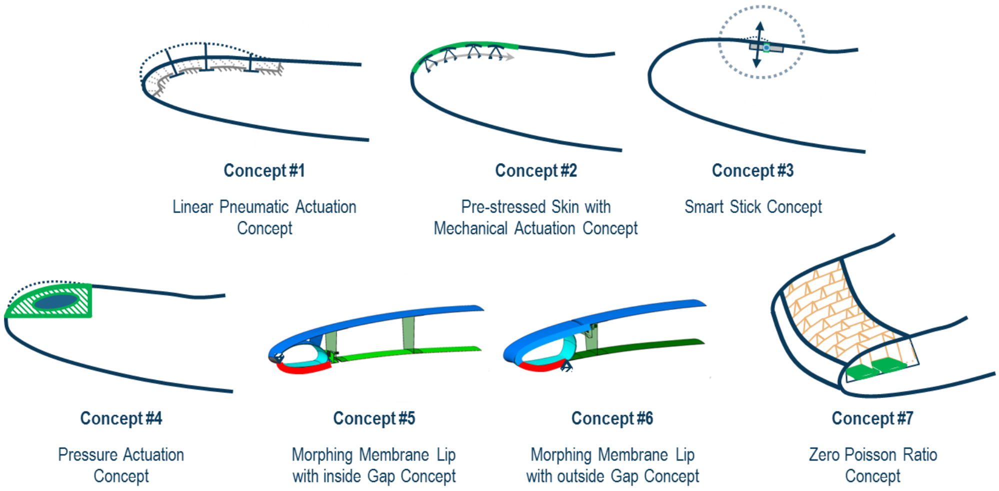

Figure 6: Overview of concept cloud considered during down-selection

In order to facilitate transparent concept down-selection and the robust identification of a most promising concept candidate for further elaboration, a well-structured of process was formulated and prepared. The process was founded on qualitative concept performance rating through expert questionnaire, maturity assessment, and, concept robustness gauge. Therefore, a comprehensive set of qualitative concept evaluation criteria was defined, covering four main categories:

- the improvement of system integration;
- the improvement of cruise performance (i.e. high-speed, high-altitude operation);
- the improvement of take-off performance (i.e. low-speed, high angle-of-attack); as well as,
- the reduction of system weight.

These four categories were assigned identical weightings, and, included a total number of 18 multi-disciplinary criteria. The definition of criteria was performed mindfully of crucial aspects for the planned, subsequent numerical and physical experimentation and multi-disciplinary design optimisation. Important evaluation aspects such as noise and NOx emissions were incorporated in the take-off, i.e. low-speed, low-altitude, performance category.

For the rating of concepts, an expert workshop was prepared and hosted by BHL on 3 November 2014 under participation of all MorphElle project partners. Individual concept ratings were given via consensus expert decision after the dialectic discussion of crucial effects and implications. The rating process was moderated by BHL. The robustness of concept down-selection was gauged through systematic permutation of criteria weightings, and, concept maturity was evaluated based on the expected likelihood success and the effort required to reach target technology readiness level (TRL) 6. The down-selection workshop including the concept rating results, maturity assessment and robustness analysis was documented and issued to the MorphElle consortium. A compact visualisation of the down-selection results is presented in Figure 7.

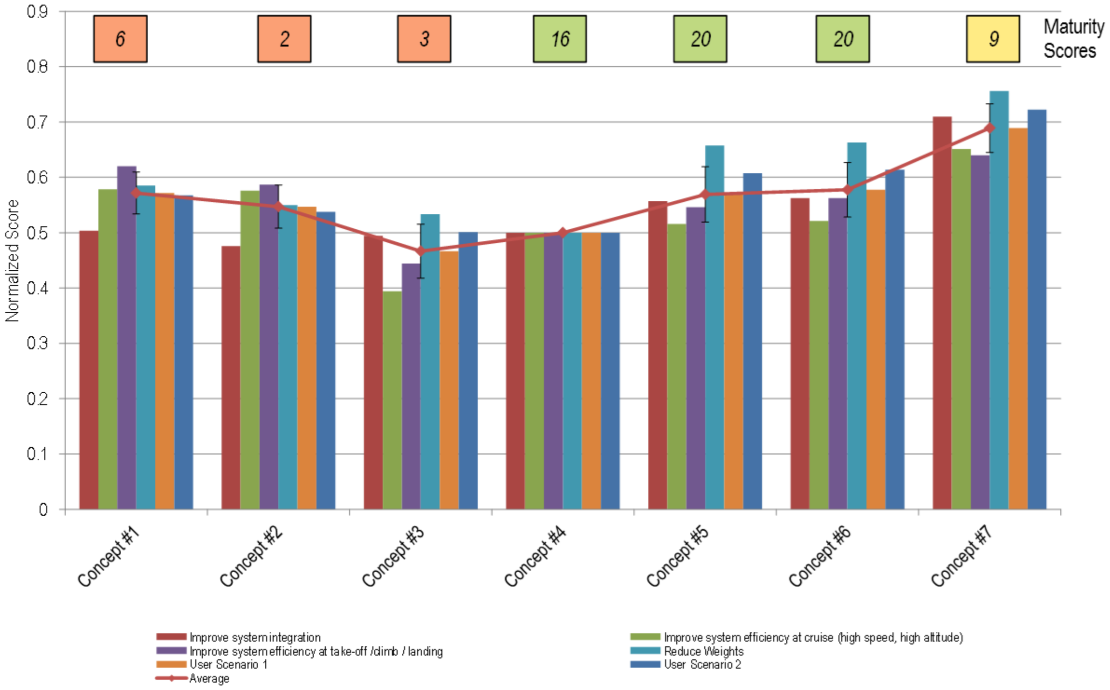

Figure 7: Synopsis of down-selection scoring results including robustness analysis

<u>Description of the consolidated Morphing Nacelle Lip Concept</u>

Based on Concept #7, the result of the down-selection process, the following morphing nacelle lip concept has been developed. An overview of the structural concept is given in Figure 8. The Concept is based on an aluminum support structure, that is relatively similar to the original nacelle

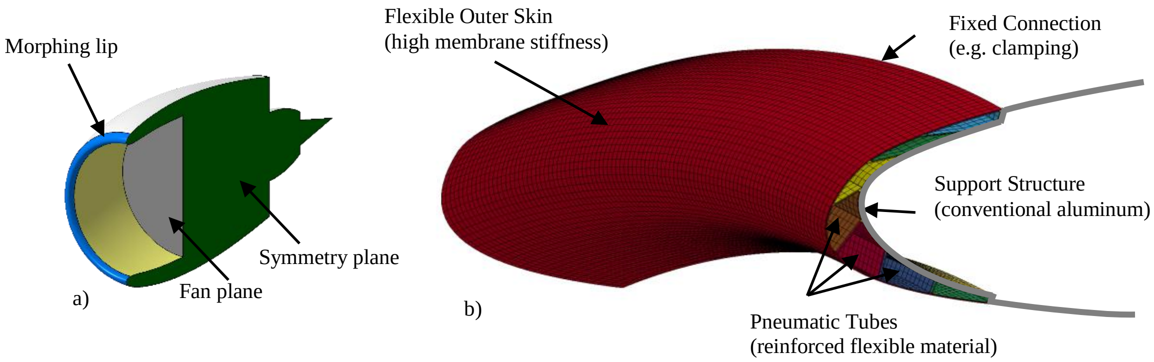

Figure 8. Pneumatically actuated morphing inlet of nacelle. Overview (a) and detail (b)

lip. This support structure is covered by a series of deformable but reinforced tubes, similar to a fire hose. The tubes are covered by an external skin that has a high membrane stiffness. This allows to modify the external contour by variation of the pressure distribution in the various tubes.

Compared to the baseline design from the down-selection process, it is most notable that this concept extends around the entire lip, greatly increasing the morphing degrees of freedom. Additionaly, this extension solves the initial conflict regarding strain in the skin. With this improved design, it is possible to achieve large shape variations without changing the length of the skin contour, i.e. without requiring displacement of the attachment points or alternatively large strains in the skin.

Concept components and materials

A major challenge that separates this type of aerodynamic contour morphing from 2D airfoils is the circular nature of the nacelle inlet lip which requires 3D morphing capabilities in order to accommodate significant circumferential skin strains. The skin is required to have a high in-plane tension stiffness to provide an accurate shape even under external pressure influence, but it must have a low in-plane shear stiffness and a moderate bending stiffness in order to achieve the required morphing capabilities. To be more exact, the skin shear deformation is in this case defined as a strain deformation in circumferential direction, as illustrated in Figure 10.

The outer skin consists of a steel wire mesh that is reinforced with an elastomeric matrix. The detailed product data are given in Table 2 and Table 3.

