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MORPHING TURBOFAN ENGINE INLET AT TAKE-OFF CROSS-WIND CONDITIONS

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ABSTRACT

Aeronautical engine inlets are designed as a compromise between low-drag configurations for cruise condition and high airflow incidence angle during take-off and landing. In order to fulfill all the requirements belonging to different operating points, adaptive or morphing structures could be a feasible solution, and they could potentially have a positive impact in terms of aerodynamic performance, therefore leading to a substantial reduction in fuel consumption. However, designing morphing inlets is challenging because of the coupling between aerodynamics and structural analysis which is crucial in order to consider both the feasibility of the adaptive structure and its effects on the aerodynamics of the nacelle. This paper outlines the structural design of an adaptive inlet which features hybrid elastomeric composite materials and a means of active actuation. Since the inlet geometry features both radial and circumferential axes, any change in one axis creates a change in the other resulting in the need of stretchable materials if unwanted steps and gaps are to be prevented for favorable laminar-turbulent transition. To evaluate the aerodynamic effects of such a morphing inlet, a computational fluid-dynamic analysis is coupled with the finite element analysis leading to a "one-way" fluid-structure interaction approach. The goal of the presented method is the definition of an automatic aero-structure coupling framework in order to ease the exploration of a variety of designs over the feasible design space. Results highlight pros and cons of three different design approaches with a particular focus on promising aerodynamic results despite some difficulties in the structural feasibility.

Keywords: Turbofan inlet, Nacelle, Morphing

1. INTRODUCTION

The civil aviation industry has defined as major development goals the improvement in efficiency, emissions, and travel speed while ensuring safety and reliability [1]. In particular, emission and noise of aircraft engines have to be significantly reduced, and the efficiency further increased in the future. One way to achieve these goals is the improvement of the airflow through the engine by actively changing the shape of the inlet region. Different flight conditions require different optimal nacelle shapes; therefore, the use of variable inlets instead of rigid ones can decrease the aerodynamic drag, and increase the efficiency and the flight speed [2]. Several research studies concerning variable and adaptive inlets with adjustable lip and duct geometries have been carried out [2–12] but such technologies have not yet appeared in the market. The main reason of that seems to be a potential lack of safety and reliability since the "adaptive" characteristic leads to an increased complexity of the inlet system [2]. The engine inlets have to properly adjust the airflow from outside to the entry of the fan and/or compressor with high mass-flow and highest achievable pressure. Different flight conditions require different optimal nacelle shapes: the inlet should be "thin" during cruise when high Mach numbers are achieved; it should be "round" during take-off and landing when high angles of attack lead to flow separation [9]. Initial studies on morphing nacelle were carried out in the MorphElle project funded by the European Commission [6–9, 12]. In this research, considerations on system and engine level together with related simulation tools and also proper morphing technologies are investigated [9]. The main challenges of adaptive technologies are the conflicting requirements of the structure: proper structural flexibility on one side; the ability to safely hold the different loads on the other side. As mentioned before, the inlet lip shape should be different depending on the operating condition: during cruise, the lip contour is designed to maximize the efficiency; during flight with high angles of attack and gusts, the optimal lip shape should prevent flow separation. The MorphElle project proposed an adaptive lip able to satisfy the contrasting requirements given by different operating conditions. All the developed concepts are shown in Fig.2 in [12].

Another interesting work on adaptive nacelle inlets can be found in [3]. A modified system engineering approach was applied to the concept of variable nacelle intakes for aeronautical engines in subsonic civil aviation. As a result, thirty concepts were developed, and five of them (Fig.8 in [3]) were considered

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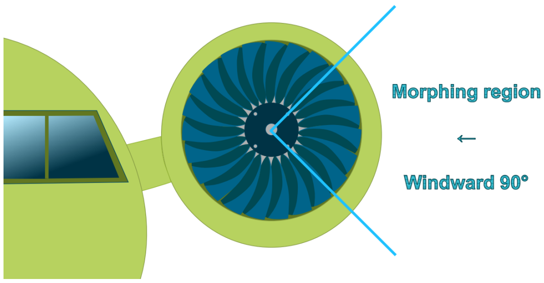


FIGURE 1: MORPHING REGION OF INTEREST.

