Augmented Aircraft Performance by the use of 2 Morphing Technology for a Turboprop Regional Aircraft Wing 4

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Article

Augmented Aircraft Performance by the use of Morphing Technology for a Turboprop Regional Aircraft Wing

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Abstract: This article presents some application of the morphing technology for aerodynamic performance improvement of turboprop regional aircraft. It summarizes the results obtained in the framework of Clean Sky 2 REG-IADP AIRGREEN2 program on the development and application of dedicated morphing devices for take-off and landing, and their uses in off design conditions. The wing of the reference aircraft configuration considers Natural Laminar Flow characteristics. A deformable leading edge morphing device ("drooped nose") and a multi functional segmented flap system have been considered. For the drooped nose, the use of deformable compliant structure was considered, as it allows a "clean" leading edge when not used, which is mandatory to keep NLF properties at cruise. The use of a segmented flap makes possible to avoid external flap track fairings, which will lead to performance improvement at cruise. An integrated tracking mechanism is used to set the flap at its take-off optimum setting, and then, morphing is applied in order to obtain high performance level for landing. Finally, some performance improvements can be obtained in climb conditions by using the last segment of the flap system to modify the load distribution on the wing in order to recover some extended laminar flow on the wing upper surface.

Keywords: morphing; drooped nose, flap; NLF wing;

1. Introduction

Since the beginning of the aviation history, the use of deformable surfaces for controlling the flight is present. The most famous example is the Ader's Eole airplane which design was inspired by analogy of bat or bird wings (or Leonardo da Vinci drawings).

Leonardo da Vinci drawings [1] | Clément Ader's *Avion III* [3]

Figure 1 : How to fly? First ideas.

Surface shape modification by the use of flexible structures was used for flight control for most of the airplanes at this period. However, due to the increase of flight speed, and consequently of the dynamic pressure in flight conditions, these structures appear to be fragile and need to be reinforced, leading to a dramatic increases of the weight of the deformation system. The use of rigid structures in combination with surface control elements became the standard. Note that strictly speaking, the use of an aileron for flight control or the deployment of flaps or slats at take-off or landing phases can be considered as “morphing”: the shape of the wing is modified in order to improve its performance for a flight “off design” condition. Nowadays, a shape is considered as morphed if it considers deformation of the initial surface by the use of flexible materials or mechanical systems.

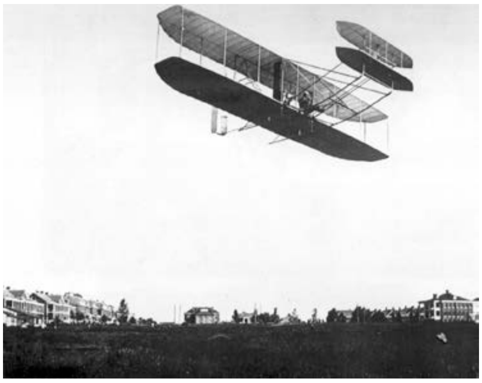
	
Wright brothers’ *Flyer* [4]	Santos-Dumont’s *Demoiselle* [5]

Figure 2 : Pioneer ages – Use of morphing for flight control surface.

Introduction of morphing technology on military aircrafts have shown significant performance improvements on a large spectrum of flight conditions. For instance, the use of variable swept wing of supersonic aircrafts to improve performance at transonic or low speed conditions, is a good illustration (Figure 3).

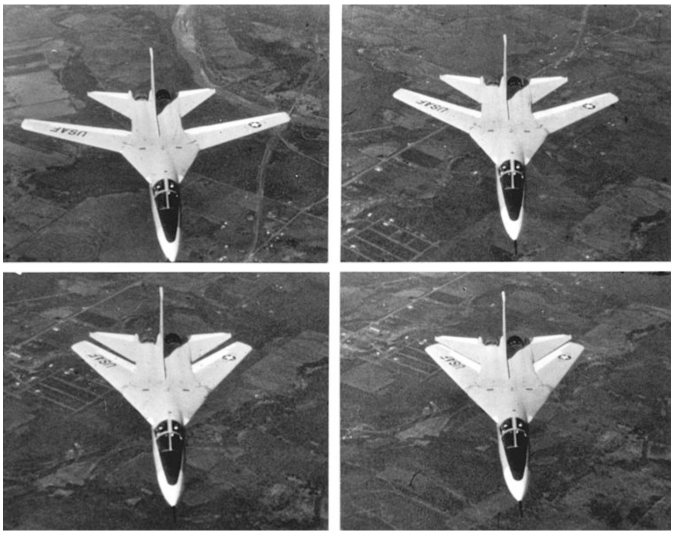


Figure 3: F-111 Aircraft wing sweep modification sequence [6].

In the Advanced Fighter Technology Integration (AFTI) program, by NASA and USAF, the F-111 wing was equipped with control surfaces so that the airfoil camber was modified and monitored during flight (Figure 4), and flight tests confirmed significant gain in aerodynamic performance compared to the reference wing [7].

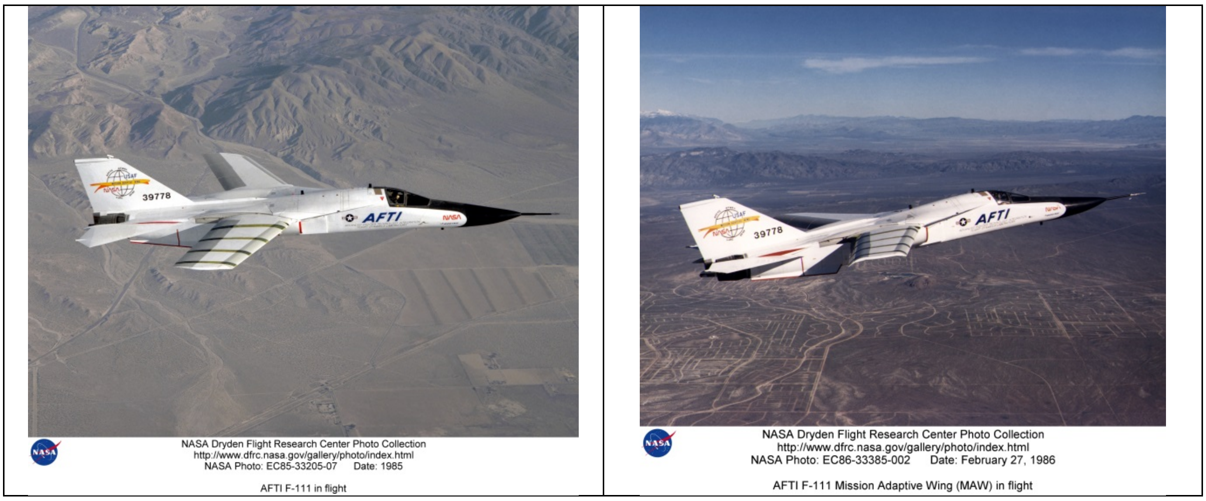


Figure 4 : AFTI/F-111 aircraft in flight [8] with variable camber wing.

