Hybrid Laminar Flow Control Activities within the Frame of Clean Sky 2

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Reducing the environmental footprint of passenger aircraft is one of the most important challenges the aircraft industry is facing today. A decrease of fuel burn and consequently also CO_2 plays an essential role in defining next generation aircraft. Obviously, any means to lower cruise drag are to be explored, where Hybrid Laminar Flow Control (HLFC) is one promising option. By influencing the boundary layer of a wing section in a way that delays the transition of the flow from laminar to turbulent, i.e. by increasing the laminar flow wing surface region, a significant drag reduction can be achieved. Within the Clean Sky 2 programme HLFC activities were focused on maturing existing HLFC principles with the goal to provide solutions which can be easily adapted for industrial needs of aircraft manufacturers. During the last eight years the HLFC activities concentrated on developing and maturing manufacturing technologies for HLFC up to a Technology Readiness Level (TRL) 5/6. Moreover, an innovative and simplified HLFC system was elaborated and its system integration into a wing was demonstrated with a final maturity of TRL 4. This paper aims to give an overview of the work performed and describes the chosen design approach to achieve an overall solution for an HLFC wing. In the end, the final overall solution and its key features is explained on a ground-based demonstrator manufactured within the programme.

I. Introduction

The improvement of aircraft efficiency and thus the reduction of fuel burn is vital to reduce the emission impact like CO_2 or NO_X on the environment. Approximately 2.5% of all human-caused CO_2 emissions are related to air traffic. In fact, the number of passengers traveling by airplane increased year by year between 2000 and 2019 in the US [1]. Therefore, aircraft efficiencies must be raised in order to lower the impact due to the increasing number of travelers. Already in 2011, the European Commission recognized such evolution and formulated a strategy paper of European's vision for research, technology and innovation in the European aviation sector by 2050 [2]. The Clean Sky 2 Joint Undertaking is an initiative, which addresses these research ambitions. The aim is to develop the most promising technologies for higher Technology Readiness Level (TRL). One technology is Hybrid Laminar Flow Control (HLFC) on a wing within the project HLFC-WIN in order to reduce the drag of an aircraft and thus saving block fuel. The key aspect is to keep the boundary layer laminar as long as possible. This influences the friction drag on the wing, which is one major drag component as it is shown in Fig. 1.

An overview of previous HLFC applications on aircraft are available in the literature by Collier [3] or by Joslin [4]. Already in the 1980s and 1990s, flight tests were done to show HLFC. These includes tests at a wing of the JetStar [5]

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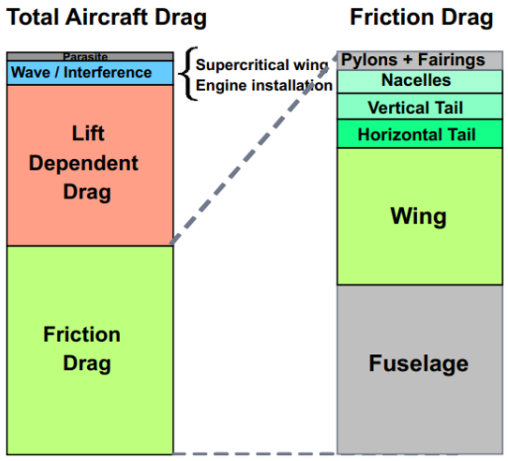


Fig. 1 Relative breakdown of aircraft drag components and detailed breakdown of friction drag to components

and the Boeing 757 [6] or at the fin of an Airbus A320 [7]. All the investigations focus on the aerodynamic investigations of HLFC and the benefit quantification. Hence, the systems were too complex and could not be directly applied on a serial aircraft. Within the HLFC-WIN project, a multidisciplinary approach of aerodynamic, structure and system is followed to develop a suction system for HLFC application, which can be integrated into a wing leading edge. One major result of the project is a Ground Based Demonstrator (GBD) with a span of 2.5 m. This paper presents the HLFC concept on the GBD and give some in-sights of the project. The first part focuses on the overall design approach in order to show the key features. Afterwards, the different systems like high-lift, ice protection and suction system will be described. Finally, validation aspects on the GBD will be presented and challenges will be discussed.

II. Overall Design Approach

Previous projects, such as [8–10], primarily concentrated on validating and verifying the HLFC concept and the associated aerodynamic design methods. However, the system design and manufacturing processes were not sufficiently mature for industrial application. Therefore, the objective in Clean Sky 2 was to elevate HLFC technology to a level enabling economical operation in an airline environment.

This effort was divided into two main streams. Firstly, HLFC was explored for implementation on the Horizontal Tailplane (HTP) of a long-range aircraft. This stream prioritized the maturation of manufacturing processes, focusing on aspects as the industrial micro-perforation of titanium panels [11], the bonding of titanium with Carbon Fiber Reinforced Polymers (CFRP) including the associated laser pre-treatment [12] and tolerance management to maintain laminar flow. The outcomes from this stream served as an enabler for the second stream, which aimed to apply HLFC on the wing leading edge of the XRF-1, a long-range research model.