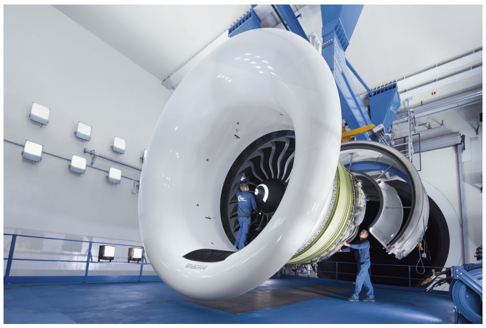


FIGURE 2: BELLMOUTH AIR METER.

the most promising.

In the present work, the structural design of an adaptive inlet is outlined. Three different approaches are described highlighting their pros and cons, and the aerodynamic effects of the corresponding morphing inlets are evaluated by running a computational fluid-dynamic (CFD) analysis. The main challenge in designing morphing inlets is to couple aerodynamic and structural analyses in order to take into consideration both the feasibility of the adaptive structure and its effects on the aerodynamics of the nacelle. Therefore in this work, a "one-way" fluid-structure interaction (FSI) framework is developed in order to ease the exploration of a variety of designs over the feasible design space.

The first section of this paper (Sec.2) describes the main goal of the work and it includes some subsections that present the FSI framework (Sec.2.1), and the three approaches developed for designing the morphing inlet (Sec.2.2,2.3,2.4). Then, Sec.3 is the final section with a summary and the conclusion of the present work.

2. GOAL AND DESIGN APPROACHES

The main goal of this work is to morph the inlet of a turbofan engine nacelle in order to improve the aerodynamic performance at two different operating conditions: cruise and cross-wind during take-off. The morphing region of interest was originally a nacelle sector of 90°in the windward direction (Fig.1) but in order to simplify the problem as a preliminary step, it has been decided to morph the whole circumferential region similarly to the Bellmouth air meter (Fig.2) used for the test of the aeronautical engines.

As said, the main goal of the morphing inlet is to improve the aerodynamic characteristics of the nacelle depending on the operating condition considered: avoid flow separation in take-off cross-wind; reduce drag in cruise. Based on that, three approaches are now described for designing the morphing inlet when cross-wind or cruise conditions are considered. Moreover, a "one-way" fluid-structure interaction framework is also integrated in the three design approaches in order to get a complete and reliable solution.

2.1 Fluid-Structure Interaction Framework

As mentioned before, an important aspect in the design of morphing aeronautical structures is the coupling of two fundamental disciplines: structural mechanics and aerodynamics. It is important to evaluate the aerodynamic effects of the morphing component together with the feasibility and reliability of the structure. Therefore, another goal of the present work is to develop an automatic fluid-structure interaction (FSI) framework able to link the structural model of the morphing inlet with the aerodynamic analysis. The FSI tool is completely developed in Ansys Workbench©with the support of some Matlab©scripts for the complete automation of the process. The framework consists of three main blocks: geometry generation, finite element analysis (FEA), and CFD. An additional fourth block ("System Coupling" in Fig.3) will be inserted in future works and it will be used for a "two-way" coupling which gives a back and forth connection between FEA and CFD. The FSI tool presented in this work is a "one-way" framework where the link between FEA and CFD is unique and straight without a backward step from CFD to FEA. The reason of that is because after a preliminary estimation of the aerodynamic loads involved in the actual study, it has been noticed that their effects are negligible on the nacelle structure, and therefore, they don't need to be passed back to the FEA solver. This implies a straightforward link between FEA and CFD, and therefore, a "one-way" aero-structure coupling. However, it must be said that the "two-way" approach will be developed and presented in future works.