However, we have to take care when we extrapolate potential benefits for transport aircraft applications, for which flight conditions to be considered are more limited. For these applications, the introduction of multi point MDO process in the design has leaded to highly efficient design and it is quite difficult to expect some significant extra gains. For instance, the possibility to play on load distribution by variable twist technique in order to match the elliptic span loading distribution is often presented as a good point for the use of morphing technology. However, for transonic aircraft for which wing flexibility has to be taken into account, it is known that the optimum span loading considering aero-structural optimization is not elliptic (Figure 5), and is found by MDO processes.

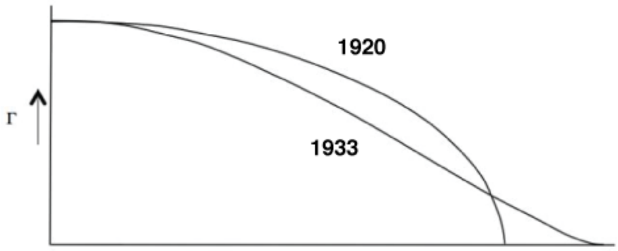


Figure 5 : Optimal span load distribution for minimum drag [9] from Prandtl's studies. No constraints: elliptic shape (1920) – Wing with the same structural weight: bell-shaped (1933).

On the other hand, for subsonic aircrafts, such as turboprop, the trapezoidal unswept wing shape generates naturally a quasi-elliptic span loading. It is therefore very difficult to significantly improve the lift induced drag component for a well optimized airplane around its design point.

However, optimization based on fuel consumption and weight minimization lead generally to solutions that are much more sensitive to off-design conditions. The use of morphing technology on wings can help to improve performance for these off design conditions (climb, high speed) or to extent the flight domain (buffet alleviation, load control, response to gust), as described in the famous article from Hilbig and Koener [10]. It is also possible to use morphing technology on surface control such as aileron or on rudder to replace the current mechanisms based on rotation of a rigid shape.

A final application of morphing technology by the use of deformable surfaces is noise reduction. It is known that major acoustic sources are located at surface discontinuities (slat and flap ends, Figure 6) and the use of continuous surface will suppress the noise emission at these locations. For instance, tests carried out by NASA on a business jet configuration (Figure 7) will certainly show significant noise reduction when compared with the reference plane. However, a global performance assessment has to be stated because for some cases, the existence of discontinuities helps for aerodynamic efficiency. For instance, for high lift configurations, a slotted flap is much more efficient than a plain flap, and sometime, some vortices are created in order to improve maximum lift (slat/fuselage junction or nacelle strakes).

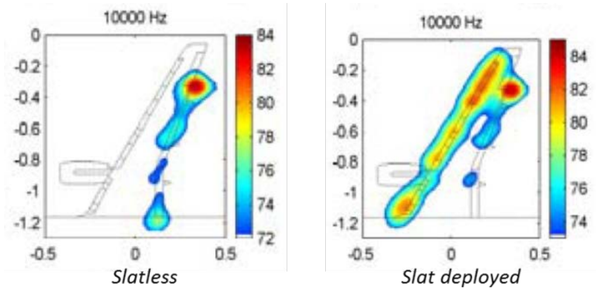


Figure 6 : Acoustic sources identifications on an A321 model in landing configuration (from [11]).

Figure 7: ACTE flaps on NASA's Gulfstream III aeronautical test bed [12].

Finally, at the end of the design process, there is to verify if the gain in aerodynamic performance is not balanced by an increase of weight due to the system itself or the structure enforcements.

All the pre-mentioned benefits provided by the use morphing technology are for high speed flight conditions. However, the use of morphing technology at low speed can also be the source of significant performance improvements. As already mentioned, high lift devices can be considered as belonging to the family of morphing systems, and the performance level obtained by a system made of a single slotted Fowler flap and a slotted leading edge slat is almost the maximum achievable level without active flow control. The drawback is that heavy complex mechanisms are necessary to set the elements at their position. And when stowed, some external fairings are considered to hide the mechanics in order to minimize both friction and lift induced drag components in cruise conditions. However, the selection of a high lift system depends on the performance required for take-off or landing conditions, the main one being the maximum lift and the stall angle. And the specificity of high lift systems is that depending on the needs, one system has to be used [13]: If there is a need to increase the stall angle of attack, a leading-edge device has to be used; if the need is to increase lift at a given flight angle, the use of trailing edge device is necessary. For both cases, morphing technology can be considered. Among the different well known leading edge devices, the droop nose is a good candidate for the application of morphing technology by the use of compliant deformable structures [16][17]. For trailing edge devices, the use of twistable segmented flaps can be used to increase the deflection at a fixed global position [19]. Additionally, when flap is stowed, the last segment can be used in high speed conditions to optimize the wing twist or load distribution. And, last but not least, if the actuation system can be hosted into the wing airfoil shape without external fairing, a significant drag reduction will be achieved for high speed conditions.

Figure 8 : Example of airplanes with Flap Track Fairing (FTF) that lead to significant extra drag at cruise conditions. Image from [14][15].

Such application of morphing technology to improve low speed performance has been evaluated in the framework of the Airgreen 2 EU funded program. This program considers a regional turboprop aircraft configuration for which Natural Laminar Flow (NLF) technology has been considered for the design. This article presents the main outcomes of the use of morphing technology for advanced high lift systems designed on this NLF wing in order to reach the performance level required. In a second phase, the use of the flap deformation system in climb conditions has been considered for performance enhancement in this flight condition.

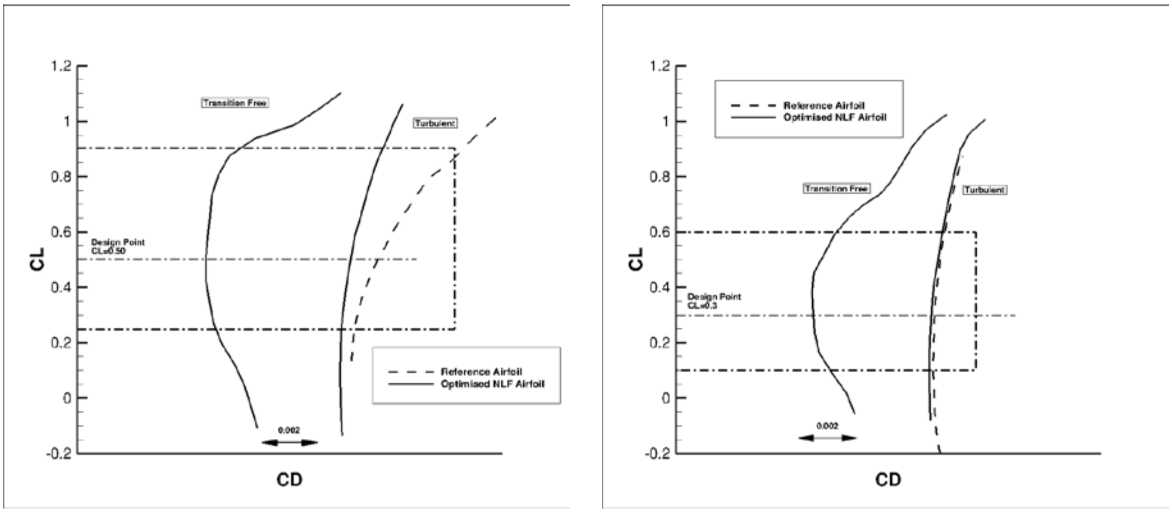
3. Baseline configuration

The reference aircraft considered is a 90-pax turboprop configuration (Figure 9) designed by Leonardo Company in the framework of CleanSky 1 GRA-ITD program.