Apart from providing HLFC functionality, the second stream focused on system integration aspects, particularly addressing the challenge of allocating sufficient space for all systems installed on the wing. The strategy to avoid interference was to define designated areas for each system, as detailed in subsection III.A. This approach allowed the derivation of maximum dimensions for components in the beginning, facilitating the initiation of the design for each system. The maturation of techno-bricks followed a method similar to the test pyramid, progressing from small-scale demonstrators at a low integration level to higher integration levels (see Fig. 2). During this process, real tests and virtual analyses complement each other. Conclusions on each level were used to continuously optimize the design and validate applied assumptions. Several demonstrators were developed to evaluate key performance characteristics and gradually increase knowledge (e.g. [13–16]). Logically, the number of specimens reduces with increasing level. The superior solution for each system was integrated into a common large GBD, presenting the overall solution on a representative wing segment. The GBD served as major milestone to prove TRL 4 maturity for an HLFC wing, while manufacturing processes achieved TRL 5 through the first stream's work on HLFC for the HTP. Hence, efforts within the project go up to demonstrator level, which can be regarded as a first step towards a potential industrial application. This paper will primarily focus on describing the overall HLFC solution on the wing and highlight key features of the GBD, affirming the progress in HLFC technology within Clean Sky 2.

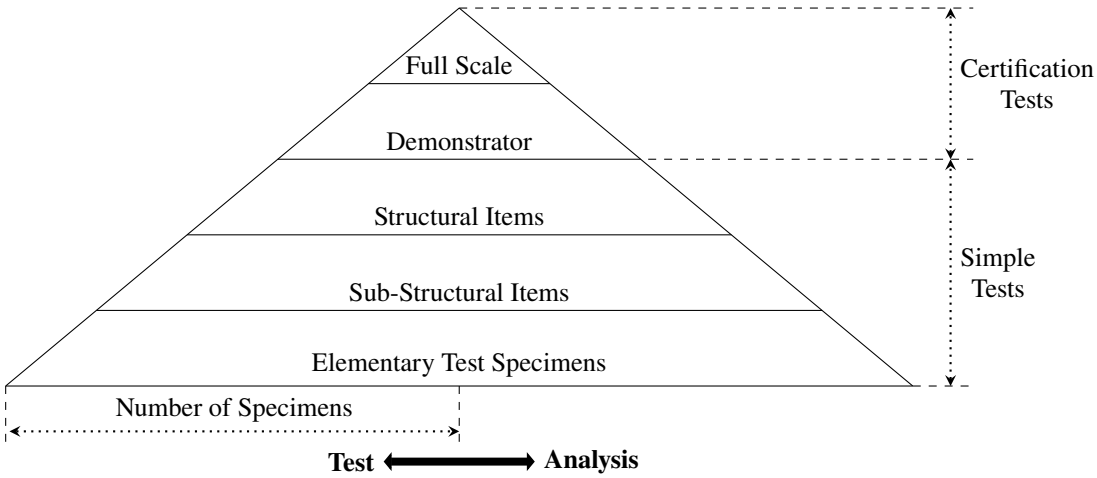


Fig. 2 Test pyramid approach to mature HLFC technology

III. Final Solution

After studying the general approach, the resulting design shall be explained in this section. Initially, the concept to enable the multidisciplinary solution on the wing leading edge is discussed. Thereafter, the integration of each system on the GBD and its values will be assessed in detail.

A. Leading Edge Concept

The transition from a laminar to a turbulent boundary layer on an airfoil is initiated by various flow instabilities. To delay the transition, it is crucial to control these instabilities. One way to achieve this is by modifying the pressure gradient on the airfoil, which can be accomplished through wing shape optimization. However, this approach is not always feasible, especially when it comes to a high Reynolds number or wing sweep angle. An alternative method to stabilize the boundary layer involves the suction of air through a porous outer surface. Underneath the surface, chambers are incorporated to adjust the local pressure and mass flow in accordance with the requirements of the boundary layer above. The combination of these two methods is referred to as HLFC and can result in a substantial increase in laminar flow length, thereby reducing drag.

In earlier HLFC designs, multiple valves and pipes were used to independently adjust the pressure, leading to a complex and heavy system. A significant advancement in system design was achieved through the EU-funded project ALTTA (Application of Laminar Flow Technology on Transport Aircraft) [17]. The refined concept, illustrated in Fig. 3, utilizes two mechanisms to precisely adjust the pressure for each chamber. Firstly, a defined pressure drop is created by an outer surface composed of titanium with a specific porosity distribution. Secondly, finer adjustments are possible through orifices in the inner sheet, typically made of CFRP. Only the inner sheet needs to meet structural requirements, while the outer skin solely generates the required pressure drop. Due to its simplicity, this concept has been applied in subsequent projects, just as for HLFC-WIN.

