Design of a morphing leading edge as a high lift device for a regional aircraft

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Abstract. Morphing technologies can provide a significant contribution to reduction of noise and fuel consumption for future aircraft. In the framework of the European Aviation research programme Clean Sky 2, a design of a morphing leading edge was developed, which allows the simultaneous increase of wing chord and camber to adapt the airfoil to different airspeed conditions. The final design has a sliding contact at the bottom, whereas the upper surface is continuous with variable camber. In contrast to classical high lift devices, the lift coefficient can be increased without adding sources for turbulences at the upper wing surface. CFD analyses have been performed in order to quantify the aerodynamic performance of the designed morphing leading edge. Furthermore, a design concept both for the skin and for the actuation system is presented. The skin is designed using carbon fiber reinforced plastics (CFRP). In order to achieve both the required stiffness and flexibility, a customized non-constant layup is developed. Its feasibility for the high deformations during morphing is demonstrated by means of both numerical analysis and experimental validation. The electro-mechanical actuation system is designed to completely fit inside the morphing leading edge while still considering space for other subsystems. Besides the space requirements also weight, mountability and bird strike aspects are taken into account. Altogether, for the overall design of a morphing system is presented in this paper, various design challenges are highlighted and appropriate solutions for these challenges are discussed.

1. Introduction

The reduction of noise emission by aircraft is one of the most important research tasks for future aircraft development. Ever stricter noise limitations at airports, which are located very close to urban areas, are a challenge especially for regional aircraft, because their benefit in terms of travel time in comparison to other means of transport depends on the possibility to use these near-city airports.

A possibility to reduce noise emission of regional aircraft is the application of a seamless morphing leading edge. This allows adaption of the wing’s airfoil to a low landing/take-off speed and therefore increasing the lift coefficient, thus allowing a reduction of approach speed. As a result, noise emission reduces, without the disadvantage of classical high lift devices which generate noise radiation caused by the geometrical gaps.
Within the European research program “Clean Sky 2” Fraunhofer LBF, Fraunhofer IBP, Fraunhofer EMI and Airbus are developing a next generation morphing leading edge (MLE) made of CFRP as a high lift device for regional aircraft. In this paper the development of the MLE with a stiffened composite skin, kinematics and an actuation system is described. The finite element (FE) and computational fluid dynamics (CFD) analysis, as well as the bird strike investigations are elaborated.

2. CFD Analysis

2.1. Analyzed airfoils
Four airfoil profiles under development were analyzed to show the aerodynamic effect of the MLE. Their leading edge (LE) profiles are compared in Figure 1. Profile S4 is the cruise airfoil. Airfoil S5 is the target profile having the LE fully drooped. Airfoils BL and 050 are intermediate airfoils between S4 and S5. Airfoils with the suffix HL (high-lift) have a deployed trailing edge (TE) flap for analysis in the landing condition.

![Figure 1. LE comparison of profiles S4HL, BLHL, 050HL and S5HL.](image)

2.2. Method, conditions, domain and mesh
Stationary Reynolds-averaged Navier-Stokes (RANS) simulation with a k-omega Shear Stress Transport (SST) turbulence model was performed. This is so-called high Re-type simulation using wall functions.

Profiles BL and S4 were analyzed in both cruise and landing conditions, whereas the other profiles were analyzed only in the landing condition. The cruise condition was defined as 240 knots (134 m/s) flow velocity and the standard atmosphere at an altitude of 25,000 feet (air density $\rho = 0.549 \text{ kg/m}^3$). The landing condition was defined as 140 knots (72 m/s) flow velocity and the sea-level atmosphere ($\rho = 1.23 \text{ kg/m}^3$). The Reynolds number per 1 m amounts to 1.42E07 and 1.47E07 for cruise and landing conditions, respectively.