Figure 9 : Reference TP90 aircraft (Leonardo).

The wing airfoils were redesigned by ONERA at cruise conditions for Natural Laminar Flow capabilities, but the wing planform was not modified. The design considered a multi-point optimization of the tip and root airfoils for cruise, climb and low-speed conditions, in order to have a satisfactory performance level on a large part of the flight domain through an extended natural laminar flow on the upper and lower surfaces. Some details about the NLF wing design are given in [16]. Here, only main results are recalled. This configuration is referred as AG2-NLF in the following.

Figure 10 presents the two-dimensional computed performance of the re-designed root and tip airfoils of the AG2-NLF wing at nominal cruise conditions (M=0.52, Altitude=20000 ft). Performances of the reference (turbulent) airfoil at the same conditions are indicated. The new airfoils exhibit NLF characteristics on a large range of local C_L around the design value. In addition, the performance of these airfoils in turbulent conditions are similar (a tip) or event better (at root) than for the reference one. Then, the wing has been generated considering these two airfoils and twist was adapted in order to take low speed performance into account, with no impact on the computed laminar flow extent on both surfaces at the design point (Figure 11).



(a) : Root Airfoil (b) : Tip airfoil

Figure 10 : Root and Tip airfoil performance of the AG2-NLF wing at nominal cruise conditions.

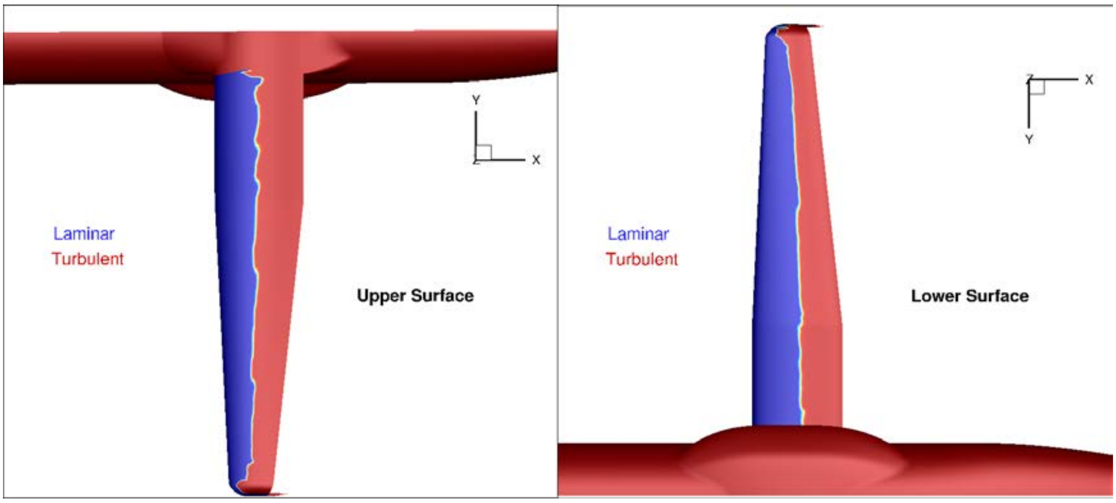


Figure 11 : AG2-NLF wing at nominal cruise conditions – Computed extension of laminar flow on the wing surfaces.

In a second phase of the project, some high-lift devices have been designed and adapted to this wing. Considering the high level of performance required at low speed, the use of morphing technology was mandatory for both leading-edge and trailing-edge devices.

4. Use of a drooped nose

Figure 12 presents the computed pressure distribution at low speed conditions (M=0.15 at sea level) for the clean AG2-NLF wing case. It can be seen that a significant pressure peak is found on the wing at high incidence. This is a common behavior observed for wing designed in order to have laminar flow characteristics (NLF or HLFC technologies) at cruise. In that case, the airfoil leading-edge radius is reduced compared to a turbulent one, in order to drive the favorable pressure gradient to maintain the flow laminar. The drawback is that at high angles of incidences, a strong acceleration is found at the airfoil leading edge that will increase the risk of leading-edge stall occurrence. It is therefore necessary to use a leading-edge device in order to act on the pressure peak at low speed conditions. Moreover, this device has to be compatible with the constraint of keeping laminar flow at cruise conditions when not deployed, and the morphing drooped nose device was retained.

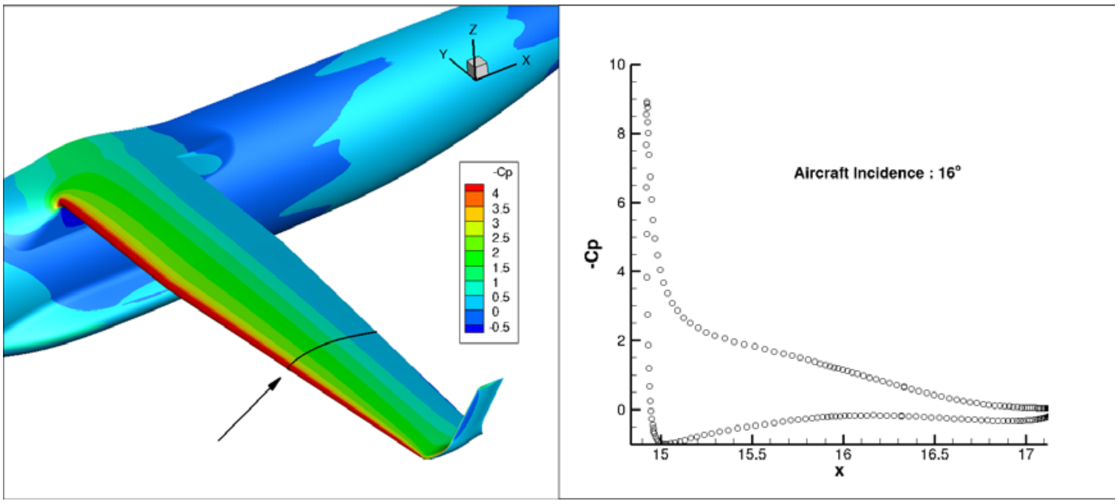


Figure 12: AG2-NLF wing at low speed: development of a large suction peak at leading-edge.