As mentioned above, the finite element analysis and the aerodynamic calculation are performed in Ansys, and in particular, the geometry is generated by SpaceClaim©, the FEA by Ansys Workbench©, and the CFD by Ansys Fluent©. The FSI framework starts with the geometry parameterization of the baseline nacelle which is done by using the class/shape transformation (CST) tool. Then, the baseline nacelle is generated in SpaceClaim and transferred to the FEA solver. In the FEA block (Fig.3), the composite layup and the actuator are modelled, the structural mesh is automatically generated, and the resulting forces, strains and stresses are calculated. The output geometry of the FEA block is the morphed inlet which goes directly into the CFD solver. There, the fluid domain, the mesh, and the boundary conditions are automatically defined, and the flow analysis starts. As mentioned before, the whole framework is automatic, this means that geometry generation, FEA, and CFD use journal files based on the Python language for the set-up and the run of each software; moreover, a Matlab script is used to connect all the steps together in a single run. Therefore, the input of the whole automatic one-way FSI framework is the baseline nacelle geometric parameters, and the output is the morphed inlet shape with the associated aerodynamic results.

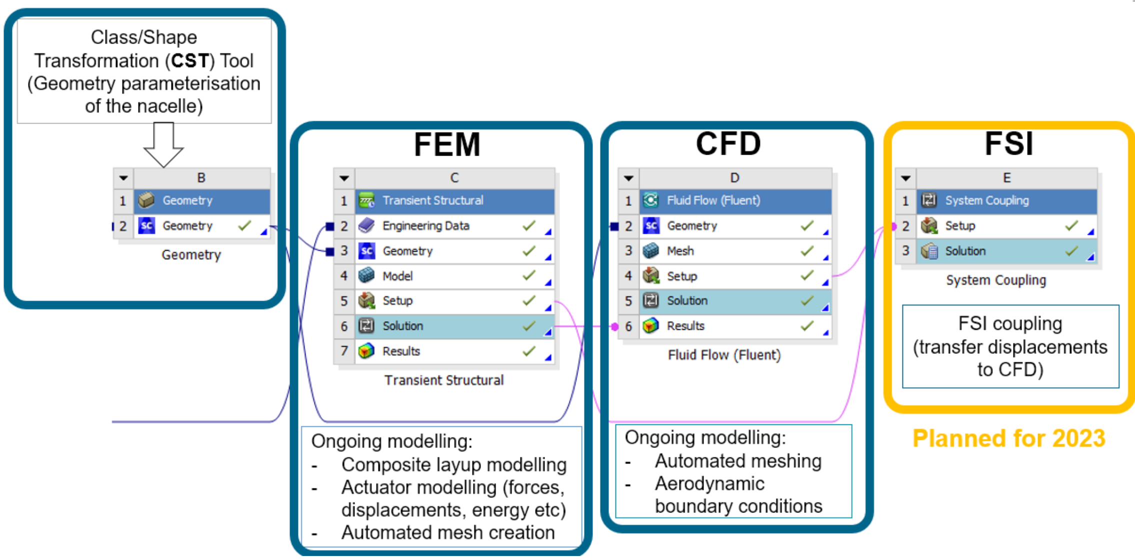


FIGURE 3: FLUID-STRUCTURE INTERACTION FRAMEWORK.

TABLE 1: CFD SET-UP FOR THE THREE DESIGN APPROACHES.