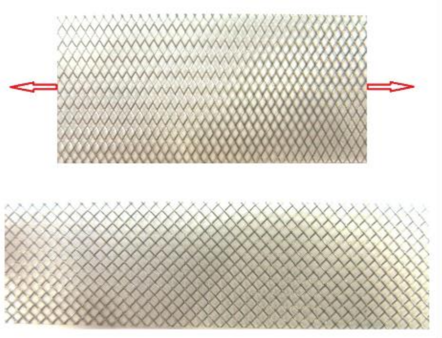

Figure 9: small demonstrator of the skin material (metal wire mesh with silicone matrix)

Table 2: Metal mesh material data

	Scaled Demonstrator	*Full Scale Morphing Lip*
Supplier	Spörl KG[3]	Spörl KG
Product	Square mesh weave	Square mesh weave
Aperture size (w, mm)	0.8	4.0
Wire diameter (d, mm)	0.2	1.4
Yield strength (N/cm)	110	1000
Open mesh area (A0, %)	64	55
Material	Steel DIN 1.4301	Steel DIN 1.4301

Table 3: Elastomeric matrix material data

	Silicone	*Thermoplastic PU*
Supplier	Altropol	Estane
Product	RTV23 / A7	58271
Shore A hardness	20	85

Both the silicone and the TPU matrix , combined with the orthogonal metal wire mesh can potentially fulfil all requirements for the external skin. These are in more detail:

- Structural:
    - High membrane stiffness and strength

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[3] Sigmaringendorf, Germany

    - Low in-plane stiffness in circumferential direction
    - Low bending stiffness
- Environmental:
    - Operating temperature range (-55°C / 80°C)
    - Ice build-up
    - Lightning strike resistance
    - FOD resistance, bird strike mechanical robustness

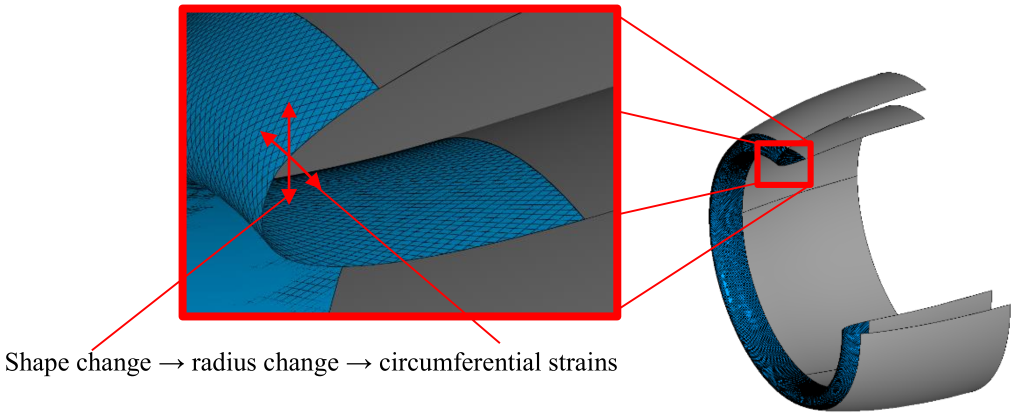


Figure 10: skin reinforcement orientation, illustration of circumferential strains

Especially the lightning strike resistance is of interest here, since it is not necessary to add additional meshes purely for this purpose, as seen on other composite aircraft components.

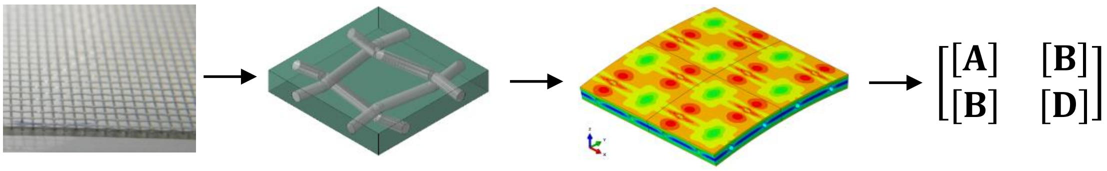
Due to the large shape change capabilities, the deformation can potentially also be used for de-icing of the nacelle inlet by performing one or more actuation cycles in flight. The accompanying aerodynamic effects will be temporary and have to be anticipated accordingly.

As an alternative to the metal wire mesh, “conventional” biaxial fiber weaves with an elastomeric matrix would be an alternative, provided the fiber volume fraction is not too high. In that case, they could show sufficient shear deformability for the use case at hand. This has been investigated by Datashvili et.al.[19][20].

Furthermore, deformable but reinforced tubes are required, that allow the application of different internal static pressure levels to different tubes. The difference between internal and external pressures determines the curvature of the outer skin, which acts as a membrane. Higher internal pressures lead to lower curvatures. The typical pressure ranges used in this study are between 1 and 15 bars. The lower limit of 1 bar has been chosen to always have a significant positive differential pressure. These tubes can be thought of as very similar to fire hoses. They consist of a fiber weave, potentially glass or aramid fibers due to their mechanical robustness, reinforced with an elastomeric matrix for air-tightness and flexibility.

Modeling and Simulation

In order to investigate the model behaviour and perform design opitimizations, several FEM models have been created on multiple geometric scales and with varying modelling fidelity. On the micromechanical scale, a representative unit cell (RUC) model of the skin has been created.



$$\begin{bmatrix} [\mathbf{A}] & [\mathbf{B}] \\ [\mathbf{B}] & [\mathbf{D}] \end{bmatrix}$$

Skin parameters:

- Materials
- Wire diameter
- Wire distance

Micro-mechanical high fidelity unit cell FEM model

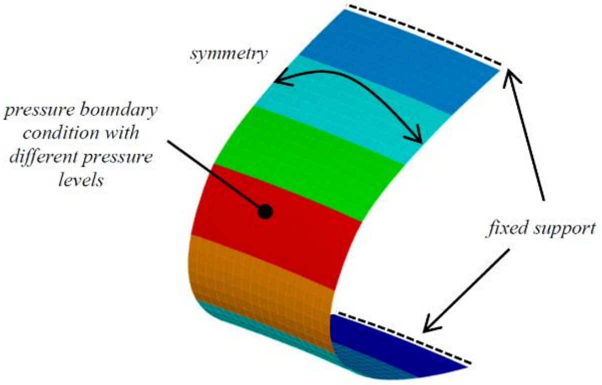
Homogenized stiffness matrix for use in larger scale simulations

Figure 11. Micromechanical model for wire reinforced flexible matrix and macro scale stiffness to be used in structural analysis

By applying six unit deformations to this RUC (3 x in plane, 3 x out of plane) and evaluating the resulting reaction forces, the homogenized stiffness matrix (ABD matrix) can be derived, using the virtual work method (see [21]). This stiffness matrix is used in larger scale models in order to reduce computational effort while still accurately representing the mechanical properties of the skin.
Using this skin model, two large scale simulations are set up.

Low Fidelity Morphing Lip Model and Numerical Optimization

Using the aforementioned homogenized stiffness representation of the outer morphing skin as the basic building block, a simple, yet accurate and meaningful FEM model is created. The setup is outlined in Figure 12. It represents an angular section of the entire lip that is coupled using cyclic symmetric boundary conditions. Both ends of the outer skin are fixed in place.



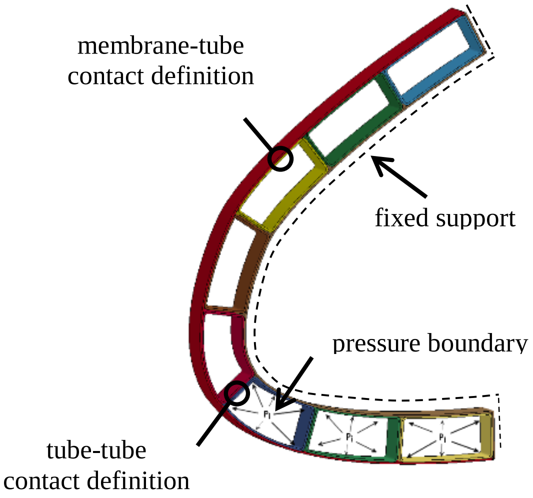
Model type	3D (angular section), shells
Boundary conditions	Cyclic symmetric Constant pressure on skin Fixed support at edges
Solver	Ansys (implicit nonlinear)
Pre & Postprocessing	Ansys
Modeling (Tubes)	Constant pressure regions
Modeling (Outer Skin)	ABD material model
Used for	quick analyses and parametric studies, numerical optimization

Figure 12: Setup of the low fidelity morphing lip FEM model

The inner tubes are not explicitly modelled, but represented as different pressures that are applied to the inside of the membrane. These zones are highlighted using colors in the figure. By defining the applied tube pressures as static pressures on the inside of the membrane and solving the problem using a geometrically nonlinear solver (in this case: ANSYS), the resulting contours can be calculated. The computational cost of such a solution is relatively low. Therefore, it is feasible to perform extended parameter studies and numerical optimization processes.

High Fidelity Morphing Lip Model and Detailed Design

For further design purposes, a more detailed FEM model is developed, that also takes into account the pressure tubes, the support structure, and the contact conditions between these. The setup of this model is illustrated in Figure 13. Due to the greatly increased solution complexity, mostly caused by numerous contact conditions, the evaluation of such a model has a higher computational cost. It is therefore not directly suited for numerical optimization, but more for the detailed design process. In this case, the solution is calculated using LS-Dyna, an FEM solver that uses explicit time integration. It is typically intended for high speed load cases such as crash simulations, but in can be used for quasi-static simulations as well, given the correct choice of solver parameters. Mainly, this requires a comparatively high system damping, which causes a quick decay of oscillations in order to get a converged solution.