Moreover, compared with a standard droop nose, a morphing droop nose allows redesigning the baseline wing shape that can be optimized considering only the flight conditions that does not require the shape changes introduced by the morphing. This aspect provides an additional advantage in terms of aerodynamic benefit because different external shapes can be defined to optimize the aerodynamic performances in different flight conditions. The different shapes can be designed separately considering that the morphing allows the transition between them, preserves the shape continuity and avoids any type of step and gap. This advantage is greater in the case of laminar wing where the NLF wing can be optimized for the high—speed conditions and the same wing, equipped with the morphing droop nose, for the low—speed conditions.

The detailed process considered for the design of the droop nose adapted to the AG2-NLF wing can be found in [16][17][18]. It considered aero-structural optimizations carried out by Politecnico di Milano and aerodynamic performance assessments done by ONERA. First, a preliminary performance assessment has been done in two dimensional flow for a pre-designed landing configuration considering a standard flap. Figure 14 presents the computed $C_L(\alpha)$ curves for a geometry considering a droop nose or not. As for any leading edge devices, the use of a droop nose leads to an increase of maximum lift and stall angle, but with nearly no effect on the lift level for lower incidences. Values indicated for the gains (+11.5% in C_{Lmax} and +4° in stall angle) are for information only, as they are based on a 2D airfoil, and not on the 3D wing.

Figure 13 : Final 3D drooped nose designed by PoliMi [18].

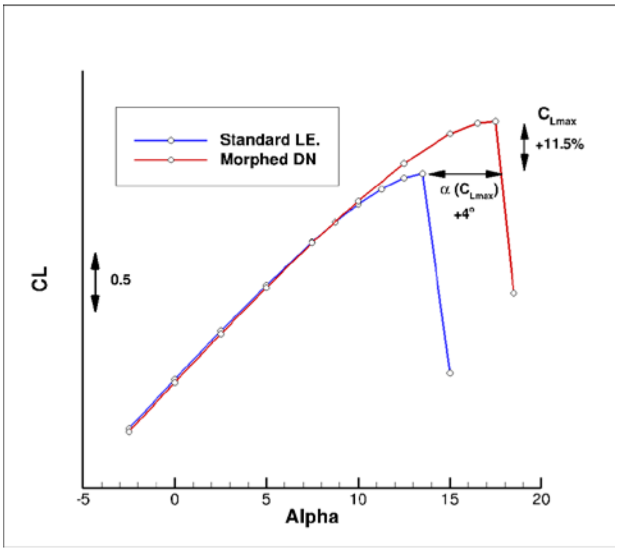
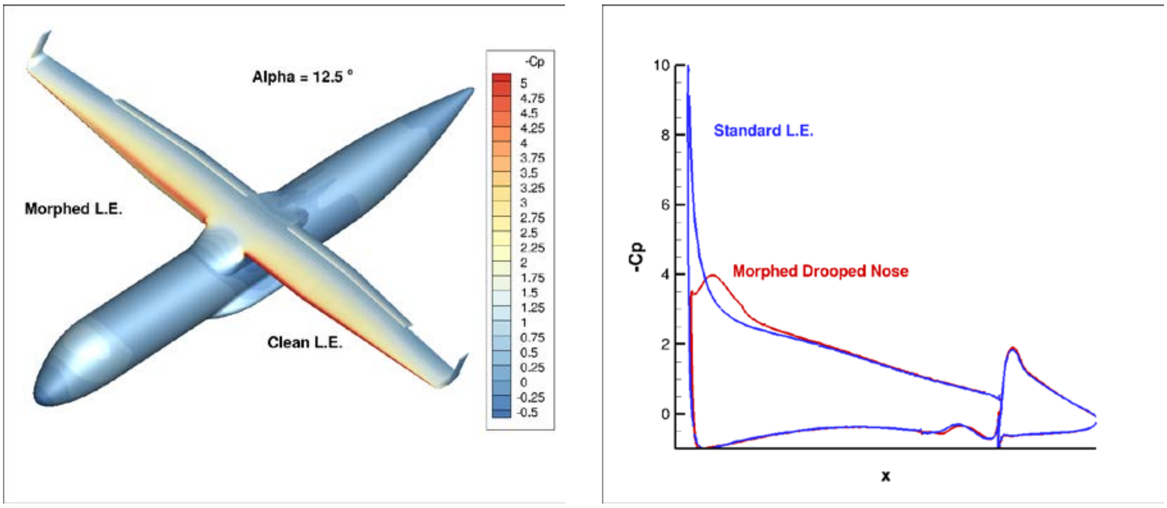


Figure 14 : Use of a morphed drooped nose device – 2D Evaluation of $C_L(\alpha)$ curves – Landing conditions.

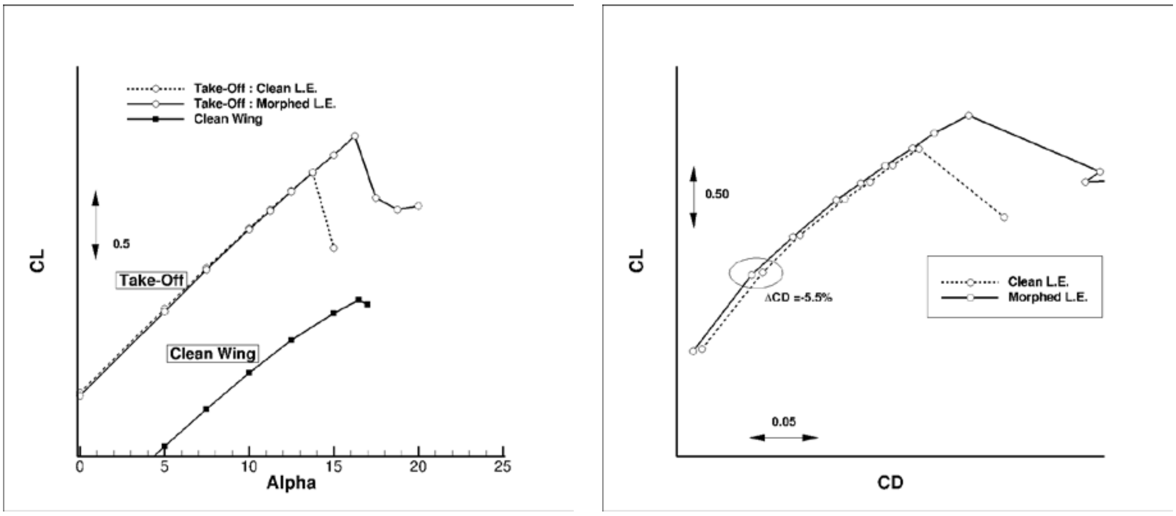
Different drooped nose shapes have been compared leading to the selection of a geometry that has been adapted to the 3D wing-body configuration for a CFD evaluation of the performances. Figure 15 compares the pressure distributions computed on the AG2-NLF airplane at take-off conditions (M=0.20 at sea level) for an incidence of 12.5°. The use of a drooped nose decreases significantly the suction peak at leading edge, which makes the pressure gradient less favorable for a leading-edge stall occurrence. Therefore, stall will occur at a higher incidence, as observed in Figure 16(a).