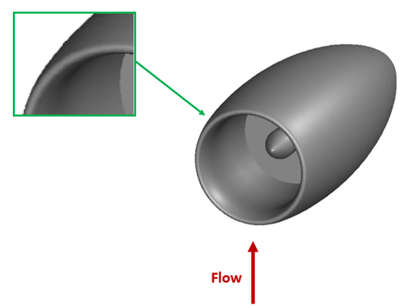
Design	Flow	Mesh Nodes	Mach	Turb. Model
1	Cross-wind	1.9e6	0.04	$k-\omega$ SST
2	Cruise	3.6e6	0.9	$k-\omega$ SST
3	Cross-wind	1.3e6	0.04	$k-\omega$ SST

2.2 First Approach: Baseline 1 – Low-Drag Nacelle

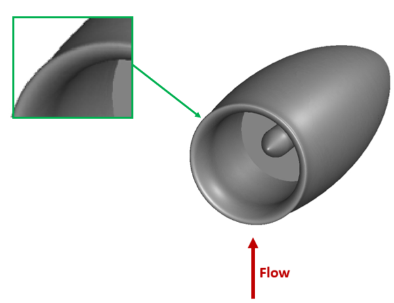
The first approach considers a low-drag nacelle designed for cruise conditions as baseline geometry. The inlet shape is morphed and adapted to the take-off cross-wind conditions in order to reduce or avoid the strong flow separation that usually appears in such regimes. It is important to remind that axisymmetric analyses are considered in this and the following approaches to start with a simplified problem. The baseline nacelle for this first approach – called baseline 1 – and the morphed nacelle are shown in Fig.4. The direction of the flow in cross-wind condition is from the bottom of the nacelle, as shown by the arrow in the figure.

For the design of the morphing mechanism in this first approach, it is important to consider biaxial deformations, and the smoothness of the nacelle leading-edge required for the aerodynamic characteristics. Based on that, the morphing mechanism is represented in Fig.5. It is characterized by a linear actuator that moves the structure backwards leading to a pushing of the lip in the direction of the flow (upwards in Fig.5). The choice of materials for such a morphing device is based on the experience coming from previous projects: it consists of hybrid elastomer composites, e.g. fiberglass and elastomer materials.

The aerodynamic effects of the morphed shape are shown in Fig.6 where the total pressure at the fan sections of the baseline and morphed nacelles are represented. Moreover, some of the CFD settings for the three design concepts are summarized in Tab.1. As it is possible to see in Fig.6, the total pressure distribution visualizes the strong flow separation that appears in both the



(a) Baseline 1



(b) Morphed nacelle

FIGURE 4: BASELINE 1 AND MORPHED NACELLES AT CROSS-WIND CONDITION.

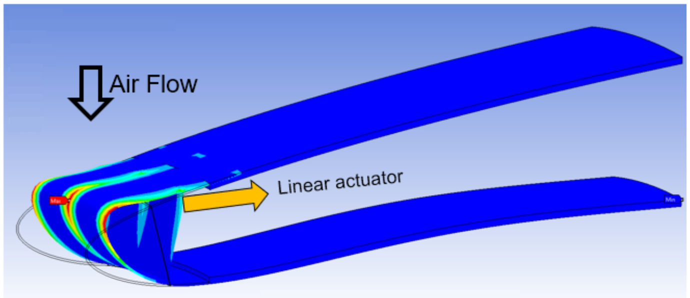
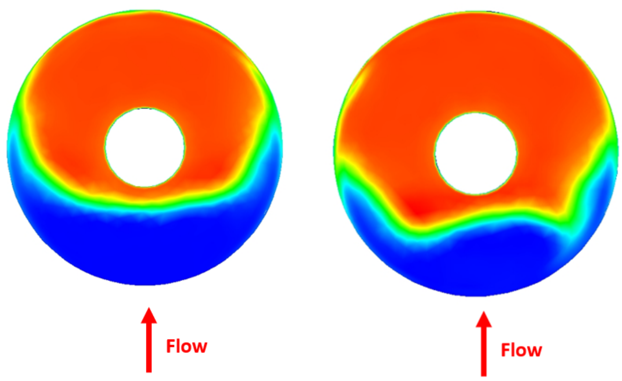


FIGURE 5: MORPHING DEVICE FOR BASELINE 1.



(a) Baseline 1 **(b) Morphed nacelle**

FIGURE 6: FLOW SEPARATION AT THE FAN-SECTION OF BASELINE 1 AND THE MORPHED NACELLE AT CROSS-WIND CONDITION.