Model type	**3D (angular section), shells**
Boundary conditions	- Cyclic symmetric - Constant pressure inside tubes - Fixed support at edges - Contact between all parts
Solver	LS-Dyna (explicit nonlinear)
Pre & Postprocessing	Ansys
Modeling (Tubes)	Membrane elements
Modeling (Outer Skin)	ABD material model

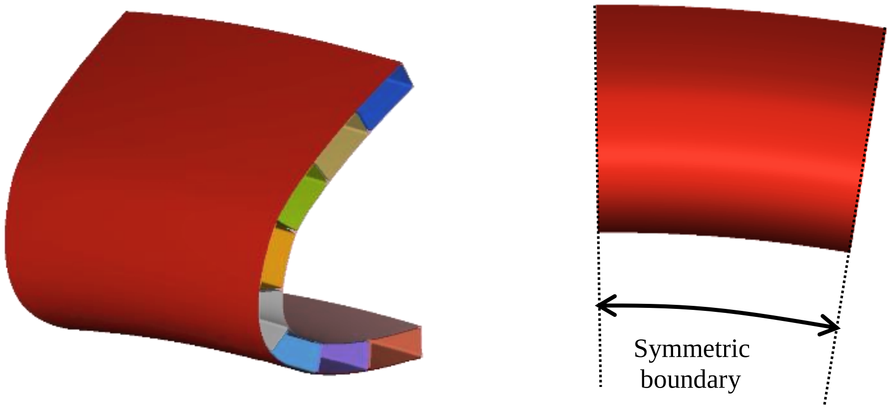


Figure 13: Setup of the high fidelity FEM model used for the detailed design process

The simulations performed using this model also greatly contributed to the final design of the support structure. As opposed to its initial design seen in Figure 13, the later iterations of the support structure are already adapted to the goal design. This is required, since only a limited diameter increase can be achieved for each tube, before it reaches its maximal diameter in a circular shape. This is best illustrated in Figure 14, which shows the initial simulation model as well as the cruise and take-off optimized contours.

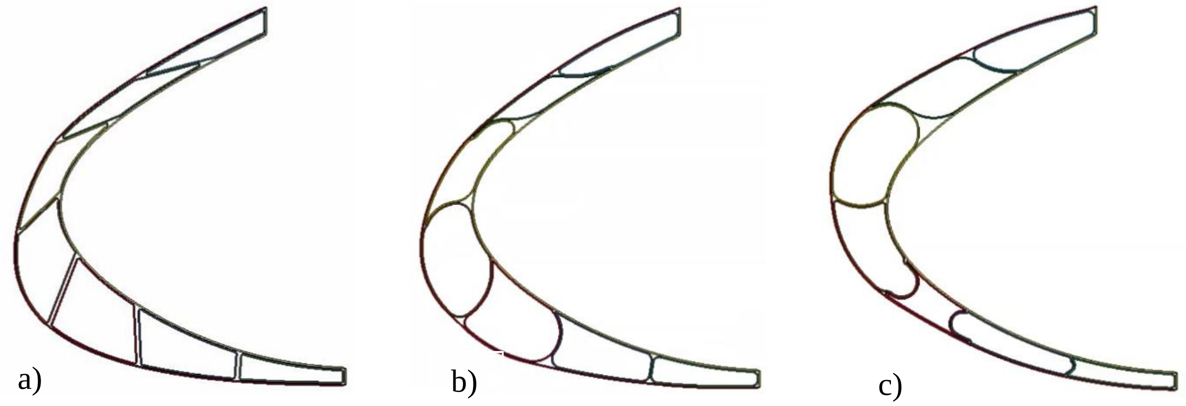


Figure 14: Initial simulation model (a), cruise optimized contour (b), take-off optimized contour (c)

This illustrates the comparatively large deformations that can be achieved using this approach. The basic mechanics of the morphing concept can be well observed. Tubes with a high actuation pressure tend to take a rounder shape, causing a high outer surface curvature. Lower pressure tubes are compressed by the surrounding structure, which cause a more flat, lower curvature external skin. In any case however, the external skin remains convex (seen from the outside), which is a main constraint of this concept. Concave section of the skin are not possible in any morphed configuration.

Influence of external aerodynamic pressure

The shown morphing lip concept features no feedback shape control, it is assumed that the resulting contours are known within an acceptable margin for each given pressure distribution. In order to validate this approach simulations have been carried out, that apply the external aerodynamic pressure to the default contour in the low fidelity FEM model. The simulation setup is shown in Figure 15. The external differential pressure in this simulation is in the range of [-0.067 MPa ~ 0.0124 MPa] while the internal pressures in the actuation tubes are in the range of [0.1 MPa ~ 1.5 MPa]. The results of the simulation show a RMS difference of $RMS < 0.5\, mm$, which can not be seen in a plot. It can therefore be said, that the assumption of a mostly invariant contour with regards to the external aerodynamic pressure is valid. For future studies, it can be investigated further, which internal absolute pressure values are actually necessary to define a given shape in flight in a stable manner. It has to be noted, that dynamic instabilities such as flutter are not considered here. This would require a fully coupled Fluid-Structure-Interaction model with coupled FEM and CFD models, which was out of the scope of this study.

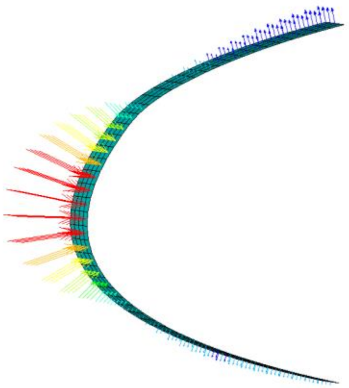


Figure 15: Aerodynamic pressure for the cruise condition applied to FEM model

Resulting Design Range for the Morphing Nacelle Lip, Design variant

The previously presented concept is merely one possibility of possible designs that can be based on this design principle The beginning and end of the morphing contour (as opposed to the

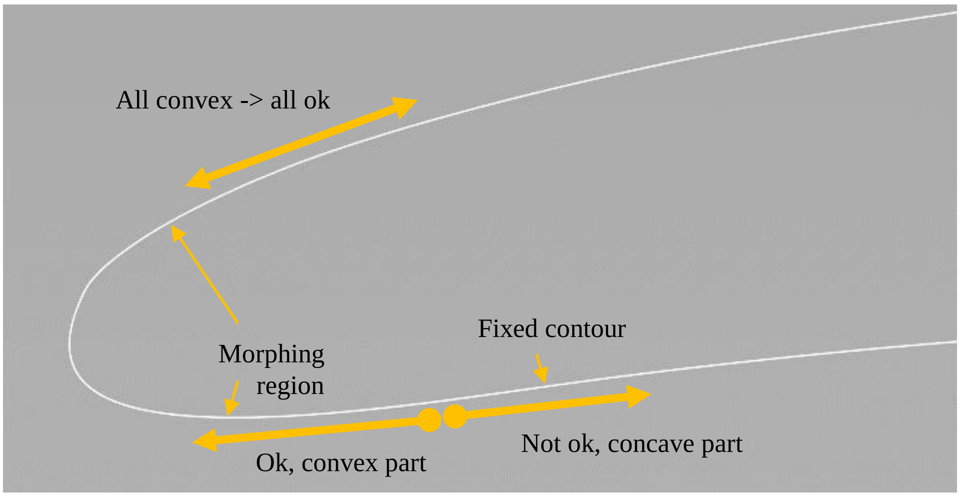


Figure 16: Design constraint: Only convex contour sections

conventional, fixed parts of the nacelle) can be moved along the contour with a major constraint: Since all parts of the outer skin need to be under pressure at all times, the outer skin can only achieve convex contours. This is further illustrated in Figure 16.

The second constraint for achievable contours is the length of the outer skin, which needs to remain constant (disregarding limited elastic strain), since both ends of the morphing skin are clamped and no displacement is allowed.

A possible modification of the concept may circumvent this requirement, as shown in Figure 17. One of the two attachment points could be made movable. This could be implemented by attaching the inner edge of the morphing lip to a movable ring around the entire inner contour of the nacelle. Such a displaceable ring would introduce gaps, which would have to be covered in a suitable way. Once this obstacle is overcome, this may allow further morphing degrees of freedom. Lip extension at the top edge and retraction at the lower edge would result in a modification of the scarfing angle. This could also be used for adapting the nacelle inlet to cross-winds by extending / retracting on the left / right edge of the nacelle lip.

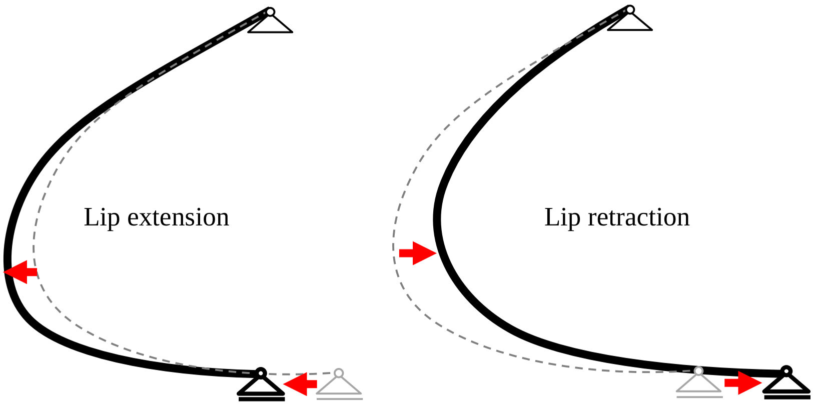


Figure 17: Potential further modification of the morphing lip: lip extension and retraction

Numerical investigation of morphing leading edge concept

The investigation is concentrated on the adaptable leading edge of the inlet presented in Figure 18. The adaptable contour has six movable knots (P1 – P6) and at two fixed knots. The contour had to fulfil two criterions, the constant contour length and convex curvature of the contour. The process of contour adaptation was performed in two steps. In the first step, the knots P2 and P3 were moved in order to attain certain shape, while other knots were kept fixed. In the second step the knots P5 and P6 were moved in order to attain original contour length.

The performance and shapes of the nacelle adaptations were compared with reference contour. The reference contour was selected as a best guess contour. In the frame of the project there was no available contour from the recent real engine nacelle and there was neither resources for the performance of optimization. The aim of the simulations was to investigate the effect and performance of the limited leading edge adaptations.