(a) (b)

Figure 15 : Effect of a drooped nose on pressure distribution (Take-off configuration, Alpha=12.5°). Pressure distribution on the wing (a) and at the outboard flap section (b).

There is another (favorable) effect observed on drag. The change in pressure distribution at the wing leading-edge leads a constant decrease in drag coefficient, corresponding to a reduction of about 5.5% at flight condition for the wing-body configuration.



(a) (b)

Figure 16 : Effect of a drooped nose on performance at take-off conditions. (a) $C_L(\alpha)$ curve , (b) $C_L(C_D)$ curve.

5. Use of a multi segmented flap system

Among the different possibility to deform a wing for performance improvement, one considers multifunctional wing trailing edge. Such system acts on local wing shape deformations in order to modify the span load distribution. Detailed information about the design of the reference flap system used on the AG2-NLF wing are given in [16] and [19]. However, its spanwise extension corresponds to the place dedicated to trailing edge flaps (Figure 17). This system has therefore to be integrated to the flap, which leads to constraints for the design of the high-lift system. Considering the multi-segmented flap system retained, the use of the last segment as morphing device when flap is stowed leads to a maximum shroud location at 92.5% on the wing upper surface. Location of the cove on the lower surface is driven by wing structure rear spar location.

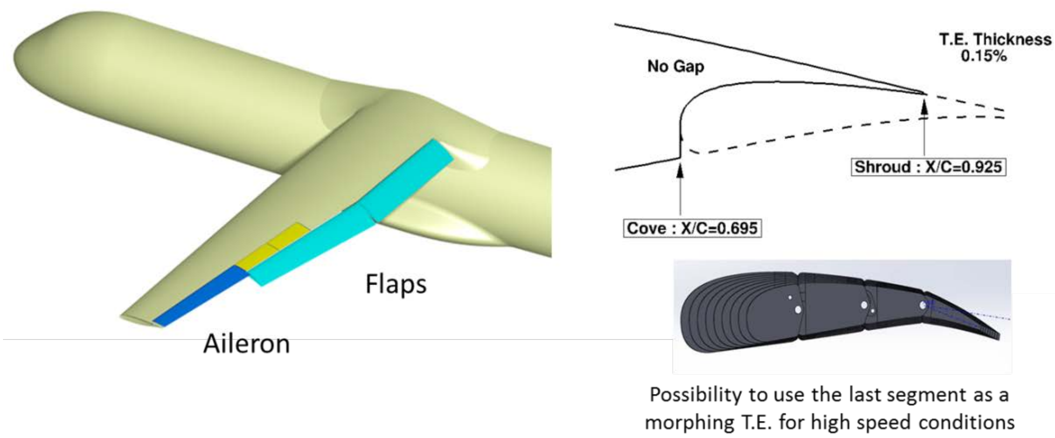


Figure 17 : General layout of the AG2-NLF wing for flap arrangements and flap design constraints.

As mentioned in [16], it is possible to find an optimal aerodynamic setting for landing conditions when considering the rigid flap shape used for take-off. Different flap deployment progression laws were investigated by Siemens Industry Software NV [20] [21], who was responsible of the flap actuation system in the project, and evaluated by ONERA, but it was not possible to find a kinematic that will ensure take-off and landing settings that will not need an external fairing. However, it was possible to design fully integrated tracking system to set the flap at the optimized take-off configuration. It was therefore decided to investigate the possibility to deform the flap shape by the use of morphing in order to obtain "sufficient" aerodynamic performance for landing conditions (Figure 18). Note that it is not evident that such process would necessarily works as we start from a take-off setting and shape (for the front flap segment) that are parameters usually to be optimized for landing conditions.

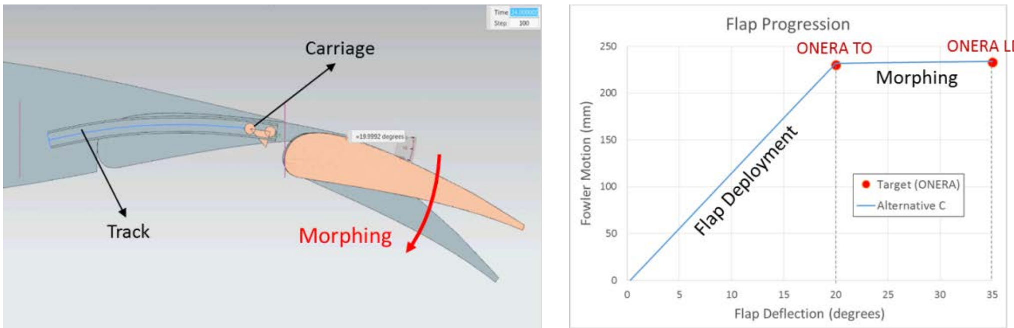


Figure 18 : Best alternative for a solution with no external fairing: Take-off configuration, then apply morphing for landing (Siemens).

Figure 19 presents the morphing flap system from UniNa adapted to the AG20-NLF wing geometry. Note that the different hinge lines are parallel to the flap trailing edge, and not at a constant local chord. It means that when deformation is applied, the flap shape is 3D and that the performance evaluation considering a 2D wing section is not possible. Three-dimensional numerical evaluations are mandatory.

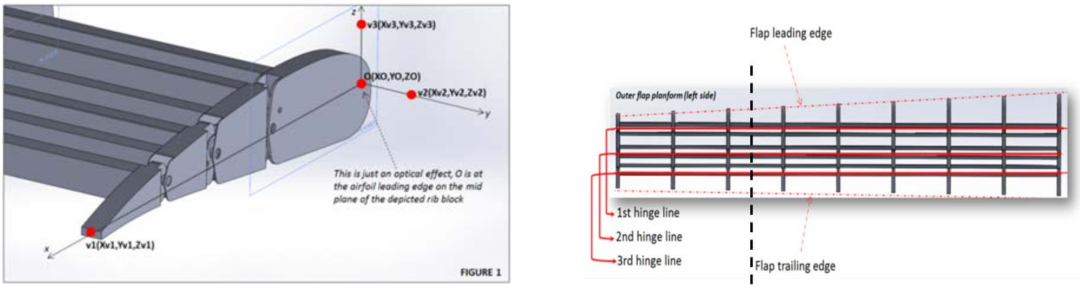


Figure 19 : Trailing edge morphing flap: general layout from UniNa.

Due to mechanical constraints, there are some physical links existing between hinge 1 and 2 leading to the kinematic law presented in Figure 20 for the rotation angles between these two hinges. For instance, it means that applying 5° deflection at hinge 1 leads to 15° at hinge 2 as a global deflection value (or +10° applied at hinge 2 after the 5° deflection for hinge 1). Deflection values for hinge 3 are free, but limited to 10° in amplitude. The symbols correspond to the configurations that have been evaluated numerically. Indeed, preliminary studies carried out based on the rigid flap shape gave an optimum flap deflection around 35° for landing. Taking into account the initial flap deflection of 20°, corresponding to the take-off case, we have to investigate configurations with a deflection angle of the second hinge around 15°.