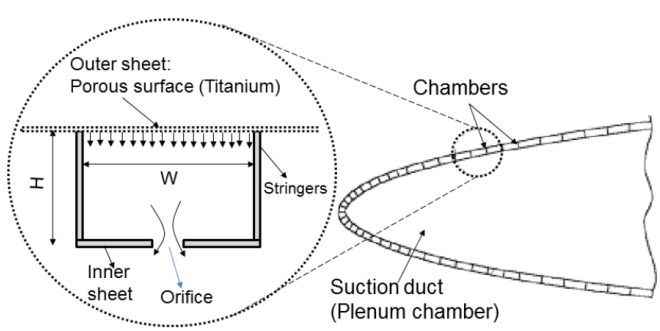


Fig. 3 Visualization of the ALTTA concept, from [18]

As mentioned earlier, the XRF-1 research model served as a basis for incorporating HLFC on the wing. Due to the challenging shock wave system on the inner wing, the primary focus was towards the region outboard of the pylon. The considered section spans a total of 20 m. However, a single perforated titanium panel of this size would not be practical, neither in terms of operability nor on manufacturing feasibility. Consequently, the suction area has to be divided into multiple segments. Introducing too many segments would escalate system complexity and diminish laminar benefits. Conversely, a few segments with larger spans would be difficult to handle during installation and maintenance. After carefully weighing operability, manufacturing capabilities, system complexity and potential benefits, it was decided to implement four segments, each with the same spanwise extent. This results in panels of 5 m length each.

In chordwise direction, the HLFC area in the leading edge is constrained by the front spar, which ensures that fuel capacity and range remain unaffected. Furthermore, only the wing upper side was utilized for suction, as it exerts a more substantial impact on drag reduction compared to the lower side. More precisely, the upper side accounts to approximately 65% of the drag, whereas the lower side only makes up the remaining 35%. Figure 4 illustrates the overall suction area. The remaining available space in the leading edge is designated for system installation. Concerning the HLFC system, investigations revealed that the wing's pressure distribution did not suit for the use of a passive flap to generate suction, as seen in [8, 9, 19]. Consequently, the adoption of an active system with compressors became necessary.

The initial architectural assessment, applying the methodologies outlined in [18], indicated that the optimal solution, considering penalties associated with additional mass, power consumption and the maximization of drag reduction, was to fit two compressors on each of the three inner segments. Typically, the required mass flow decreases towards the outer wing, allowing the use of a single compressor on the fourth segment (refer to [20]). The compressor locations are also represented on the left side of Fig. 4.

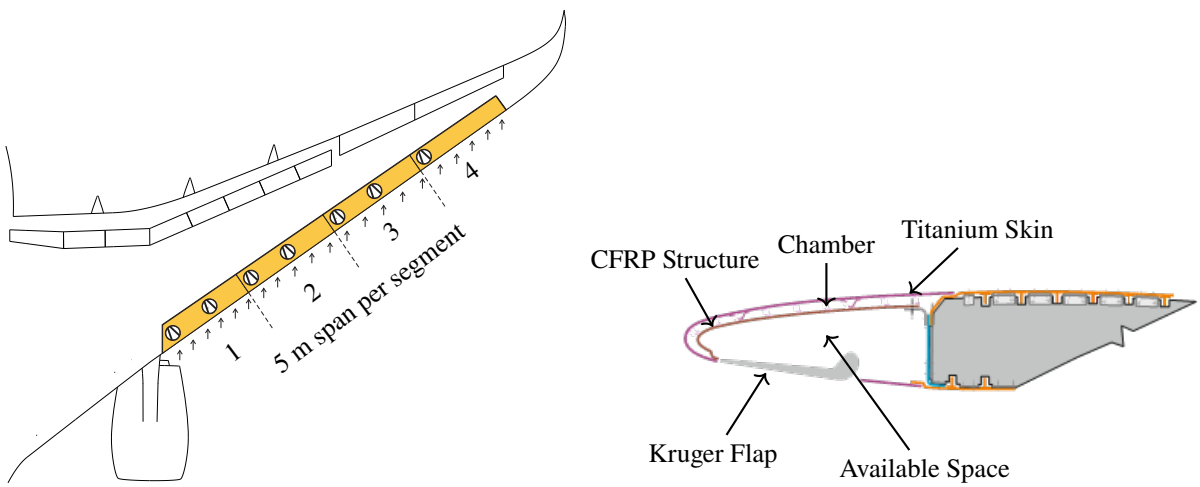


Fig. 4 Concept for applying HLFC on the wing

In addition to HLFC, other critical systems must be taken into account for the leading edge of the wing. Firstly, integrating a high-lift device is crucial to ensure appropriate low-speed behavior. When considering laminarity, it also has the task to shield the leading edge against contamination (e.g. by mosquitoes). In line with other laminarity projects, a Krueger flap is employed for this purpose (refer to the right-hand side of Fig. 4) as it delivers the best compromise for these two basic requirements. Secondly, compliance with certification regulations necessitates the prevention of ice accretion on the wing. This is addressed by an inductive heating system, with coils situated in the chambers between the outer titanium skin and the inner CFRP structure. Finally, the installation of the systems (including bonding, power supply and communication) is a vital aspect for completeness. Further details on the elements will be elaborated later in this paper.