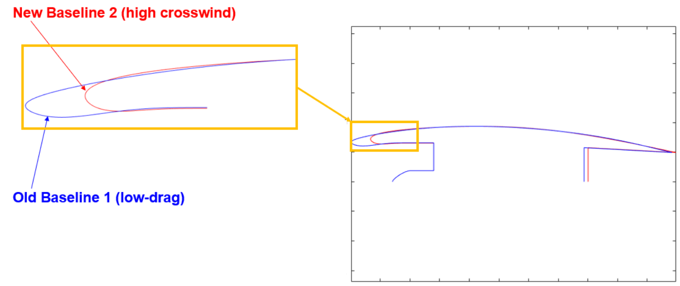
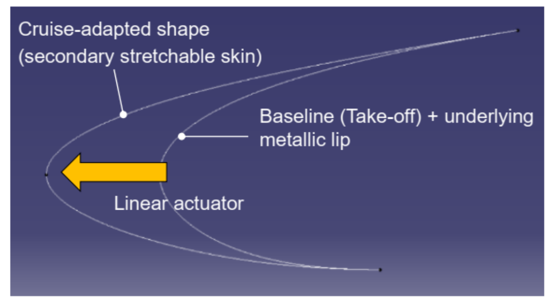
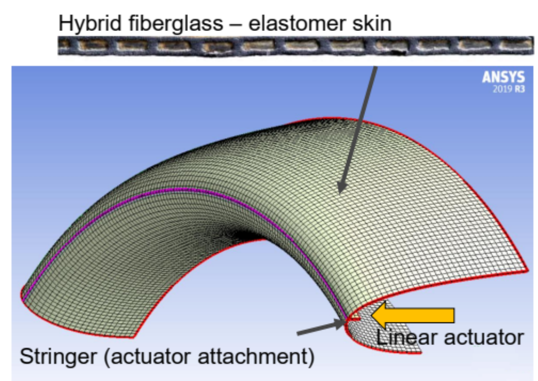


FIGURE 7: BASELINE 1 AND BASELINE 2.



(a) 2D morphing mechanism



(b) 3D structural model

FIGURE 8: MORPHING MECHANISM FOR BASELINE 2.

nacelle shapes. The morphed inlet shows a different pattern in the flow separation but it is still relevant and unacceptable from an aerodynamic point of view. Based on these observations, the first approach described in this section results to be structural feasible from one side but aerodynamically unacceptable from the other. At this point, it is interesting to see a new approach where a different baseline is chosen, and the morphing of the inlet is done in cruise condition instead of take-off cross-wind which is more complex from an aerodynamic perspective. This is realized by the second approach which is described in the following section.

2.3 Second Approach: Baseline 2 – High Cross-Wind Nacelle

As described in the previous section, the morphing of the nacelle starting from a low-drag baseline did not give any relevant aerodynamic results in cross-wind conditions. Therefore, this second approach uses a new baseline, and in particular, a nacelle shape suitable for high cross-wind. Figure 7 shows the two baselines: Baseline 1 (low-drag nacelle) used in the first design, and Baseline 2 (high cross-wind) which is the new choice for this second concept.

In this approach, the baseline nacelle optimally works in take-off cross-wind conditions, therefore, the morphing concept is intended to adapt the inlet shape to the cruise configuration. As shown in Fig.7, the inlet in cruise must be more slender, thin and longer compared to the cross-wind conditions. Therefore in this case, the morphing mechanism should push forward the lip from the baseline configuration to the desired one (Fig.8a). To do so, a linear actuator is implemented, and a secondary stretchable skin covers the underlying metallic lip of the baseline shape. In such a way, the linear actuator can push the skin forward, and the underlying shape keeps the original position (Fig.8). The materials used for the stretchable skin are hybrid fiberglass and elastomer materials, based on the experience from previous works.