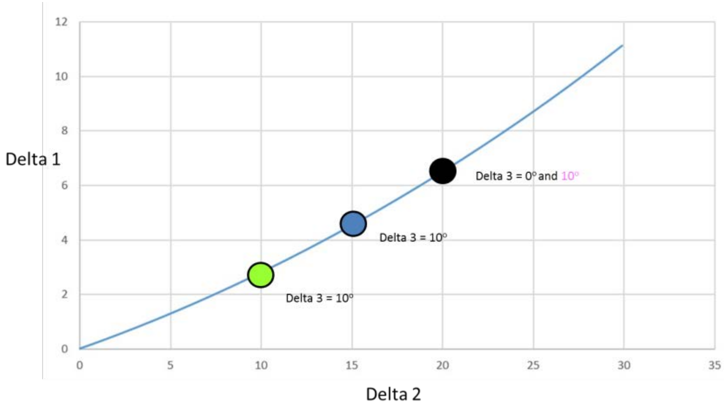


Figure 20 – Morphing mechanism: Kinematic law for the rotation values at Hinge 1 and Hinge 2. Rotation at Hinge 3 is free**.** Symbols correspond to configurations considered for morphed flap at LDG conditions.

Based on results presented in Figure 21, the best combination for maximum lift optimization corresponds to a deflection of 15° for the second hinge, and a 10° extra deflection for the last segment.

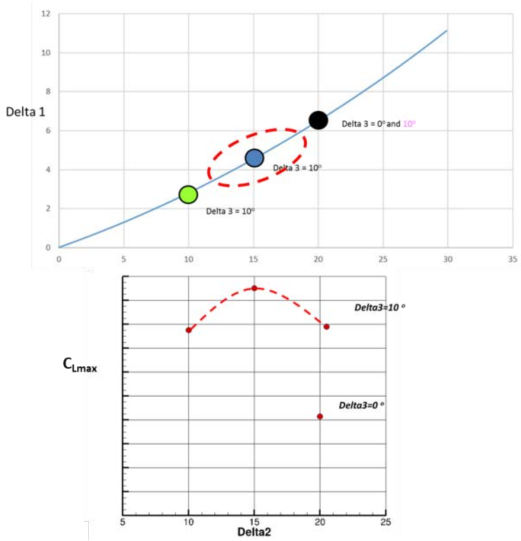


Figure 21 : Optimization of the flap morphing system for landing.

The final performance assessment for the landing configuration (M=0.150 at sea level) considered the use of the drooped nose designed previously in combination with the deformable flap. Figure 22 compares the computed performance for both cases. It can be seen that the combined used of these two morphing devices leads to a significant improvement in both C_{Lmax} and stall angle. The requirement in term of C_{Lmax} level is respected, whereas it is not reached for the configuration equipped with the standard leading-edge.

A final verification considered the stall process of the wing equipped with the drooped nose. It was asked to verify that there is no separation onset in the aileron area for flight control considerations. Figure 23 presents the computed skin friction lines for the landing configuration with the standard leading-edge. It can be seen that a separation occurs on the complete wing upper surface at stall. Figure 24 presents similar plots for the configuration equipped with the dropped nose. Stall occurs more gradually, and starts from the wing-body junction.

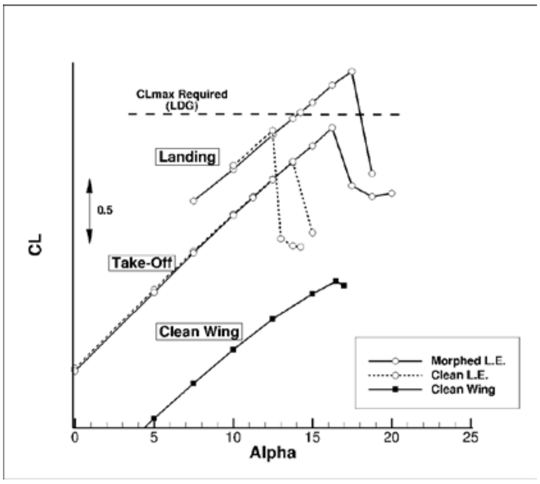


Figure 22 : High lift performance of the AG2-NLF equipped deformable elements (drooped nose and multi-segmented flap system).

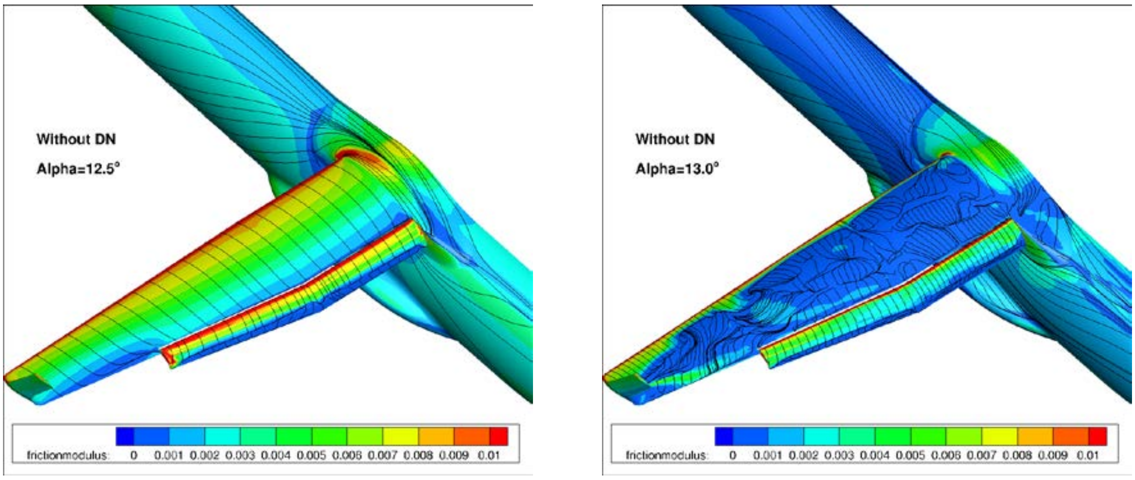


Figure 23 : Landing configuration: stall process with standard leading-edge.