This emphasizes that space allocation is a critical risk for HLFC on the wing. In order to overcome this issue, dedicated areas for each system were defined. In spanwise direction, the 5 m segments were further subdivided. Within every segment, there are two zones designated to the high-lift system kinematics and two zones for the HLFC system, as illustrated in Fig 5. Regarding chordwise separation, the space ahead of the front spar must be kept clear for the harnesses. Furthermore, the zones for the kinematics are divided into two additional sections: the front area is reserved

for the Wing Ice Protection System (WIPS) power electronics and the middle area is allocated for the components driving the Krueger kinematics. In contrast, the HLFC system zones can utilize the total chordwise length up to the limitation for harness installation. This approach aims to mitigate clashes between the systems.

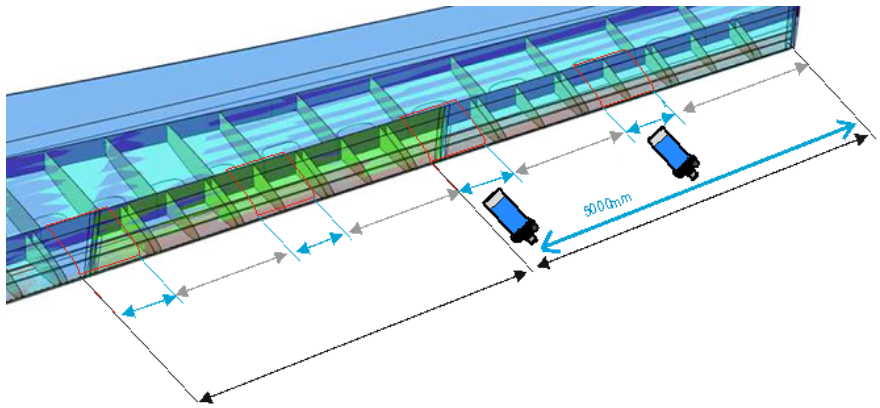


Fig. 5 Spanwise distribution of systems per segment

B. Validation on GBD

The aforementioned leading edge concept served as a basis for the detailed design of each system. The resulting solutions were then incorporated into the final demonstrator. The GBD not only validates the overall feasibility of the developed concept but also stands as the primary achievement proving a TRL 4 maturity level. In general, it has a span of 3 m and represents the outer part of segment 3. This section was selected as it comprises all the mentioned systems and is most critical in terms of space allocation due to the tapering of the wing. The forthcoming explanations will describe the basic integration of each techno-brick on the GBD and outline its key features.

1. Leading Edge Structure

The main components from structural point of view are the micro-perforated outer skin, which is supported by spacers, and the underlying CFRP structure. To describe the major design elements of the final solution as a conclusion of the project, a top-bottom approach will be followed in the next paragraphs.

The outer skin was divided into the minimum segments (gloves) as small as possible within the limits of operations (handling and time to install-removal) and relevant enough from manufacturing capabilities perspective. These gloves were designed "in line of flow" to minimize turbulent wedges in-between segments (right-hand side of Fig. 6). As an initial step in the manufacturing process, the flat panel will be treated with a high-speed laser that drills the variable micro-perforation to tailor the porosity for having the desired pressure distribution in the chambers. The variable porosity is achieved by keeping a constant hole diameter (55 μm) and altering the distance between each other. Within Clean Sky 2, a facility was developed that can realize this process on an industrial level (up to 300 holes per second). After perforation, the panel is press-formed to obtain the leading edge double curvature. Figure 6 shows the titanium skin installed on the GBD.

The outer skin goes beyond the front spar hiding the fasteners between the leading edge and the wing box to the airflow as they could otherwise cause a flow transition (see subsection III.B.3). The external micro-perforated skin is fully detachable in a very short time (3-4 hours, estimated by simulation and demonstrator practice, figure 3) using an ad-hoc sensorized autonomous Ground Support Equipment (GSE). This is aided by virtual or augmented reality googles that guide the process ensuring key quality (laminar steps and gaps) with feedback in real-time. Part of this success is driven by the developments of no visible fasteners and no-seal joint between leading edge and wing box. For the cleaning of the outer skin, a non-contact ultrasonic equipment was used.

When considering the wing leading edge, bird strike resistance must be proven. Generally, there are three potential impact scenarios for the HLFC wing, which are also depicted in Fig. 7:

- Impact on the Krueger flap when it is deployed
- Impact on the inner leading edge when the Krueger is deployed
- Impact on the leading edge when the Krueger is retracted

Fig. 6 Leading edge on the GBD and the wedge between the segments

In the third scenario, the energy shall be taken up by the CFRP structure, so that it needs to be properly sized. Same applies to the Krueger panel (first case). In any case, the titanium skin does not need to fulfill structural needs, though a critical detachment has to be avoided. However, the second scenario seemed to be the most critical one as the bird could directly hit the front spar. For this reason, a multi-material shield (metal-composite) and an aramid covered metallic foam baffle was designed to protect the front spar. Throughout the project, several bird impact tests were performed with different structures in order to validate the simulations performed. In this way, it can be assured that the leading edge would meet the corresponding certification regulations.