Baseline 2 and the resulting morphed nacelle are represented in Fig.9. Both are simulated in the CFD analysis at cruise condition; as expected, the results show a strong reduction of the drag force on the morphed nacelle. Due to the complexity of the calculation of the real drag force on the nacelle, the results represented here give an estimation of the drag calculated in first approximation as the force along the horizontal axis (x-force). Table

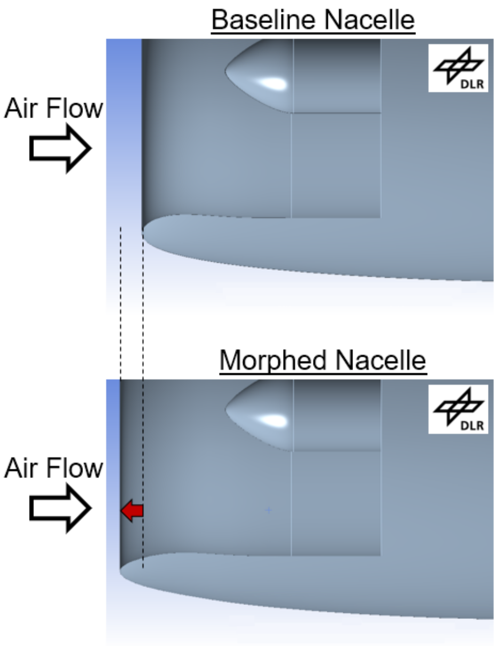


FIGURE 9: CROSS-SECTIONS OF BASELINE 2 AND THE MORPHED NACELLE AT CRUISE CONDITION.

TABLE 2: X-FORCE VALUES FOR BASELINE 2 AND MORPHED NACELLE IN CRUISE CONDITION.

Nacelle	X-Force [N]
High cross-wind baseline (Baseline 2)	-304
Morphed nacelle	-1278

2 highlights the reduction of the drag force by showing a lower negative value of the x-force for the morphed inlet compared to Baseline 2. Therefore, this approach shows very promising results in terms of aerodynamics because Baseline 2 is optimally designed for high cross-wind and therefore, no flow separation appears in such conditions; moreover, the morphed configuration can be considered a low-drag shape that optimally works in cruise conditions. Unfortunately, the main challenge of this approach is on the structural side. Morphing the inlet from the high cross-wind baseline to the low-drag shape implies very high strains generated in the material during the morphing process. Due to the hybrid structure of elastomer and fiber composite, these large deformations also lead to significant stresses which exceed the material limits implying a structural unfeasibility of this second approach, and therefore, the impossibility to adapt a high cross-wind baseline to the cruise condition. Since the lip deformations are distinctly smaller in the first approach, this means that the more reliable way to proceed with the morphing of the inlet is to start with a low-drag baseline and adapt it to take-off cross-wind conditions. In the next section, the third approach is described with a new baseline and a new morphing mechanism.

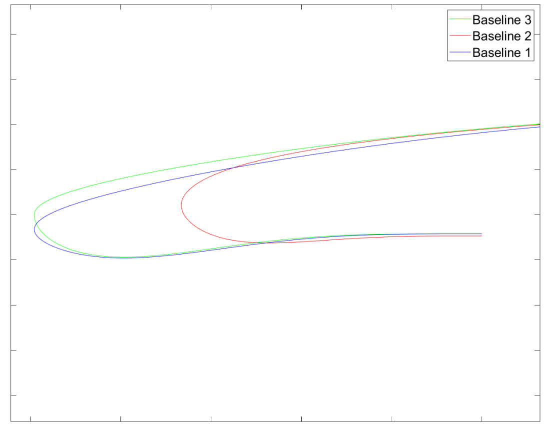


FIGURE 10: BASELINE 1, BASELINE 2, AND BASELINE 3

2.4 Third Approach: Baseline 3 – Modified Low-Drag Nacelle

In the third attempt, the basic idea is to come back to the first approach meaning to start with a low-drag nacelle as baseline and to morph it for take-off cross-wind conditions. The reason of that is mainly driven by the need to reduce structural stresses in the materials. In order to ease the morphing process and avoid possible aerodynamic issues, it has been decided to start with a low-drag baseline similar to baseline 1 but with a non-continuous lip radius and a slightly higher contraction ratio, as shown in Fig.10.