Aerodynamic performance

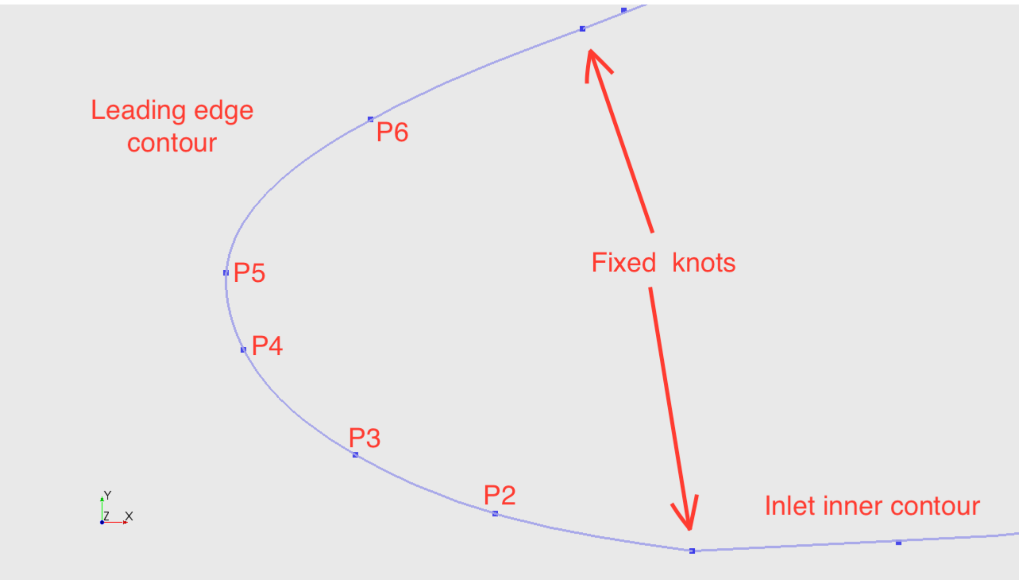


Figure 18 Adaptable leading edge knot positions

Aerodynamic performance of the adaptable nacelle concept was primary evaluated using the total pressure recovery

$$\eta = \frac{\bar{p}_{T_{\mathrm{FAN}}}}{\bar{p}_{T\infty}} \ ,$$

where $\bar{p}_{T_{FAN}}$ and $\bar{p}_{T_\infty}$ are surface averaged total pressures at the fan plane and free stream, respectively. Among other parameters monitored during the aerodynamic simulations the drag coefficient referenced on the frontal area of the fan plane and DC60 parameter [12] were monitored. DC60 parameter was calculated with following equation

$$\mathrm{DC60} = \frac{\bar{p}_{T_{\mathrm{FAN}}} - \bar{p}_{T_{60}}}{\bar{q}} \cdot 100\%$$

where $\bar{p}_{T_{60}}$ is minimum surface averaged total pressure of all fan sectors of 60° extent and q is dynamic pressure of the free stream. The aerodynamic performance of nacelle was investigated for three flight conditions, take-off, cruise and climb.

Take-off condition

In Figure 19 the comparison of the reference contour and contour optimized for the take-off is presented. It can be observed that the inlet side of the leading edge is curved toward outside in order to keep the flow attached at high angle of attack for take-off condition.

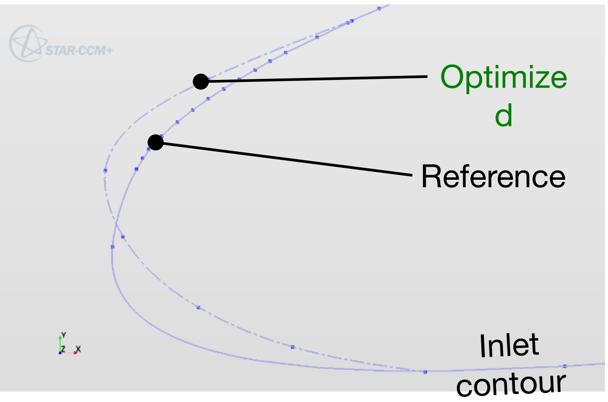


Figure 19 Take-off condition: contour comparison

In Figure 20 and Figure 21 the Mach number contours are presented for reference and optimized contour at take-off condition. It can be seen that separated region close to upper inlet wall is avoided with the optimized contour compared with the reference contour. Close to lower wall the separation region is weaker in comparison with the reference case. As a consequence of smaller region affected by separation, the flow in the optimized case reaches the fan plane with lower Mach number than in the reference case.

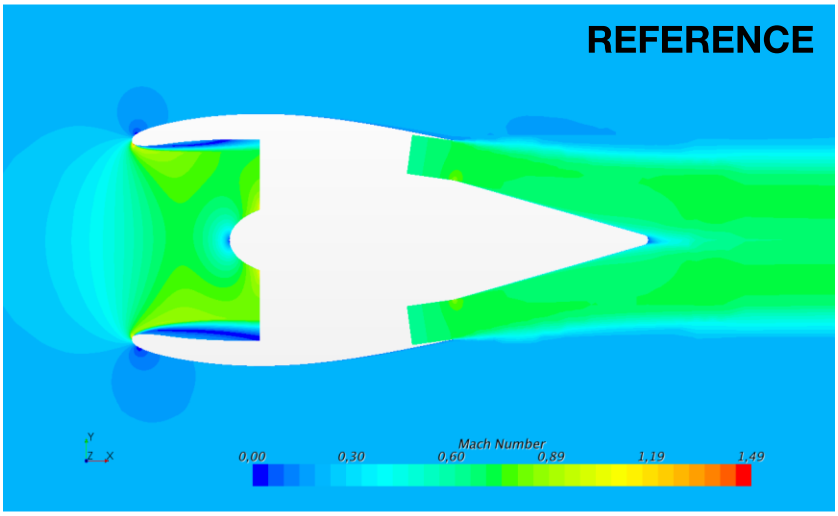


Figure 20 Mach number contours in the symmetry plane for reference contour at take-off condition

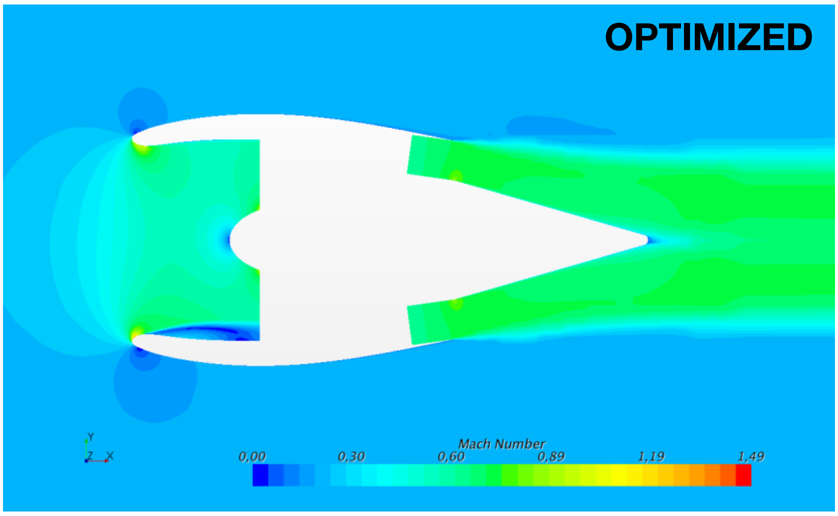


Figure 21 Mach number contours in the symmetry plane for optimized contour at take-off condition

In Figure 22 and Figure 23 the absolute total pressure contours are presented at the fan plane. From these figures it can be seen that uniformity of total pressure for optimized case is higher than for reference case. The area of low total pressure is much bigger for reference case than for the optimized case. For the optimized case only small area at the bottom of the fan plane is affected with decreased total pressure, while for reference case this area is spread over whole circumference of fan plane and boundary layer region. Also, the minimum level of the total pressure is lower for reference than for optimized case.

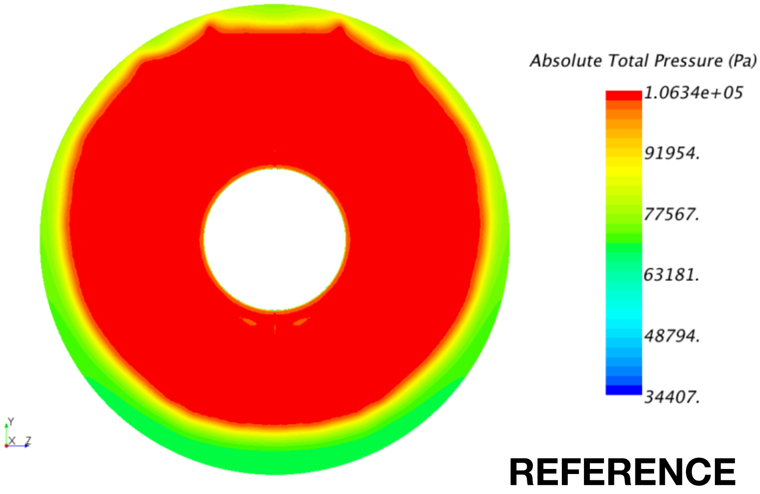


Figure 22 Absolute total pressure contours at the fan plane for reference contour at take-off condition

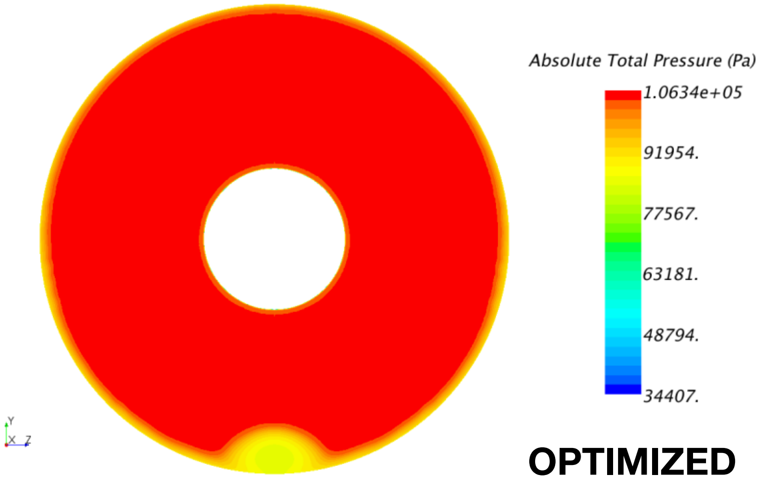


Figure 23 Absolute total pressure contours at the fan plane for optimized contour at take-off condition

In Table 4 the numerical values of the evaluation parameters for take-off condition are presented. The pressure recovery was used as a main parameter for evaluation of nacelle adaptations.