2.3. Lift and drag analysis
Calculated lift coefficients $c_l$ and drag coefficients $c_d$ are plotted as functions of the Angle of Attack (AoA) in Figure 2. The lift analysis shows that deploying the leading edge increases both lift and stall angle. As the LE is drooped from profile S4HL to S5HL, the max lift coefficient $c_l$ is increased by 14% from 2.80 to 3.06. The stall angle is also increased from 14.2 to 16.4 degrees. For AoA above 4°, the drag coefficient $c_d$ is reduced by drooping. For AoA between 0° and 4°, $c_d$ of S5HL is slightly higher than of S4HL (2.4% at AoA = 2°).
2.4. Pressure, flow and $c_p$ distributions

To estimate the largest aerodynamic load on the profiles, extreme flight conditions were defined based on the load factor $N_z$: For the cruise airfoils, three conditions for $N_z = 2.5$ (climb) and one for $N_z = 1$ (level flight), for the high-lift airfoils, three conditions for $N_z = 2.0$ (climb). The pressure coefficient $c_p$, or dimensionless pressure normalized by dynamic pressure around profile S4HL is shown in Figure 3 for a flight condition with an air speed of 72 m/s and an Angle of Attack of 10.04°. The suction peak of -6.48 appears on the upper (suction) side near the LE. The computed pressures are used as load data for the development of the mechanical actuation system and airfoil skin, which will be explained in the following sections.

![Figure 2](image1.png)

*Figure 2. Calculated lift (left hand side) and drag (right hand side) coefficients.*

![Figure 3](image2.png)

*Figure 3. $c_p$ distribution of profile S4HL.*

3. Design of skin and stringers

3.1. Material selection, baseline shape and fatigue tests

In order to select a suitable material for the MLE, it has to be considered that the material provides the stiffness required to maintain the desired contours under aerodynamic loads (see Figure 4) while simultaneously being sufficiently deformable without damage to reach (or approach) the target shapes. An iterative method with different materials was applied to a finite element model, which consists of a shell mesh for the skin and I-stringers. The selected material for the design and development of the morphing leading edge was the aviation certified CFRP material IM7/8552. A CFRP skin structure for large morphing deformations without elongation of the structure was already developed and tested in a previous Clean Sky project [1].

The laminate lay-ups for the different regions of the MLE were also defined in a process using FEA during which the degree of approximating the target shapes as well as the resulting maximum stress exposure were considered as indicators of the laminate’s suitability for the morphing purpose. The final design of the MLE is divided in 7 stacking sequences.
For the load transmission from the kinematics to the skin and for increasing the stiffness, five stringers are used. Figure 4 shows the design of MLE with color code for zones of different lay-ups as well as the stringer positions.

Whenever a morphing system is designed, the baseline shape (which describes the manufacturing geometry, which is stress free as long as no loads are applied) needs to be defined. An option for the baseline shape is using one of the target shapes, either the airfoil for cruise (S4) or for take-off/landing (S5), see Figure 1. But deformation from S4 to S5 or vice versa leads to large strains in the skin. This can be reduced by using an intermediate baseline. In the context of the work presented here material strain is quantified using the multiaxial stress failure criterion proposed by Puck [2]. According to this criterion an inverse reserve factor (IRF) is computed. An IRF of 1 or higher would indicate static failure of the composite structure. For cyclic loading an IRF below 0.5 is supposed to be acceptable. For deformation from S4 to S5 an IRF of \( f_{IRF} = 0.7520 \) (interfibre fracture with weakening) is computed by FE analysis, which is critically high.

In order to reduce material strain and required actuation forces, an intermediate baseline between the geometries S4 and S5 was derived. This intermediate baseline needs to be compatible with the movement of the kinematic system (see Section 4). Hence, the intermediate baseline was derived from a simulated intermediate shape of the skin resulting from an intermediate position of the kinematics. Using this intermediate baseline the material strains in terms of IRF are reduced by 38% to a value of \( f_{IRF} = 0.4633 \). The used material strength parameters can be found in [3].

To evaluate the strength of the material when deforming under morphing conditions, four-point bending fatigue tests for 102,000 cycles with bending strain very similar to the one computed for the MLE were performed (see Figure 5) without failure of the material.