As for baseline 1, the idea is to adapt the lip to the inflow conditions (cross-wind) by pushing the lip into the direction of the flow as shown in Fig.11. This is done by using a linear actuator (represented by a stringer) that pushes the lip in the flow direction. The lip is characterized by a morphing skin made of fiberglass and stretchable elastomer, and an underlying aluminum skin (Fig.12). By applying a force to the linear actuator, the hybrid skin structure moves away from the aluminum skin – which defines the baseline shape – and adapts the inlet geometry to the inflow conditions. An example is shown in Fig.13. The rationale behind this design is to retain the primary aluminum structure and have an adaptable hybrid morphing layer on the outside. In this manner, requirements such as robustness against bird strike, icing, lightning strikes etc may be more feasibly attained. It should also be noted that the compatibility and manufacture of certain elastomers with composite materials is widely documented and this work uses the material data from GFRP and EPDM as reported in [13]. Furthermore, the orientation of the actuator/stringer load introduction point plays a role in the reaction forces through the lip outer structure and the actuator itself. As the slot on the skin allows traversal only in the actuator direction, any loads that are exerted normal to this actuator axis will be transmitted through the skin structure which may beneficially reduce the transversal forces on the actuator shaft. The orientation of this actuator axis can be fine tuned in future studies through dedicated optimization methods.

The approach described above seems to be the most reliable in terms of structural feasibility and very promising in terms of aerodynamic results. However, the same aerodynamic issues

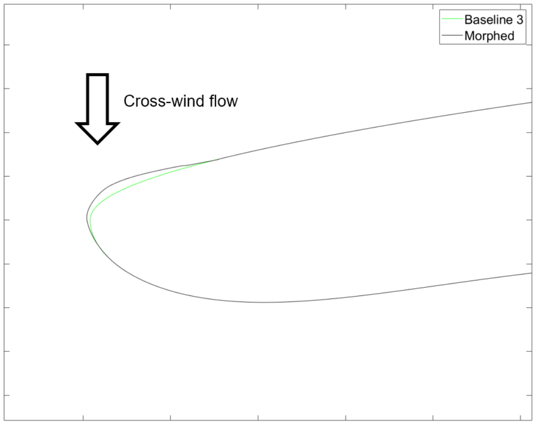


FIGURE 11: BASELINE 3 AND MORPHED SHAPE.

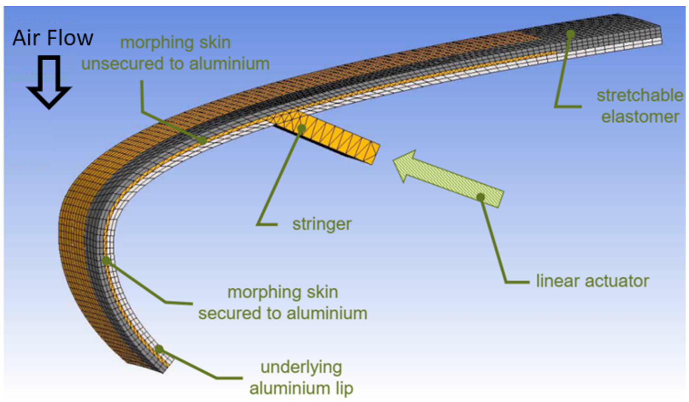


FIGURE 12: MORPHING MECHANISM FOR BASELINE 3.

highlighted in the first approach are also visible here: the optimal morphed shape still shows a separation bubble that characterizes the cross-wind condition but by morphing the inlet, such a bubble appears smaller compared to the one in the baseline nacelle (Fig.14). Therefore, in order to be able to further improve the aerodynamic results of the morphed inlet, it is necessary to adapt the outer part of the lip by pushing it more into the flow direction such that the upcoming flow can easily follow the nacelle surface without separating. The steps to reach such results imply some changes in the morphing mechanism especially in the region of the inlet leading-edge where the flow must stay attached to the surface avoiding separation. Adjustments to the structural model are still ongoing and the promising results will be shown in future publications.