Table 4 Take-off condition: the evaluation parameters for reference and optimized case and their relative difference

Evaluation parameters	**Reference**	**Optimized**	**Relative difference**
DC60	13.7%	3.1%	-77.3%
Press. recovery	0.94069	0.99160	5.4%
C_D	0.35982	0.096933	-73.1%

Aeroacoustic performance

The aeroacoustic performance was evaluated using lateral reference noise measurement point and noise intensity distribution at the circular probe line in the front field. Noise level at lateral reference point is average of the two maximum noise levels measured during take-off at two points located on lines parallel to and at a distance of 450 metres from runway centre line. Noise level is expressed as an effective perceived noise level (EPNL), which consists of instantaneous perceived noise level corrected for tones and duration.

In order to quantify relative performance of the optimized contour, the aeroacoustic performance of three adaptations are compared. Namely, optimized contour for aeroacoustic performance, optimized contour for aerodynamic performance at take-off and reference contour. In Figure 24 the leading edge contours for the three adaptations are compared and results of perceived noise level for these adaptations are presented in Table 5. The adaptation optimized for the aeroacoustic performance attains the lowest noise level, but it has poor aerodynamic performance. On the other hand, the adaptation with the best aerodynamic performance at take-off attains higher noise level than the contour optimized for aeroacoustic performance.

Table 5 Effective perceived noise level for three adaptations: optimized for aerodynamic performance at take-off, reference and optimized for aeroacoustic performance

	Reference	Aeracoustically optimized	Aerodynamicaly optimized
EPNLdb	90.23	89.96	91.05

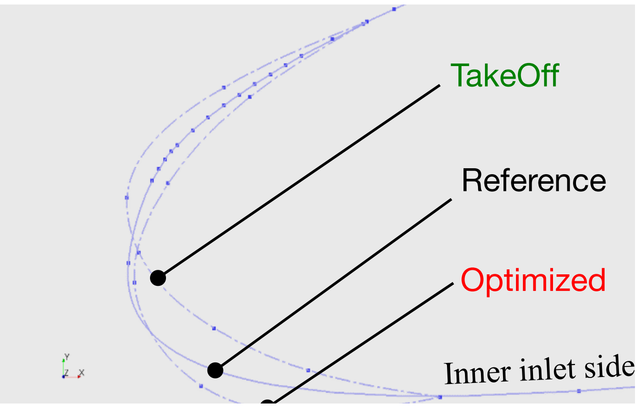


Figure 24 Leading edge contour for three adaptations: optimized for aerodynamic performance at take-off, reference and optimized for aeroacoustic performance.

In Figure 25 the distribution of noise intensity along probe line, at He=19.8, is presented. It can be seen that distribution for the optimized contour has increased maximum peak compared with reference contour at the direction closer to axis of symmetry, but it has decreased intensity level compared with reference contour at the angles close to lateral direction. On the other hand, the contour optimized for the aerodynamic performance has decreased maximum peak intensity compared to the reference contour at angles close to symmetry axis and increased intensity at angles close to lateral direction. With diagrams in Figure 25 and data in Table 5 it can be concluded that intensity distribution at angles close to lateral direction has the biggest influence on the noise level at lateral measurement points.

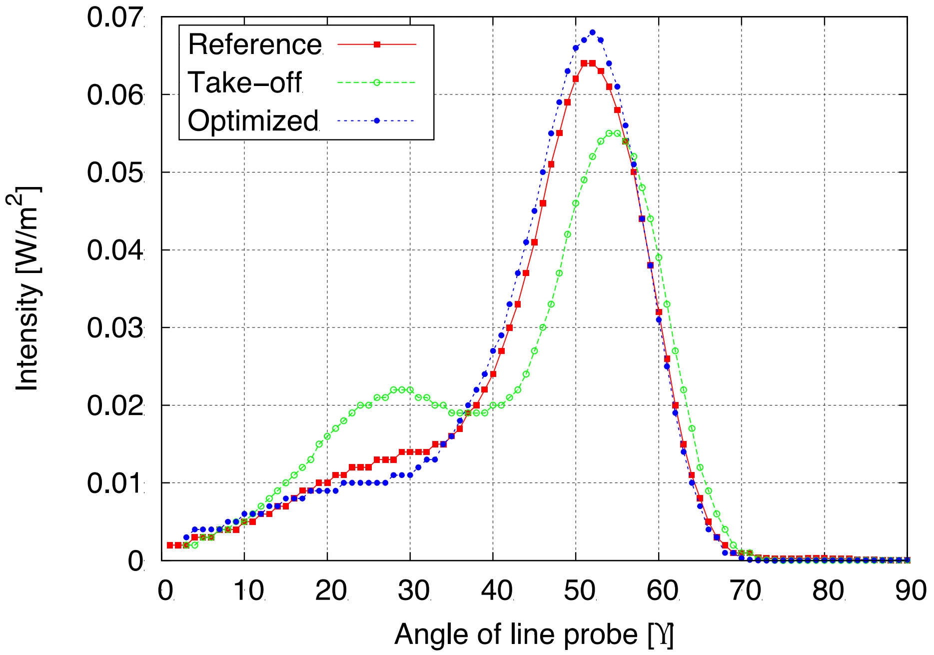


Figure 25 Intensity distributions along probe line, at He=19.8, for reference contour, optimized contour and contour optimized for aerodynamic performance (Take-off)

Development of scaled test rig for morphing capability

Scaled test in laboratory environment require an identification of the overall deformation mechanisms that the morphing structure need to undergo. The scaled rig developed at UNIVBRIS in collaboration with TUM during the reporting period M13-M24 (Figure 26 andFigure 27) allows using two inflatable structures for actuation through pneumatics and input pressures up to 7 MPa (in theory). The pneumatic actuators are embedded within a hardware support with flexible shear skins that allows reproducing parts of the overall deformation of the morphing structure for the inlet.

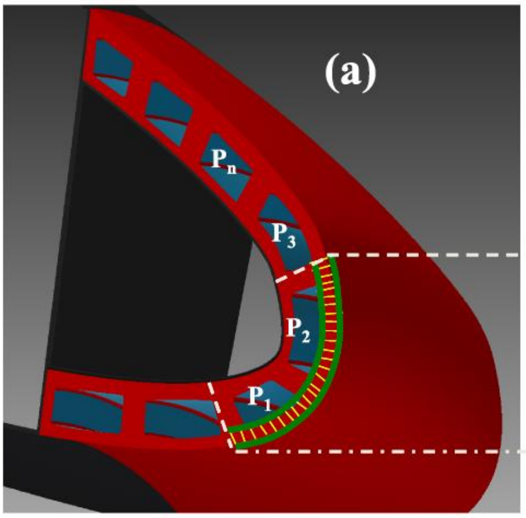


Figure 26: Concept of morphing lip

Figure 27: Scaled test rig developed

Manufacturing process for sandwich morphing structure with elastomeric graphene skin.
A major achievement of the project has been the development of a prototype of morphing sandwich structure for the nacelle inlet. The morphing component is made of elastomeric thermoplastic polyurethane (TPU) skins doped with a graphene-based ink. The ink allows a throughout coating of the TPU pellets prior to thermoforming, and create a homogeneous dispersion of the nanoparticles. The skins can be directly thermoformed using a custom-based mould on a metallic Flexcore core. The sandwich panel (Figure 28) has therefore morphing characteristics, yet it allows a through-the-thickness resistance for potential blade-off or protection containment. Quite importantly, the graphene doping in the elastomeric skins not only contributes to an increase of the membrane stiffness and strength, but also provides a percolation and facilitates the creation of an electric path between skins and metallic core to enhance the lightning strike (LS) protection capabilities. To the best of our knowledge this is the first morphing structure with embedded LS capabilities so far described in open technical and scientific literature.

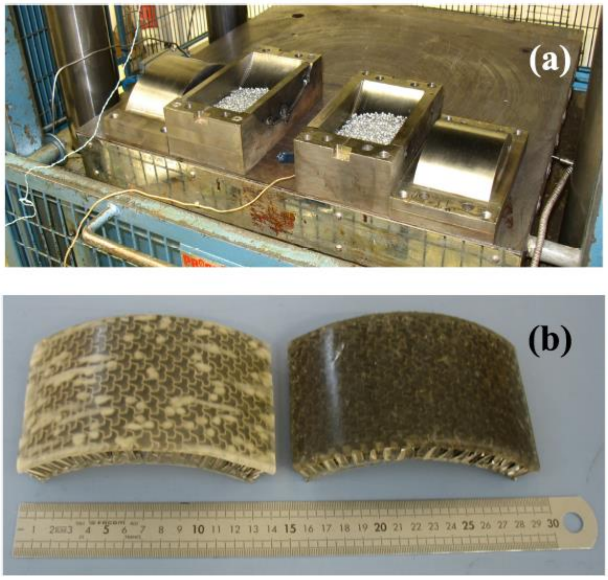


Figure 28: Mould and morphing sandwich panel samples

Mechanical tests and evidence of morphing capability
Cyclic compression tests on cylindrical samples of the TPU and TPU/GP (graphene) specimens have shown an increase on 10 % in terms of stiffness and strength for the case of the graphene-doped samples, this achieved with only 0.17 %wt of graphene dispersed. The dielectric tests have shown an increase of the conductivity in the TPU/GP of more than 4 orders of magnitude. The morphing sandwich panel has proven very good response linearity when considered as actuator (i.e., force-displacement relation at a specific input pressure of the inflatable tubes). It is also significant to notice the very good repeatability of the force-displacement responses after several pressure input cycles. The trials in the scaled test rig have shown a clear evidence of morphing capability for the shape-changing sandwich panel (Figure 29). Different combinations of input pressures produce changes in the contour profile of the panel, as well as a 2D distribution of the deflections that is compatible with the expected strain patterns on a full-scale morphing inlet skin. Also in this case, the repeatability of the results has been confirmed after several combinations of input pressures have been applied a specific number of times.