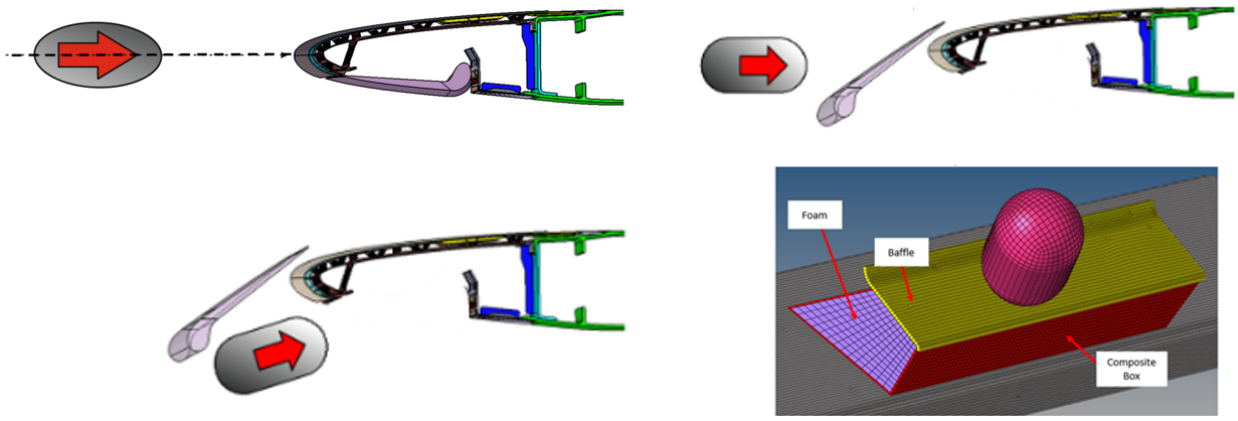


Fig. 7 Scenarios for bird impact and device to protect front spar from damage

To support the outer titanium skin, spacers are located in the chambers, which are trimmed in spanwise direction to let air pass through. In the front area, those are C-Shaped stringers made of glass fiber. For the stringers closer to the leading edge to wing box joint, the shape is “omega” and the material is changed to metal. This ensures best seat tolerances by pressing down the skin against its landing surface without affecting tolerances. It has to be noted that already small deviations on the surface can lead to a turbulent transition. Therefore, staying within the tight tolerances for laminar flow (see section III.B.3) was a main target for the leading edge design and could be validated on the GBD.

Generally, enormous effort was made by the consortium to cope with the aspects of key enablers to achieve hybrid laminar flow requirements, along with the valuable experience gained when implementing HLFC on the HTP. In the end, the leading edge design and the associated processes were matured towards a level where it can be used for industrial application (starting from TRL 6).

2. HLFC System

The decisive component for the HLFC system to generate the required suction is the compressor and its corresponding inverter, which are integrated as one component. In total, the allowed width was defined by the spanwise system distribution while leaving sufficient distance to the front spar for the harnesses (cp. previous section). To achieve this demanding target, it was decided to enclose the equipment in a so-called structural suction rib [13]. First of all, it should hold the compressor and inverter in its position. Secondly, the rib has to separate the pressure-controlled part enclosing the chambers beneath the titanium skin from the non-controlled leading edge bay. The compressor is then aerodynamically connected to the chambers by calibrated throttle holes. Figure 8 shows the solution as it was applied on the GBD.

Fig. 8 Integration in CAD (left) and on the GBD (right)

The compressor inlet is situated within the suction rib. Consequently, based on the mass flow generated by the compressor, a defined pressure drop occurs over the micro-perforated titanium skin due to its resistance to airflow. This creates a lower pressure inside the chambers than the ambient air above. To adjust the pressure chordwise as per local requirements, the porosity of the titanium skin and the throttle holes in the CFRP structure can be modified— a concept referred to as ALTTA, detailed in subsection III.A. Implementing these measures allowed for the use of a single chamber for each of the four segments, marking a significant improvement over previous designs requiring multiple sealed chambers. Furthermore, the compressor outlet blows the compressed air into the leading edge bay, from where it goes back to the environment as the leading edge is not perfectly airtight. As a result, the HLFC system operates entirely without pipes, simplifying the overall system complexity.

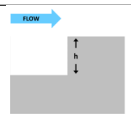
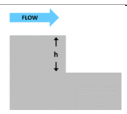
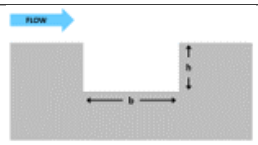
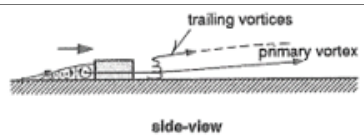
The compressor itself was investigated through a preliminary design study due to the fact that no appropriate equipment is currently commercially available. Results indicate that a good overall efficiency can expected when using a permanent-magnet synchronous motor in combination with gas bearings. Moreover, the mass is kept low with only 11.4 kg for one compressor with an integrated inverter. Hence, the penalty for increased mass and power consumption due to HLFC was minimized, so that the drag reduction prevails.