The test specimens were manufactured with IM7/8552 from Hexcel® and the layup of the most highly stressed region of the MLE was selected for the tests.
3.2. Gap closure
The deformation of the MLE from S4 to S5 generates a structure elongation of 90 mm. This elongation is not possible with the material IM7/8552 used for the MLE. As a consequence, a gap occurs between the bottom of the wing and the front spar. To ensure the safety and reliability of the components inside the leading edge, the outer skin of the already developed leading edge was extended to close the gap at the lower side of the aircraft wing. In order to avoid discrepancies in the behaviour between the gap closure and the skin of the MLE the same CFRP was used. When the MLE is mounted to the wing, the rear end of the gap closure is pulled down by approx. 20 mm resulting in a preloading force at the slide contact the underside of the aircraft wing.

![Figure 6. Displacement of the gap closure for pre-stressing.](image)

4. Design of actuation system
The actuation mechanism designed for the MLE is depicted in Figure 7 with its components. The force for deforming the skin is applied onto the stringers 2, 3 and 4 (see Figure 7). Stringer 5 is enforced to move on a circular trajectory (which is close to a horizontal movement) by a link. The position of the rear end of the linear actuator is fixed relative to the airframe with just a rotational degree of freedom. When the linear actuator extends, it makes the bell crank rotate pushing stringer 3 into the desired position. The crank is also connected to stringer 3. When the actuator makes stringer 3 move, the crank rotates around the crank bearing. Stringers 2 and 4 are connected to the crank via separate links. The final position of these stringers is dependent on the actuator piston position as well as on the stiffness properties of the skin.

![Figure 7. CAD design of the actuation system of the MLE.](image)

The MLE skin needs to be connected to the actuation system at least at two different locations, because the stiffness of the skin is not sufficient to transfer the movement from one cross-section of the
MLE to its full span. Figure 7 shows only the mechanism for one of these locations. Two actuation positions with identical kinematics are planned for the MLE section. The linear actuator actuates only the movement of one bell crank, from where the movement is transferred to the other bell crank by a connecting rod, see Figure 8.

![Figure 8](image1.png)

**Figure 8.** Design of the actuation system with two linear actuators.

This connecting rod enforces the two actuation kinematic subsystems at both ends of the MLE to move identically. For increasing mission reliability two linear actuators are used, which are connected serially to each other. Both actuators have enough stroke and force to move the MLE alone between S4 and S5 in case that one actuator gets jammed. In order to be compliant with a more electric aircraft design, an electromechanical actor was chosen. FE analyses show that the highest required actuation force is 5.8 kN. This is feasible for this actuator type. The required total actuation stroke for morphing from S4 to S5 is 110 mm. Figure 9 shows the comparison of target shapes, which were used for CFD-analyses in section 2, and expected shape according to FE simulation for airfoils S4 and S5. In 2D CFD analysis the effect of the shape deviation on aerodynamic performance has been analyzed for S5HL (wing in high lift configuration) and S4 (wing in cruise configuration). For S5HL for all AoA up to stall angle of 18° the estimated effect of shape deviation on both lift and drag is below 1.1%. For S4 it is below 1.3% in a range of AoA from 0° to 8°, which is most relevant for cruise configuration.

![Figure 9](image2.png)

**Figure 9.** Comparison of target shapes and expected shape according to the simulation for airfoils S4 (left hand side) and S5 (right hand side).

5. **Bird strike**

In case of a bird impacting the leading edge of an aircraft, the bird should not penetrate into the front spar of the wing, which could cause severe damage to the fuel tank and be a potential fire hazard. For a morphing leading edge, this requirement is a big challenge as there must be a trade-off between the stiffness of the leading edge (a high stiffness would improve the impact response) and the required flexibility allowing morphing between the target shapes. For the specific case analysed here, featuring very large changes of leading edge deformation, it does not seem possible to avoid perforation of the composite skin. For such a case, where penetration of the bird into the wing cannot be avoided, it must
be shown that the fuel tank, located behind the front spar is not impacted by the bird in order to avoid the hydrodynamic ram effect, which could result in a catastrophic loss of the aircraft [4],[5].