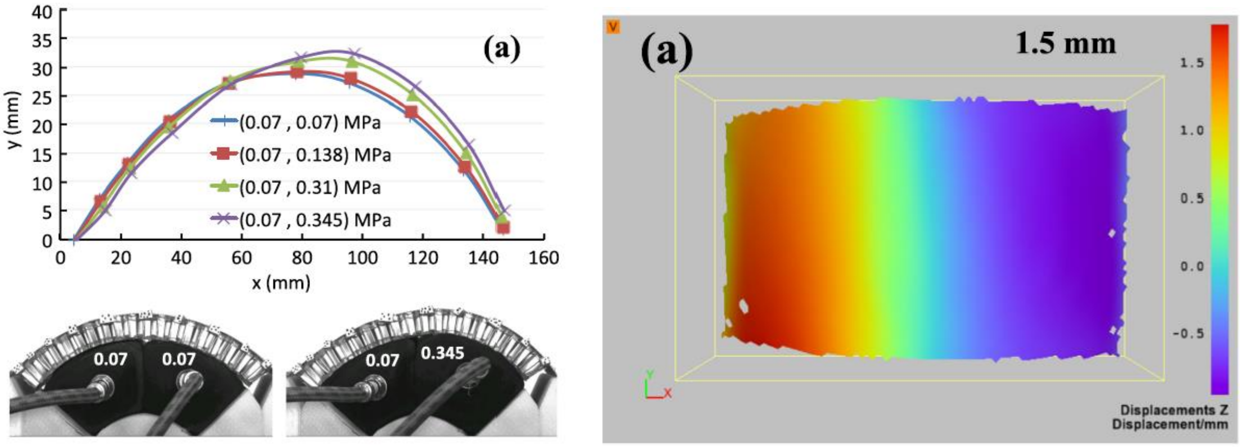


Figure 29: An example of morphing contour of the sandwich panel when tested in the scaled experimental rig

The results acquired for the morphing sandwich panel and its implementation on the scaled test rig are significant, and they have been used to produce a journal paper in Smart Materials and Structures accepted in September 2015 [18]. The pre-print and online paper have been put in open public access servers and they have already generated a substantial interest within the community, with more than 150 papers already downloaded.

Mass and Energy Estimation

Based on the geometry models, materials and simulation results, a preliminary mass and energy estimation of the system has been performed. The mass estimation for two variants is listed in Table 6. The first (membrane skin) featues a single layer of the elastomeric metal mesh skin, the second (sandwich-skin) features the additional flexible sandwich core for increased mechanical robustness. In order to represent both variants, an estimated additional mass of 100 kg per nacelle has been included in the performance estimations.

Table 6: Preliminary system mass estimation for variants with a single metal mesh outside skin (membrane) and a combined sandwich skin (membranes + core)

Component	**Mass [kg]**	**Mass [kg]**
Clamping Setup	16	16
Skin (membrane)	28	
Skin (sandwich)		45
Tubes	39	39
Pneumatic Accessories	10	10
Total Additional Mass per Nacelle:	**93**	**110**
	(membrane-skin)	(sandwich-skin)

The Energy estimation in Table 7 is based on ideal gas compression calculations with preliminary design volumes and pressure levels. Energy is only required for the initial inflation and once per shape change process. Only very little continuous power is required for the compensation of leaked air. The power requirements are therefore neglected in the overall performance evaluation.

Table 7: Actuation Energy estimation results

	Energy [kJ]
Initial Inflation	213
Shape Change	74
Continous Power Demand	negligible

Evaluation and Benchmarking

In this task evaluation and benchmarking was carried out to evaluate the performance of the morphing nacelle concept, which was developed in the previous work packages by the consortium partners. The goal was to conduct an engine and aircraft level assessment of the morphing nacelle concept in comparison to corresponding reference systems, in order to be able to estimate the possible benefits of such a novel nacelle concept. The assessment focused on fuel reduction, but a first qualitative noise assessment was also performed.

Results from Computational Fluid Dynamics (CFD) calculations executed by one of the consortium partners, Kungliga Tekniska Hoegskolan (KTH) [9], for a defined nacelle geometry were used to set up engine performance models. For the CFD simulations no state-of-the-art nacelle geometry was used due to lack of available data. However, the performance of the used base nacelle geometry is not optimized in terms of nacelle drag and inlet pressure drop compared to a state-of-the-art nacelle geometry. Therefore, two different engine and aircraft models were set up. The first engine model uses the absolute values of the CFD calculation as input. This model shows in principle the influence of the not optimized base nacelle geometry of the CFD simulations. The second engine model used the relative improvements of the adaptive nacelle concept compared to the base nacelle geometry. For the nacelle drag on aircraft level the same procedure was applied. This resulted in two variants: Variant Reference (VAR REF), which shows the influence of the not optimized base geometry compared to a state-of-the-art nacelle, and Variant Morphing (VAR MORPH), which show the possible (positive) impacts of the adaptive nacelle concept. The model setup is displayed in Figure 30.

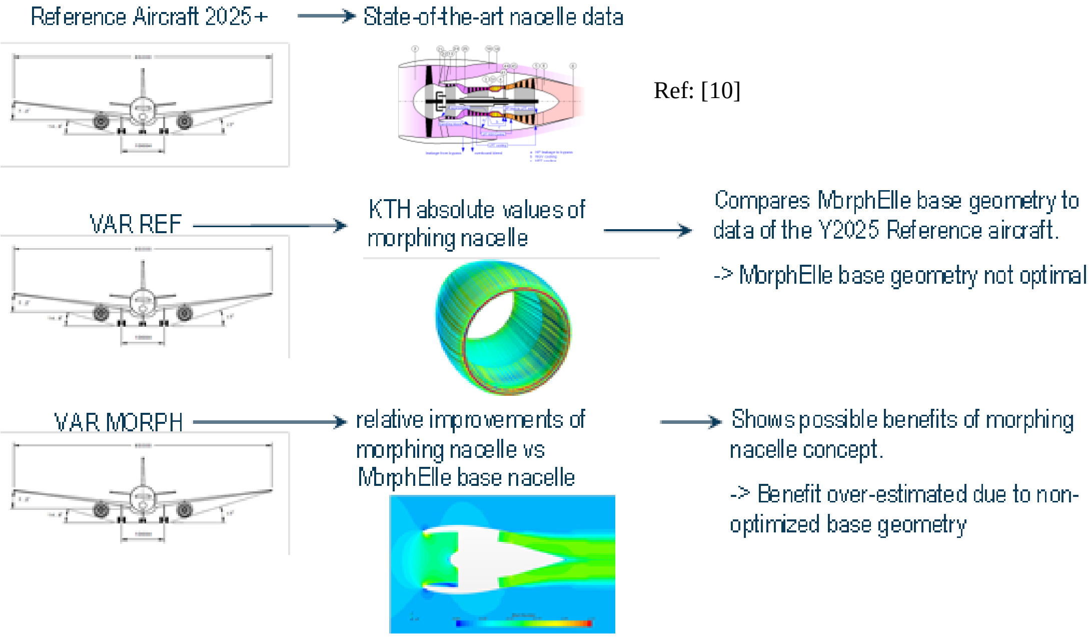


Figure 30: Setup of variants for assessment

VAR REF showed increased specific fuel consumption for almost all considered flight phases except take-off. The nacelle drag was more than +250% higher for the different flight phases. The predicted Maximum Take-Off Weight (MTOW) for the corresponding VAR REF aircraft model was +2.5% heavier than the year 2025+ reference aircraft model and the fuel burn was around +8.5% higher. In contrast VAR MORPH leaded to a reduction of almost -2% in MTOW and a fuel burn reduction of -5% compared to the 2025+ reference aircraft. These results are again graphically displayed in Figure 1. In Table 1 the results of VAR REF and VAR MORPH are stated again in absolute numbers and in comparison to the year 2000 and year 2025+ reference aircraft.

The also conducted qualitative noise assessment of the adaptive nacelle concept concluded only a marginal influence of the adaptive nacelle concept on engine and total aircraft noise.

The most important point for future work is to use a state-of-the-art nacelle geometry as input for the CFD simulations, which serves as input for the engine and aircraft model. Thereby, the benefit of the adaptive nacelle concept could be quantified more reliable as the benefit predicted by the VAR MORPH is probably too optimistic. Also, more advanced methods for the noise calculation could be used.