Operational considerations were also a priority. First, there is just one compressor model that fits all seven locations along the wing. Every compressor can be freely accessed for maintenance and replacement from below the wing with minor disassembly. A dedicated service cover, as depicted in Fig. 8, allows for inspection of the chamber's condition. The image also reflects the actual installation on the GBD. Apart from the integration work, functional tests were performed with that setup as well. For that, a functional compressor with known mass flow was installed. The measured pressure distribution in the chamber was as anticipated, which means that the system design works as intended. In conclusion, a lightweight, efficient, and easily maintainable solution was achieved. Compared to previous designs, system complexity was significantly reduced. Future projects should focus on the detailed design of a suitable compressor for integration into a real aircraft.

3. Leading Edge to Wing Box Joint

One essential component for the HLFC system is the joint between leading edge and wing box. In case that the suction is applied only at the leading edge, the transition of the flow has to be delayed as far as possible in order to maximize the drag benefit. One reason for flow transition from laminar to turbulent are disturbances on the wing like rivet heads or steps and gaps between components. The joint between leading edge and wing box requires a sophisticated concept to minimize such disturbances. It is also vital to know at which condition of a disturbance a transition between laminar and turbulent flow is triggered. In Table 1 is a list of different disturbance types with a criterion related to Reynolds number for defining the transition.

Table 1 Overview of aerodynamic criteria for discontinuities [21–23]

Type	Sketch	Literature criteria
Forward Facing Step		Nenni et al.: $Re_h < 1800$
Backward Facing Step		Nenni et al.: $Re_h < 900$
Gap		Nenni et al.: $Re_b = 15000$
3D Disturbance		Klebanoff et al.: $Re_{hh} = 500 - 800$

These criteria were applied on different chord sections for the HLFC wing. The essential transition region where the leading edge and the wing box are close to each other are in the relative chord position (X/C) between 15% and 30%. This leads to requirements, which have to be considered for tolerances in the manufacturing process between components. A summary of these requirements is in Table 2.

Table 2 Dimensions for different disturbance types on HLFC wing

Type	Chord range	Dimension
Backward Facing Steps	0.15<X/C<0.30	Step Height <0.12mm
Forward Facing Steps	0.15<X/C<0.30	Step Height <0.5mm
Gaps	0.15<X/C<0.30	Gap Width <0.11mm
3D Disturbance	0.15<X/C<0.23	Height <0.11mm
3D Disturbance	0.23<X/C<0.30	Height <0.16mm

The advantage of the elaborated solution is a titanium skin, which can be used as an exchangeable glove and represent the outer aerodynamic skin. The riveting of wing box and leading edge is underneath the titanium skin. The underlying CFRP skin of the leading edge will also carry the complete loads. Therefore, the rivets will not disturb the flow. The only transition can occur in the area, where the outer skin reaches the wing box. Here, the skin is pre-bent, so that it presses down on the wing box and achieves a tight fit. It has to be ensured that the limitations from literature given in Table 2 are not exceeded.

4. WIPS

In this project, it was chosen to implement an inductive ice protection system to heat the titanium skin on the outer surface of the leading edge. The reasons for that choice were multiple. An electro-thermal system made of heating mats was incompatible with the HLFC system, as it would have implied a resistive heating layer in contact with the titanium skin, thus obstructing the micro-perforations. A conventional bleed air system would have been challenging to fit into the relatively small space between the CFRP structure and the titanium skin, while being based on a less innovative technology. Thus, induction heating appeared to be the most innovative option, compatible with the HLFC system, and also compatible with future aircraft, which are expected to be more electric. The basic principle of induction heating is that an alternating current is passed through spiral coils to create a strong alternating magnetic field. This alternating field then induces eddy currents in the electrically conductive titanium skin, generating through the Joule effect the heat

required to protect the leading edge from ice. The inductive coils are made of specialized Litz-wire, adapted for carrying the high-frequency current, and are held in the required spiral shape by specially designed 3D-printed supports. The supports are placed onto the CFRP structure, underneath the titanium skin (see Fig. 9). It is assumed that future more electric aircraft generations will be based on high-voltage direct current (DC) power supplies. Therefore, frequency converters are required to transform the DC supply of the aircraft's electrical network into the aforementioned alternating current. All the involved power electronics are placed inside protective casings underneath the CFRP structure. It should be noted that an adaption to a conventional aircraft power network relying on alternating current would be feasible as well.

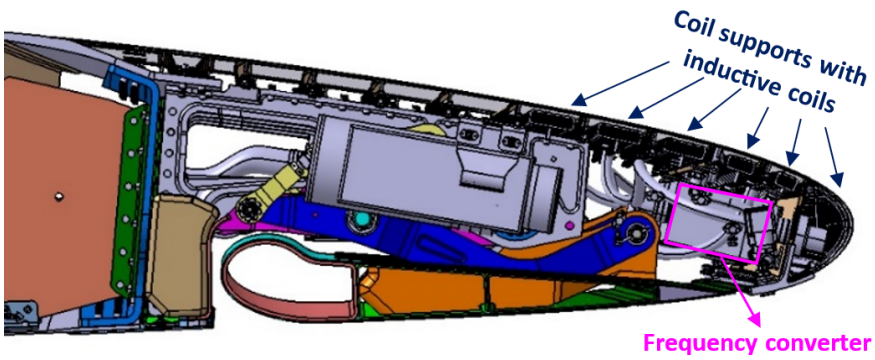


Fig. 9 Integration concept of the inductive system on the GBD

The inductive ice protection system was designed using several types of numerical simulations. In order to specify the power requirements, Sonaca performed a combination of aerodynamic and thermodynamic analyses. Subsequently, the inductive coils were designed using finite elements representations of the electromagnetic induction process. The demonstration of technical feasibility as well as the system and simulation validation was based on two test campaigns (see Fig. 10).