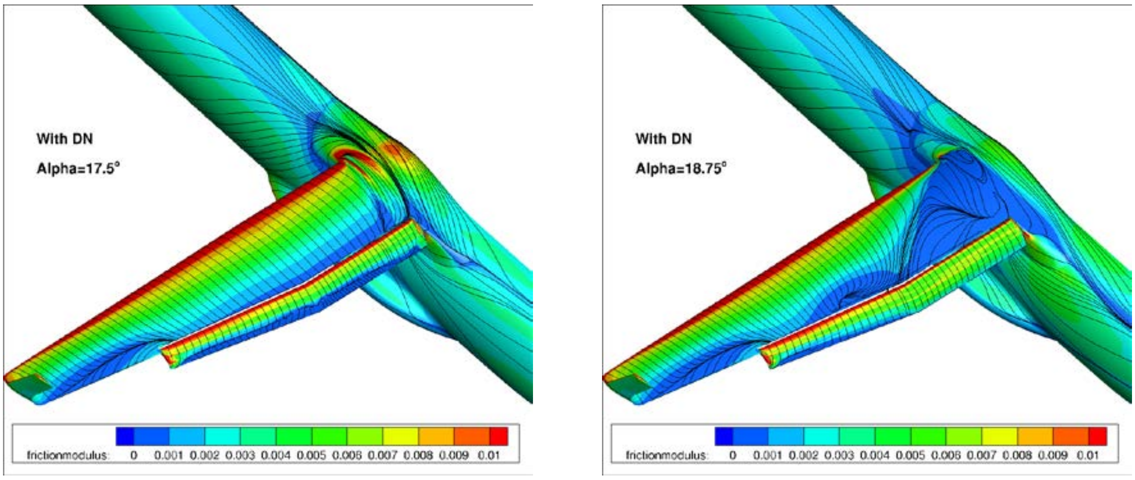


Figure 24 : Landing configuration: stall process with drooped nose leading-edge device.

6. Use of flap morphing system for performance improvement in climb conditions

For the AG2-NLF regional airplane, multifunctional twistable trailing-edge could help to recover the laminar extent by an adaptation of pressure gradient in off-design condition [19]. Considering the C_L related to high speed climb condition (M=0.36, Altitude 15000 ft), free transition computations show that laminar flow on the upper surface starts to be lost on the outer wing. It was therefore investigated the possibility to deflect the last segment of the multi functional flap in order to improve performance in these conditions. Different tab deflections have been considered (2.5° , 5°, 8° and 10°). For the performance evaluations by CFD, the surface grid used for cruise evaluation has been deformed in the tab region and a mesh deformation technique, similar to the one used in the SARISTU project and described in [2], has been used. Figure 25 shows such configuration with a tab deflection of 10°.

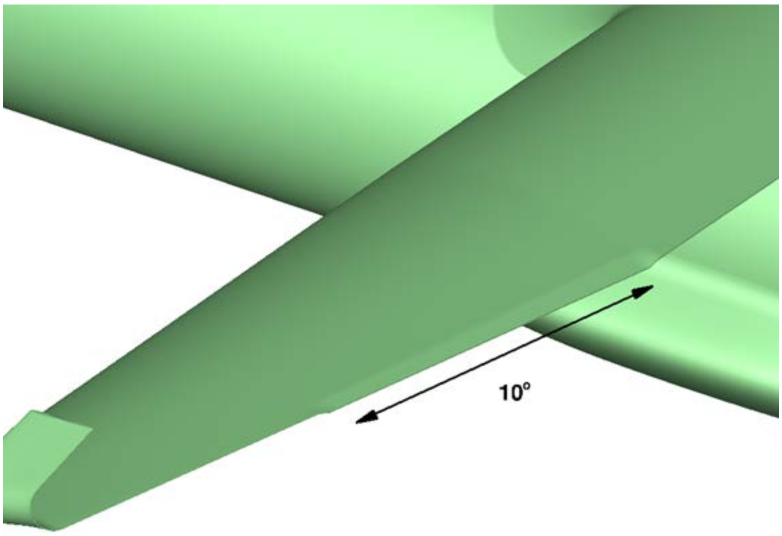


Figure 25 : Configuration considered for multi functional flap at climb conditions (example: deflection of 10°).

Figure 26 presents the computed LoD for the wing-body configuration of the AG2-NLF airplane for climb conditions. The black curve corresponds to the performance of the reference wing. For these conditions, the aircraft C_L is around 0.84/0.90. For these conditions, a loss of performance is observed due to the loss of laminar flow on the wing upper surface (Figure 27 (a)).

The use of small tab deflections (2.5° or 5°) allows recovering part laminar flow on the wing upper surface (Figure 27 (b)) and shifts the LoD curve to higher C_L values and increases the performance of about 2%. However, higher deflection angles (8° and 10°) lead to a global decrease of performance. When considering the drag breakdown between friction and pressure components (Figure 28), it can be seen that if an increase of tab deflection leads to a continuous decrease of friction drag, there is an increase of pressure drag that is associated, leading to an optimum value for low tab deflections.

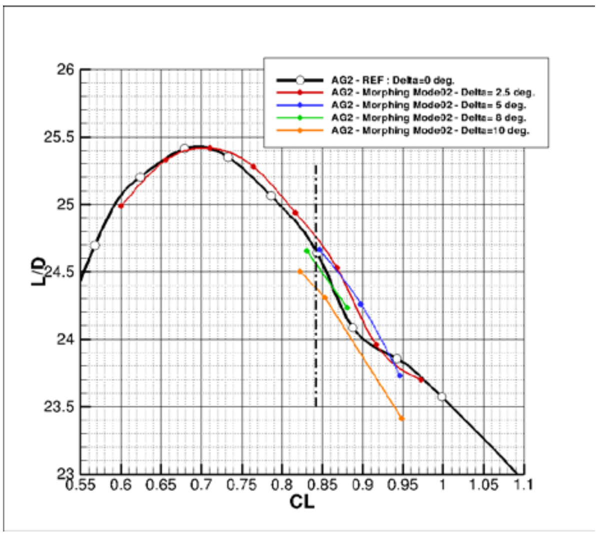
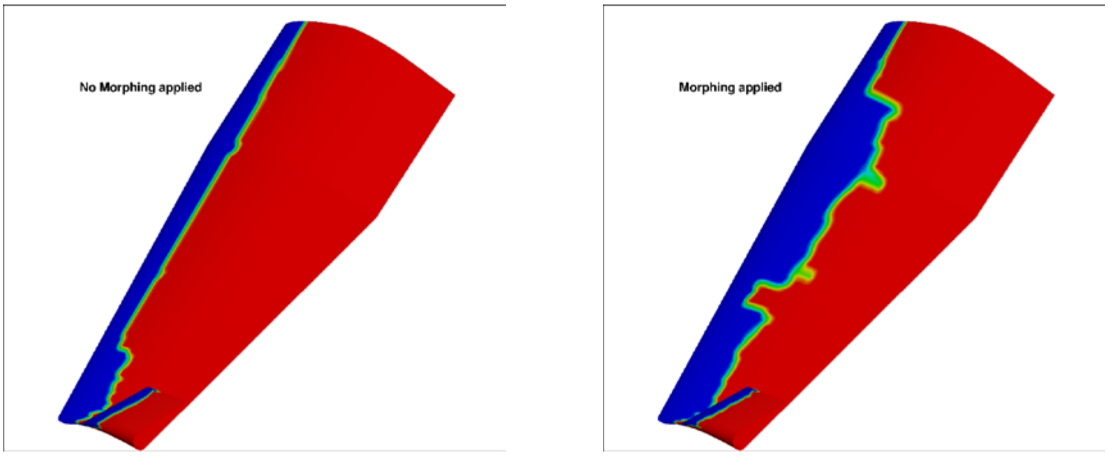
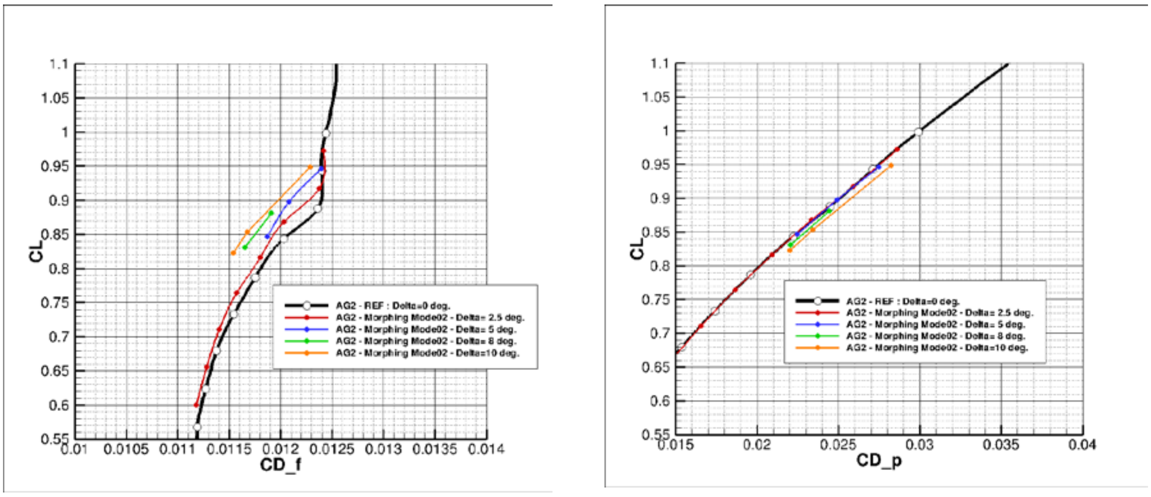