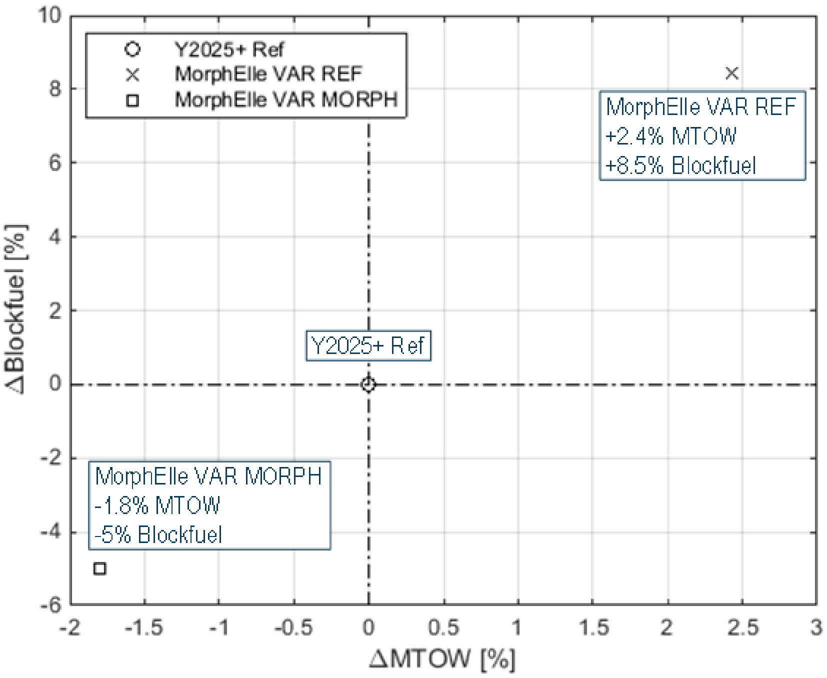


Figure 31: Results of VAR REF and VAR MORPH in relation to reference aircraft 2025+

Table 8: Results of aircraft level assessment

Property	**Y2000 (Ref)**	**Y2025+ (Ref)**	**MorphElle VAR**	**MorphElle VAR**	**Unit**
MTOW	217000	214029	219232	210173	[kg]
MLW	179000	181925	186347	178648	[kg]
OEW/MTOW	0.56	0.60	0.59	0.60	[-]
PAX (3 class)	295	340	340	340	[-]
Thrust/MTOW	0.275	0.23	0.25	0.23	[-]
MTOW/Sref	598	615	615	615	[kg/
Reference Area (Sref)	361.3	348	357	342	[m²]
Aspect Ratio	9.302	11.93	11.85	12.14	[-]
Wing ¼ chord sweep	29.74	29.74	29.74	29.74	[deg]
TOFL @ ISA,SL	2280	2078	2158	2104	[m]
Appr. Speed (MLW, ISA, SL)	131	134	134	134	KCA
Design Range (LRC, ISA, International allowances, 200 nm	4890	4800	4800	4800	[nm]

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4.1.4 Potential impact, main dissemination activities and the exploitation of results

Expected Impact Listed in the Work Programme

The strength of the European economy, especially in areas as specialised as the aeronautical industry, depends above all on innovative power, productivity and the ability of satisfying consumer demand. It is therefore of strategic importance to identify key factors of competitiveness for air transport systems and to maximize the benefit of research and innovation.

The MorphElle Project was conceived to complement the objective of investigating

> *"[...] breakthrough technologies and concepts that have the capacity to cause a step change in aeronautics and air transport in the second half of this century." (2012 work programme)*

Besides, the project picks up the considerations of the ACARE Strategic Research Agenda 2 that suggests that research should be

> *"[...] not only concerned with direct technology programmes but also about the factors that will enable these to be productive and efficient"*. (SRA-2, ACARE 2005).

The key factors addressed by the MorphElle Project and the expected impacts follow the challenges and research objectives formulated in the 2012 work programme:

Activity 7.1.6–Pioneering the Air Transport of the Future

Exploring

- *more radical,*
- *environmentally efficient,*
- *accessible and innovative technologies*

that might facilitate the step change required for air transport in the second half of this century and beyond.

The expected impact of the MorphElle Project may be described by the following points:

Reduction of Fuel Consumption

The global objectives of the MorphElle Project is to utilise ground-breaking adaptive structures technologies applied to the nacelle in order to bring about a dual set of reductions: CO_2-emissions and perceived noise of future propulsion systems. In conjunction with the engine-airframe integration benefits, compatibility with hybrid energy propulsion solutions could be exploited. The combined effect of these two aspects allows significant reductions in fuel consumption, such that emissions in CO_2, CO, NO_x and UHC are reduced accordingly.

Ensuring Cost-effective Mobility in the Future

MorphElle lays the foundation for fulfilling Flightpath 2050 in a sustainable and economical way: as part of the project, propulsion architectures suitable for providing efficient solutions for mid and long-term future aircraft will be considered. This allows to analyse the propulsion system in a holistic way and to determine areas that potentially contribute to emission reductions at the overall aircraft level.

With this background, the project contributes to the ambition to reduce the environmental impact of air traffic while keeping this mode of transport available to the public at large. In a foreseeable future, the demand for air transport will keep growing, however, this demand can only be satisfied if a dramatic reduction in emissions is achieved, or alternatively if the cost related to air transportation rises. Thus, the MorphElle Project provides a perspective for growth in the air transport sector with economic considerations in mind.

Providing a Roadmap for Long-term Research Strategy

The MorphElle Project proposes research on configurations with entry-into-service dates of 2025 and beyond. Such a research effort focused on mid-to-long term applications inevitably raises questions concerning the efficient implementation of the investigated technologies in a equivalently advanced environment, and factors that will enable or impede the successful deployment of a given technology.

The MorphElle Project therefore proposes a roadmap for interim term research strategy that synthesises the results and findings of the conducted research and puts them into the context of emerging technologies in the aviation sector. This allows to gain a better understanding of future Research and Development (R&D) requirements including adjacent fields of technology that are affected by the proposed novel propulsion concepts.

Along the same line, it should be noted that through the JTAC function industry shall be actively involved in the selection and assessment process of the novel technology concepts conducted during the project. The research roadmap is thus not only of scientific interest but provides a strong link to industry.

Strengthening the competitiveness of the European Aerospace Research and Industry

The European aeronautics industry plays an important role not only in transport services but also ensures a high standard of living through job creation in its own industry. Currently this industry provides more than 1 million jobs directly or indirectly (ACARE, 2000). The aviation industry spends an average of 16% of its turnover on R&D which includes a substantial public contribution through EU, national and Research Establishment programmes.
The MorphElle Project addresses research areas in which Europe is facing competition, such as novel aeronautical propulsion systems, innovative propulsion-airframe integration and high-fidelity numerical flow and acoustics simulation. It is obvious that the creation of technology gaps in these fields need to be avoided. Investigating novel approaches in adaptive structures allows extending the knowledge of the individual research fields mentioned above.

Table 9: Summary of expected impact of MorphElle results

Impact	Main contribution from MorphElle Project
The MorphElle Project demonstrates how to complement step changes in fuel consumption and noise reduction through innovative propulsion-airframe integration	
Climate Impact	• Reducing CO_2, NO_x and CO emissions in aviation • Reducing the impact on climate change from aviation
Industrial Impact	• Providing a roadmap for strategic research orientation
Social Impact	• Ensuring that air travel is affordable • Ensuring cost effective aviation services • Reducing the level of community noise
Political Impact	• Ensuring technical leadership in key research areas • Strengthening links between academic research and industry • Creating equivalent level of research on adaptive structures in Europe as in the US

Steps Needed to Bring These Impacts

The major steps required to realize the intended impacts can be summarized as follows:

Firstly, in order to clearly demonstrate the benefit of adaptive nacelles, a reference propulsion-aircraft for EIS 2025 has to be described in detail and compared to an adaptive nacelle concept developed in the project in terms of localise propulsion systems and overall aircraft performance, e.g. fuel consumption and noise. This step requires detailed flow and acoustics simulation and description of the adaptive compliant system.

The second major step towards an implementation of adaptive nacelle concepts in “real-world” conditions is the identification and assessment of possible failure cases of the proposed concepts, and the development of suitable solutions. This concerns first and foremost cases relevant for certification; however, aspects such as system operability and maintainability, are equally important for the success of a proposed configuration and are therefore included in the study.

Finally, a roadmap for implementation can be derived. This roadmap describes a global research strategy and builds on the experience that partners have gained in previous projects, such as the FP financed FP6 NACRE and FP7 **DREAM** projects. The research roadmap could then serve to lever a European Level-1 project addressing adaptive nacelle in a more interim-term implementation context.

European Dimension

The MorphElle Project is an integral component in the development of novel integrated propulsion concepts as key emerging technology for 2025 and beyond. The collaboration between leading European research institutions and industrial partners, a contribution from an ICPC partner and the JTAC provides the combination of expertise that is essential for addressing the scope outlined within MorphElle. The partners participating in the proposed RTD programme have a long history of excellence in research and development and are world leaders in their respective fields resulting in a synergism not possible outside the consortium.

The realisation of the RTD within MorphElle will enforce the leading role of the EU in the field of sustainable and cost-efficient air transportation. All EU countries will benefit from MorphElle, as it lays the foundation for investment in research and development to further optimize the technologies. This will result in the creation of highly skilled jobs throughout Europe. An added benefit is that much of the research is performed at research organizations that closely cooperate with academic institutions, for example on the field of training future researchers. This allows for wide spread dissemination of the findings for education, enabling careers aimed at the advancement of future technologies in the aircraft propulsion sector.

The development of novel power plant systems and integration methods, funded and enabled by the EU, shows the commitment of the EU to leading edge research areas. Furthermore, the framework programme provides a structure that ensures

- resources for the individual partners while mandating a specific level of individual contributions that offer additional incentives for success
- accountability through contractual agreements, clearly-defined, systematically assigned responsibilities within each WP, and central reporting and auditing

An essential component of the project is the creation of the JTAC to advise and oversee the work. Additionally, two workshops have taken place during the project to disseminate project results to all key stakeholders in transportation in Europe.