The first one consisted of a small scale test campaign in which the inductive and thermal behavior of a small specimen (5 cm × 15 cm) was studied. This first characterization campaign allowed for confirmation of the good system efficiency as well as a better measurement of both the titanium skin and Litz-wire resistivity. Furthermore, some adaptations of the system were made in order not to induce a prohibitive level of eddy currents and heat in the CFRP structure, which is situated on the other side of the coils in relation to the titanium. This test campaign was later followed by a larger scale one, performed in an icing wind tunnel facility. The specimen represented a wing section fitted with the double skin system and four inductive coils. Thus, the system was tested in representative icing conditions. It proved adequate in several types of icing conditions (various combinations of temperatures and liquid water content), including situations of delayed ice protection activation. No major technical no-goes were highlighted during the campaign and a good match with numerical simulations was also observed.

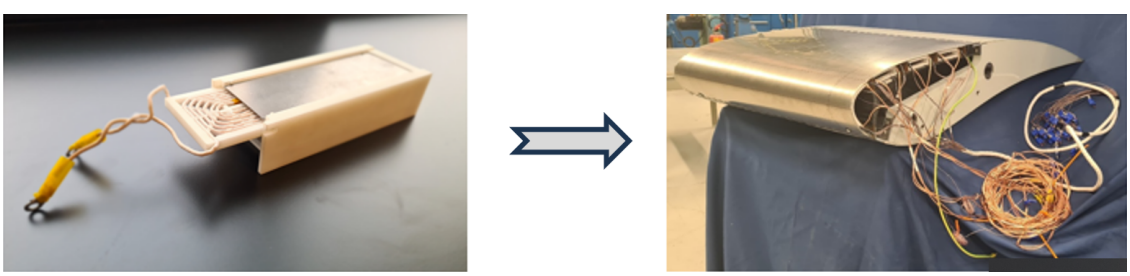


Fig. 10 Small scale specimen (left) and demonstrator for icing wind tunnel test (right)

Conjointly with the test campaigns, the frequency converters were designed, alongside with the power signal harnesses. This enabled to demonstrate proper integration into the wing from a space allocation point of view. The study also yielded a bill of material, allowing for weight and cost analyses. This resulted in an integration of the inductive coils into the GBD, with one of them being functional, albeit on low power for safety reasons due to the absence of external air cooling.

To summarize the findings, an inductive ice protection system was shown to be technically feasible for the protection of the wing leading edges. All the studies, as well the GBD, included the space allocation for the power harnesses, the power electronics and of course the system itself. The introduction of an inductive system was considered as beneficial due to the HLFC suction system with its double skin structure, which is central to the research project. Outside of an HLFC context, the inductive system also has the advantage of being independent from the aero-structure, which can be simpler and less costly when either the aero-structure or the ice protection system needs to be repaired or replaced. Other areas of the aircraft may also require ice protection (e.g. vertical stabilizer, the empennage, external measurement instruments) to which an inductive system could, in theory, be adapted. However, the advantages mentioned above would come at a cost. Indeed, the double skin system is heavier than more conventional aero-structure architectures, and is justified here only because of the HLFC suction system. Outside of an HLFC context, more conventional ice protection systems would prove lighter, when combined with a rather traditional wing architecture. Consequently, in order to achieve a similar mass with an inductive system, it would be necessary to establish a concept with a single skin. However, the challenge would then be to avoid an aluminum structure. Indeed, due to its good electrical conductivity, the Joule effect would not be sufficiently pronounced, thus requiring too much electrical power to generate the required heat.

5. High-Lift System

The applied suction at the wing leading edge requires a high lift system that does not cover the leading edge in cruise flight. Therefore, a conventional slat cannot be used, which was part of the initial XRF-1 reference configuration [24]. Hence, a Krueger flap is developed in the project, because it has an influence only on the lower side of the wing in retracted position. The complete high-lift system including trailing edge flaps and Krueger must achieve the same lift coefficient as the configuration with a slat. The target approach category of this long-range aircraft is the ICAO category C with an approach speed of maximum 140 knots. These requirements set the baseline for the aerodynamic calculation. The results of these calculationw are loads and forces for the further development.

The Krueger system development includes the design of the Krueger panel, the kinematic and actuation system. The final solution for the GBD is a Krueger with a span of approximately 2.5 m. For the final aircraft solution, the Krueger span is constant, so that one HLFC segment contains two Krueger flaps. The kinematic of the Krueger is a scissor kinematic, which is shown in Fig. 11.