For this purpose, numerical simulations were performed using the explicit commercial FE code LS-DYNA. Following general practice in the aerospace industry [6] the bird’s geometry is represented by a cylinder with hemispherical ends. The bird is discretized with 8543 irregularly arranged SPH particles using a linear polynomial equation of state [7]. The composite skin of the morphing leading edge was discretized with shell elements. The material data for calibrating the non-linear composite model *MAT_58 in LS-DYNA was taken from [8]. As the morphing process induces pre-stresses in the composite skin, which may affect the response under impact loading, these stresses had to be taken into account in the simulation. As the bird was expected to fully penetrate the composite skin, it was decided to include the internal structure of the MLE in the simulation in order to assess if the internal structure was sufficient to stop the bird before impacting the front spar or if an additional bird strike protection concept had to be added to the structure. In order to reduce the complexity and the simulation time, a simplified representation of the internal kinematics, comprising only the actuators, the support beams and a coupling rod which were modelled using solid elements and typical properties of aluminium and steel, respectively. In total, 12 different locations of the bird impact were assessed (4 different horizontal positions x 3 different vertical positions). The simulations showed that for some cases, parts of the bird would pass by the internal architecture of the MLE and potentially impact the front spar of the wing. Therefore, simulations were repeated with an internal bird strike protection system, see Figure 10. It could be shown that an aluminium plate of thickness 2.5 mm was sufficient to deflect the bird ensuring that the front spar of the wing would not be impacted.

Figure 10. Proposed bird strike protection shield.

6. Mountability concept

For the development of a mounting concept of the MLE, certain boundary conditions need to be taken into account. Due to the limited area and complex design, the kinematics and the skin element needs to be preassembled before mounting onto the front spar. Then, the preassembly can be attached to the front spar in one package. The connection points between front spar and MLE are best placed at top and bottom of the front spar (see Figure 11 left), leaving sufficient space for cable routes in-between.

Figure 11. Mounting concept.

Due to the inaccessibility from the sides as well as from backside of the front spar, the joint needs to be accessible through the skin element. This is realized via cut-outs in the top and bottom area of the
skin (see Figure 11 right), which can be closed with a lid after realizing the bolt connection. Structural analysis show that eight M8 bolts are sufficient to transmit the loads safely.

7. Summary and conclusion

The MLE system consists of a reinforced skin made of CFRP IM7/8552 connected to the kinematics and an actuation system. The skin represents the outward contour of the wing profile in the MLE region and thus needs to meet the target shapes defined based on aerodynamic considerations as accurately as possible. The kinematics transfer the actuation forces to the skin and guide its deformation. After the preliminary design of the skin iterative analyses are done to optimize the lay-up. Main criterion within the design process is the avoidance of critical fiber- and inter-fiber failure in the composite while ensuring sufficient deflection of the skin so the desired target shapes can be achieved.

In order to reduce the stresses in the CFRP skin an intermediate baseline (stress free contour) in between S4 and S5 is derived based on FE analysis with the developed kinematic concept. Simulations show that the material can endure cyclic deformation between S4 and S5. To validate sufficient fatigue strength of the material under maximum deformation, cyclic bending tests are performed, which show no failure underpinning the results of the numerical analysis. Also, a concept for closing the gap on the lower surface of the MLE is developed.

Numerical analyses of the system including skin, kinematics and aerodynamical loads are performed for dimensioning the system. The simulation results show that the target shapes are approximated with good accuracy. Based on the computed forces in the kinematics system the components have been dimensioned and an electromagnetic actuator has been selected.

Bird strike analyses are performed and a concept allowing the safe flight of the aircraft after an impact is shown. Future developments will focus on the consideration of further certification aspects.

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