Dissemination and/or Exploitation of Project Results, and Management of Intellectual Property

Dissemination Actions, including Publications

Exploitation and Dissemination have been an important integral subject throughout this project. In all cases, dissemination of results to parties outside the consortium had to be approved by the consortium.

For **dissemination** the project website is open to the public, including present information on the project objectives and work program.

Table 10: Summary of MorphElle internal and external dissemination

Dissemination activity / material	**Main objective**	**Target audience**
MorphElle Public website	Information platform about project and main results during project duration	Stakeholders and public
File Sharing Platform for Internal Collaboration	Internal file/information online platform for internal communication to all MorphElle partners. It allows to share information (upload & download) of large sizes.	MorphElle Consortium
Mid-Term and Final Workshop	Acquisition and exchange of knowledge with the greater scientific community and aviation authorities and initiation of collaboration for project exploitation	MorphElle Consortium, Joint Technical Advisory Committee

The partners participated in relevant conferences dealing with the topics that represent the scientific core of the project. These are listed below:

- da Rocha-Schmidt, L., Hermanutz, A., Baier, H., Seitz, A., Bijewitz, J., et al., “Progress Towards Adaptive Aircraft Engine Nacelles,” 29th Congress of the International Council of the Aeronautical Sciences, 2014..
- Hermanutz, A., da Rocha-Schmidt, L., and Baier, H., “Technology Investigation of Morphing Inlet Lip Concepts for Flight Propulsion Nacelles,” 6th European Conference for Aeronautics and Space (EUCASS), 2015.
- Majić, F., Efraimsson, G., and O'Reilly, C., “Aerodynamic Performance of the Adaptive Nacelle Inlet,” 33rd AIAA Applied Aerodynamics Conference.
- Özdemir, N. “Morphing nacelle with pneumatic actuators and a flexible nano composite sandwich panel”, 5th EASN Workshop, Manchester, UK, 2.-4. Sept. 2015:
- da Rocha-Schmidt, L., Hermanutz, A., and Baier, H., “A Morphing Lip Concept for Shape Variable Aircraft Engine Nacelles,” Deutscher Luft- und Raumfahrtkongress 2015, 2015.

Additionally, several peer reviewed journal publications were made in relevant technical journals:

- Özdemir, N. G., Scarpa, F., Craciun, M., Remillat, C., Lira, C., Y. Jagessur, L. da Rocha-Schmidt, “Morphing nacelle inlet lip with pneumatic actuators and a flexible nano composite sandwich panel,” Smart Materials and Structures, Vol. 24, No. 12, 2015, p. 125018.
- Gong, X., Huang, J., Scarpa, F., Liu, Y., and Leng, J., “Zero Poisson’s ratio cellular structure for two-dimensional morphing applications,” Composite Structures, Vol. 134, 2015, pp. 384–392.
- Sun, J., Gao, H., Scarpa, F., Lira, C., Liu, Y., et al., “Active inflatable auxetic honeycomb structural concept for morphing wingtips,” Smart Materials and Structures, Vol. 23, No. 12, 2014, p. 125023.
- Sun, J., Scarpa, F., Liu, Y., and Leng, J., “Morphing thickness in airfoils using pneumatic flexible tubes and Kirigami honeycomb,” Journal of Intelligent Material Systems and Structures, 2015.

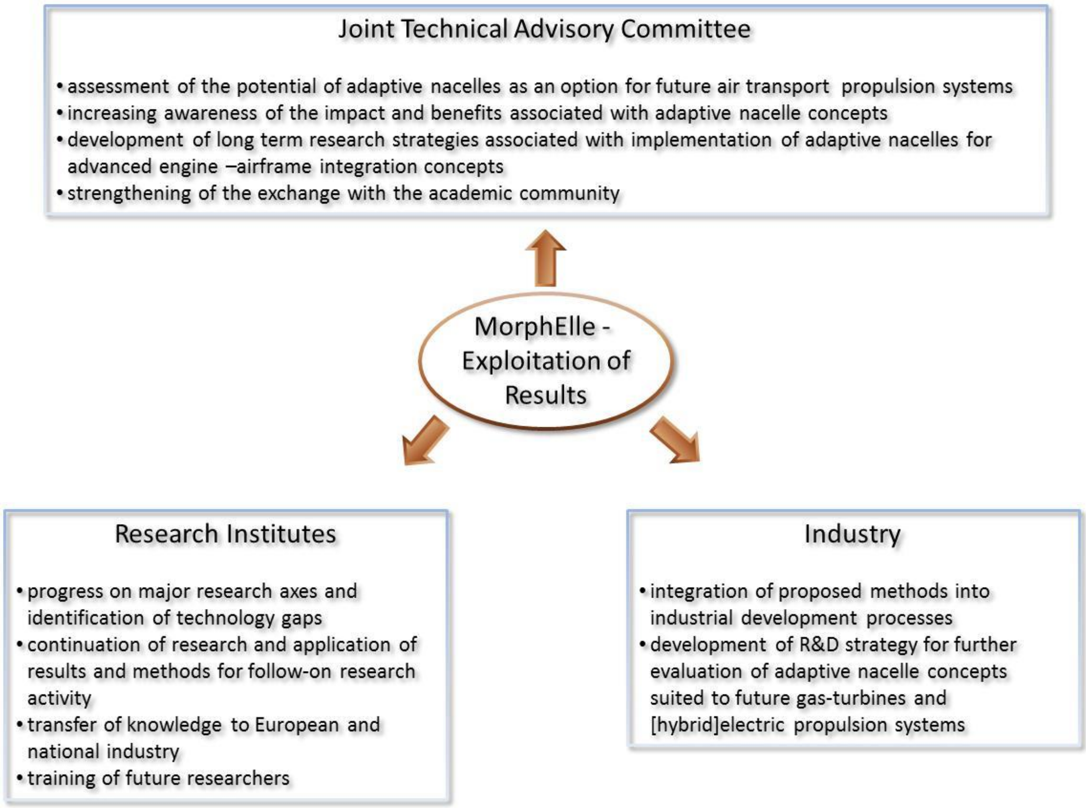
Other dissemination activities include:

- Open Day in Garching, 11.10.2014 “Lange Nacht der Wissenschaften”, Several tours through the Institute of Lightweight Strucutres at TUM including a presentation on MorphElle.
- Presentation on the project at Turkish Aerodspace Industries by N. Özdemir, ~70-80 attendees
- 2 page article in: Oorsprong, M., Gerber, A., Collis, T., O'Neill, H., and Sherwood, B., PRACE Digest 2015. Celebrating the scientific achievements of women in HPC, Insight Publishers, Bristol, UK, 2015.
- Journal Paper currently under review: Majić, F., Efraimsson, G., and O'Reilly, C., “Potential Improvement of the Aerodynamic Performance by Morphing the Nacelle Inlet”, submittet to “Aerospace Science and Technology”

Exploitation of Project Results

Exploitation of the project results by the partners was performed in various ways:

Table 11: Overview of the expected exploitation of project results



Joint Technical Advisory Committee

- assessment of the potential of adaptive nacelles as an option for future air transport propulsion systems
- increasing awareness of the impact and benefits associated with adaptive nacelle concepts
- development of long term research strategies associated with implementation of adaptive nacelles for advanced engine –airframe integration concepts
- strengthening of the exchange with the academic community

MorphElle - Exploitation of Results

Research Institutes

- progress on major research axes and identification of technology gaps
- continuation of research and application of results and methods for follow-on research activity
- transfer of knowledge to European and national industry
- training of future researchers

Industry

- integration of proposed methods into industrial development processes
- development of R&D strategy for further evaluation of adaptive nacelle concepts suited to future gas-turbines and [hybrid]electric propulsion systems

Despite the concentration of the MorphElle Project around a small number of contributing partners, the impact and possibilities of exploiting the achieved results are maximized and go beyond the involved organizations:

- The MorphElle Project will enable as the contributing research organizations and to offer their gained knowledge to industry in and outside the aerospace sector. Through close cooperation of the research organizations with academic institutions, the MorphElle Project enables also educational training and career development, for example through training of PhD students as part of the project.

- The universities involved in MorphElle benefit from the knowledge obtained in MorphElle to enable curriculum that include recent research findings in their teaching at undergraduate and graduate level.

A survey of planned product development activities by industry, comprising engine integrators, aircraft integrators and suppliers, indicated that the MorphElle Project's time frame between 2013 and 2015 for its investigative activities bodes well. To clarify, the industrial sector is currently engaged in the performing the following preliminary studies:

- Next generation of wide-body aircraft with EIS year of around 2019+, constituting a potential for sales of around 450-700 units per year
- Next generation of narrow-body aircraft with EIS year of around 2025+, constituting a potential for sales of around 1100-1500 units per year

In addition to this, the developed MorphElle morphing nacelle inlet lip could be tailored for ducted propulsion systems with at most a modest amount of development effort once fully developed. There exists potential to offer retro-fits for in-service and/or future aircraft platform variants, thus covering many more market segments than those cited above.

Another benefit to industry is posited to occur through knowledge acquisition and understanding of advanced materials (deformable and conformal), innovative actuators, novel structural morphologies and holistic sub-systems design. Familiarization with such technologies shall not only give scope to optimize propulsion system performance, but is projected to serve as a catalyst for generating new ideas for application to other aspects of airframe design and integration. It is also anticipated that, over time, accumulated in-service data and establishment of best practice design procedures associated with the utilization of such technologies will assist in securing the confidence of airworthiness authorities, thereby paving the way for certification of adaptive systems solutions beyond those considered for adaptive nacelles only.