3. CONCLUSION

The work presented in this paper outlines the structural design of an adaptive turbofan engine inlet. Three different approaches have been described, and for each of them pros and cons have been highlighted. The three methods start from three different nacelle baseline geometries, and they proceed with the morphing inlet in three different ways according to the operating conditions considered. Due to too small aerodynamic performance increases for the first approach and too high structural

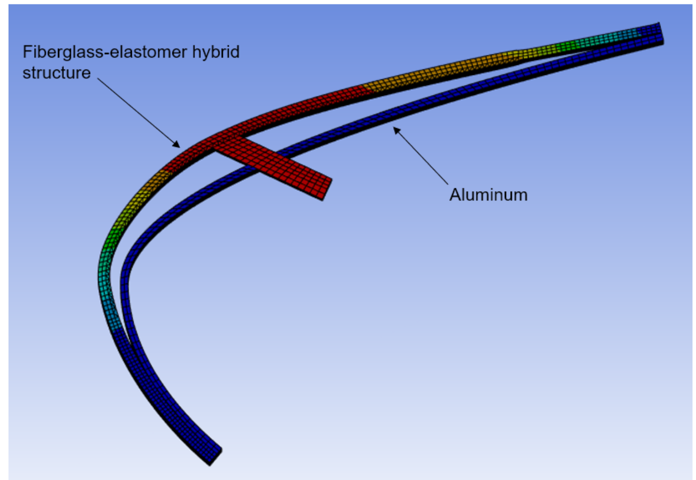
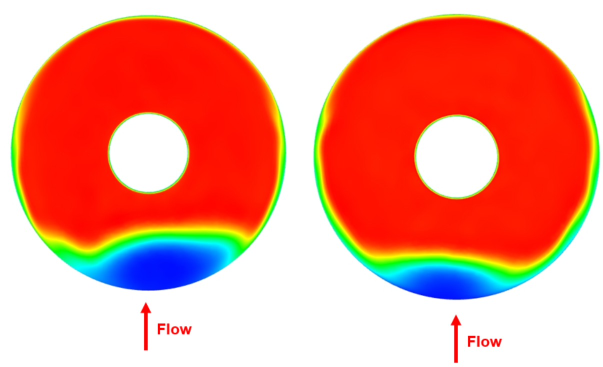


FIGURE 13: HYBRID SKIN STRUCTURE.



(a) Baseline 3 **(b) Morphed nacelle**

FIGURE 14: FLOW SEPARATION AT THE FAN SECTION OF BASELINE 3 AND THE MORPHED NACELLE AT CROSS-WIND CONDITION.

stresses for the second one, the most promising approach has been found in the third one where the baseline geometry is a low-drag nacelle with a non-continuous lip radius and a higher contraction ratio that optimally works in cruise conditions. Therefore, the inlet has been morphed at take-off cross-wind conditions, and even though the results show a structural feasibility and promising aerodynamic results, some more adjustment to the structural model are still needed to achieve satisfying aerodynamic effects. Changes to the model are ongoing and they will be shown in future works. Moreover, a fluid-structure interaction framework has been developed to connect structural and aerodynamic analyses in the design phase of the three morphing concepts. Such a tool is crucial to achieve a more complete and reliable design of a morphing structure. In the current framework, only the deformed shape from the FEA is given to the CFD solver, and the resulting aerodynamic pressure distribution is not transferred back leading to a "one-way" FSI. This is done because of the negligible effects that the aero-loads have on the nacelle structure in the simulated load cases. Nevertheless, a fully coupled FSI framework will be developed and presented in future works.

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