Figure 26 : Performance of the multi functional trailing edge flap (climb conditions).



(a) (b)

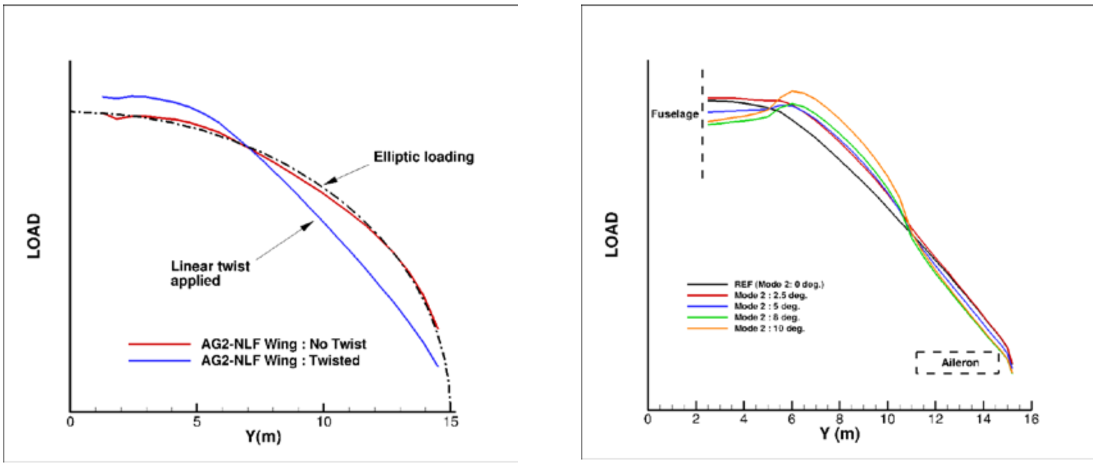
Figure 27 : Natural laminar flow extent on the wing upper surface for climb conditions. (a) Reference wing (no morphing), (b) Morphing applied (2.5° deflection). Laminar flow in blue, Turbulent in red.



(a) (b)

Figure 28 : Drag breakdown for the different configuration of multi functional trailing edge flap (climb conditions). (a) Friction drag, (b) Pressure drag.

Finally, Figure 29 compares the different wing span load evolution at the design point in climb conditions for the different configurations considered. It can be seen that the baseline does not have an elliptic distribution, due to twist optimization for low speed considerations (Figure 29-(a)). The twist of the outer part of the wing has been optimized in order to shift the stall onset outside the aileron area at low speed conditions. A linear twist of 4° between the kink and the tip has been obtained. For the untwisted wing, a nearly elliptical span loading was achieved. The application of a linear twist on the outer wing leads to nearly linear variation of the span load, which will imply a degradation of lift induced drag component through the Oswald factor. Applying a deflection to the multi functional flap system has an effect on the span load evolution (Figure 29-(b)) but only in the portion where the system is located. Recovering an elliptic span loading would mean to act on the outer part of the outer wing, where the aileron is present. Therefore, gains on lift induced drag are not possible if there is no action in this area, through an aileron deflection(or morphed aileron) or a spanwise extension of the multi functional flap system up to tip.



(a) (b)

Figure 29 : Computed wing span load evolution for the different configurations of the AG2-NLF wing. (a) Reference wing at nominal cruise flight conditions, (b) multi functional trailing edge flap deflected in climb conditions.

8. Conclusions

Aerodynamic performance for take-off and landing phases of a regional turboprop configuration equipped with a NLF wing have been significantly enhanced by the application of morphing technology for high lift devices. The use of a deformable morphing based drooped nose as leading edge device has been considered as it preserves the surface quality when retracted in cruise conditions. This device leads to an increase of both C_{Lmax} and stall angle.

For the trailing edge device, a multi segmented flap has been considered. For low speed applications, the objective was to obtain a mechanism that will not require any external fairing, which will improve significantly the drag at cruise. Different strategies have been considered in an interactive process between the partners involved (namely UniNa for the segmented flap system, Siemens for the definition of the tracking system and ONERA for the aerodynamic performance assessment), and it was found that an integrated tracking system was possible to set the flap at its take-off optimum location. Then, morphing was applied on the flap in order to reach the performance required for landing conditions.

Finally, the idea to use the flap last segment as morphing device for performance improvements in climb conditions has been verified. However, this performance improvement was obtained by a reduction of the friction drag, thanks to an adaptation of the laminar flow on the wing upper surface to flight conditions. It is therefore not sure that such performance improvement can be found when considering turbulent wings.

In this article, we only talked about aerodynamic performance improvements for the wing-body reference configuration. Of course, each component (drooped nose, flap system) has to be optimized in order to take into account the weight balance, the system complexity and aeroelastic behavior, and to be integrated into the complete aircraft architecture. Then further design phases can start by considering the propulsion system (nacelle, engines, propellers), the control surfaces (ailerons, horizontal tail, fin), the mechanical components (track systems), the structure and the energy sources. All these elements have to be integrated and considered for a complete aircraft performance on the complete flight envelope.

Finally, the use of morphing technology is not restricted to pure aerodynamic performance improvements. The use of deformable structures for load control during flight is another important application of this technology (see [22] for instance) … and was their first use in the aviation history.

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