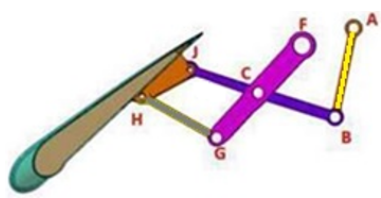


Fig. 11 Sketch of Krueger panel with kinematic

Point F is the connection to a rotary actuator while Point A is the rotary joint. The kinematic has to ensure that the Krueger panel is deployed as a shielding device for the leading edge in order to prevent contamination on the micro-perforated skin. The panel consists of three cells and a separate trailing edge, which are bonded to each other. Moreover, layers of tape are applied on top by filament winding to achieve the required manufacturing tolerances. The manufactured panel for the GBD is made out of CFRP and shown in Fig. 12.

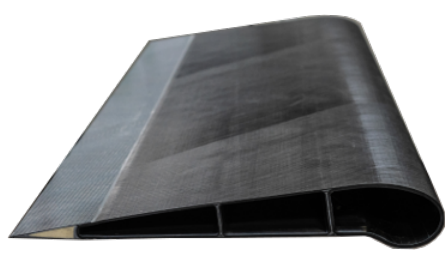


Fig. 12 Manufactured Krueger panel for GBD

The policy statement PS-ANM-25-12 has a strong influence on the high-lift design. In order to comply with it, three kinematic stations were implemented. The reference aircraft was elaborated before that policy statement and has a slat system with two stations only. Therefore, it is challenging to compare the developed Krueger system with a reference due to the clarification of the statement. Figure 13 shows the final solution with three kinematic stations for the Krueger for a span of 2.5 m. In general, the three stations allow an extension of each segment, but then the arrangement with the four HLFC suction segments is more complex. As a result, the manufacturing of the Krueger for the GBD was fixed to 2.5 m, but an extrapolation to a longer span seems possible. Such an extension of the Krueger has an impact on the overall mass, because the eight Krueger panels can probably be replaced by six panels for the four suction segments.

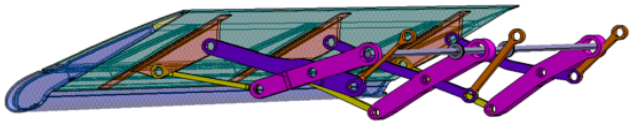


Fig. 13 CAD model of Krueger with three kinematic stations

IV. Conclusion

HLFC is a promising technology to decrease aircraft drag and thus increase efficiency. This is not only beneficial to reduce emissions, but can also be a contributor to overcome challenges on future aircraft generations, such as increased cost of sustainable fuels or the high volume demand for hydrogen-based propulsion systems.

Former projects focused on the validation of HLFC functionality. Therefore, the target within Clean Sky 2 was to advance HLFC technology so that an industrial application is possible. To attain that goal, the efforts were divided in two streams. Firstly, HLFC manufacturing processes were matured by an investigation to implement HLFC on the HTP of a long-range aircraft. Secondly, integration aspects should be proven for applying HLFC on the wing leading edge of the XRF-1 research model. Main output of each stream to validate the results was a large GBD. The focus of this paper was on the second stream. Integrating all required systems into the leading posed the key challenge for this task.

The division of available space into designated zones for each system, in both spanwise and chordwise direction, has been crucial in avoiding clashes and defining essential boundary conditions for system design. The detailed design process, addressing not only HLFC but also the high-lift system, ice protection system and overall system installation, has confirmed the complexity of integrating multiple systems within the narrow wing leading edge.

The efforts were merged in the successful final integration demonstrated on the GBD, affirming the overall feasibility. Besides the integration aspects, functional tests were performed for every system on the GBD. In general, good agreement between prior investigations and measurements was exhibited. These achievements marked a significant milestone, reaching a TRL of 4. Within this paper, the key elements of each system as well as their main features were outlined. Besides the advancements on the wing, manufacturing processes connected with HLFC obtained a TRL 5 maturity through the investigations on the HTP. Furthermore, the HLFC system complexity was significantly reduced.

Aerodynamic calculations identified a drag reduction of roughly 3.5% on the wing compared to a reference aircraft [24]. Extending the HLFC system to the inner wing could significantly increase the drag savings any further. Though, implementing HLFC comes at the cost of increased mass, power demand and complexity. This needs to be addressed on the final value assessment. The numerous demonstrators built and tests performed during the project supported the validation of previous assumptions and allowed for improved evaluation capabilities. For example, an additional power demand of 100 to 120 kW as well as a total mass increase of 1100 to 1500 kg could be identified, which is compliant with the investigations in [25]. Moreover, the assessment of additional cost for aircraft procurement and operation was refined. The overall results suggest that the cost savings due to the decreased fuel consumption still prevail throughout the aircraft lifecycle. However, it has to be noted that this assumption is based on various uncertain input parameters, which could greatly differ in future (e.g. cost for fuel and material) and impact the net profit negatively or positively.

In conclusion, HLFC and its associated technologies could be significantly advanced towards industrial applicability. It has to be noted that many techno-bricks are not specific for HLFC purposes, but can also be implemented on general aircraft design (e.g. inductive ice protection system, tolerance management, leading edge assembly concept). Current evaluations indicate that a profitable operation in an airline environment is feasible. Hence, future projects should investigate the application on a real aircraft to gain knowledge on operational aspects and improve the reliability of the value assessment.

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