Designing cleaning devices for laminar wings

Yann Steiner, Pénélope Leyland, Pierre Wilhelm, Sebastien Bustamante*
GR-SCI-IAG, EPFL, Ecole Polytechnique Fédérale de Lausanne,
CH-1015 Lausanne
** Master student*

Abstract
Future aircraft will pay even greater efforts to provide as laminar as possible wing technologies, in order to ensure lower fuel consumption and optimal cruise conditions. Small asperities deposition on the wings during take-off and climb can induce transition and partially destroy laminarity. One of the causes of such deposition comes from insect striking. In the context of the FP7 CLEANSKY JTI Initiative, EPFL has lead a study on cleaning devices for such wings with two major European Aircraft Manufacturers, Dassault Aviation and Airbus. The project was run in parallel with a student semester project campaign, integrating teaching, research and design. This paper will discuss the design parameters and strategies, backed up by simulation and multiphysics evaluations, and point–out the strength of including students' projects directly into such studies.

1. Introduction

The present work is part of the European *Cleansky* project which aims to decrease the environmental impact of todays and future aircrafts. In the frame of this project, investigations on the enhancement of the aerodynamics performances required to reduce CO2 emissions have been conducted leading to the design of some new type of natural laminar flow (NLF) wings.
In order to ensure the full efficiency of these new wings generation, a system ensuring the total cleanliness of their leading edge is needed. This paper presents the study and the strategy undertaken for the design and implementation of such an integrated and autonomous system in cruise flight on both Airbus smart fixed wing aircraft and Dassault future NLF wings.
The main responsible for leading edge surface contamination originates from insect striking during low altitude flight phases (takeoff and landing). A critical residual height has been considered as the limit where eddies are generated promoting the transition from laminar to turbulent flow. The system must ensure this level of cleanliness on the leading edge.

The strategy undertaken in the frame of this project is composed of four main parts:

- Definition of requirements. These are based on: aerodynamic, aeronautic and geometric constraints, structural and material properties, weight limitation.
- Definition and evaluation of feasible solutions. A particular attention is given to a solution coming from the sailplane industry, using mechanical cleaning during flight.
- Development and implementation of the best solution.
- Full scale test on a representative test rig. A few pre-test are conducted during the design phase to validate the physical principle.

Beside the technological challenge, the aim of the project is to include students work in the design process. Both the engineer and the student can greatly thrive from such collaboration. The student learns new software, design methods as part of his education, but also gets the opportunity to discover nonacademicals work methods and industrial partners. The engineer on his side can gather valuable information in regards of design possibilities but also flaws and possible problems which might occur in the later work.

2. Main requirements and problem approach

2.1 Technical requirements

The requirements of the aircrafts manufacturers originate from their need of a feasibility research for their future laminar wings. This corresponds to wings of about 12 to 16 meters span for 20° to 30° sweep angle without leading edge slat systems.
The leading edge is given as the only area to clean, other surfaces are not considered critical to insect striking and turbulence creation. The device is designed to clean 5% of the chord on both suction and pressure side of the wing, which also corresponds to its high lift area.
The specific requirements applied to this project are listed below. Most of them are directly linked to the general requirements of the aviation industry, other are more specific to the system itself.
The retained solution must:

a) be able to ensure a surface roughness less than the critical height;
b) be able to be applied on aluminium based alloys typically used in manufacturing of actual aircraft leading edges;
c) be compatible for a long term operation regarding corrosion, erosion and surface resistance;
d) not alter leading edge’s shape;
e) not alter surface material microstructural properties;
f) be reliable and efficient under any atmospheric conditions;
g) not create ice;
h) be autonomous;
i) not trigger the loss of large sized elements for safety reasons;
j) be as light as possible. In this project, the maximum weight of the whole system has been set to be less than 500 Kg;
k) minimize impact on aerodynamics performances during the cruise, the system has to be fully integrated in the plane structure before and after its operation;
l) be sized to resist all the surroundings loads in order to ensure stability and avoid its destruction;
m) have a movable part able to move along the wingspan;
n) must have movable parts controlled at any time;
o) be able to follow the wing leading edge’s shape all along the wingspan;
p) must be rigid enough in order to avoid any shocks between them and the wing surface;
q) not alter the wing surface shape by micro (scratch) and macro (to fatigue created by contact) deformations;
r) clean the wing leading edge in 2 passes.
s) In the case of an inflight solution, the cleaning system’s shape has to be as aerodynamic as possible in order to enhance the airflow around it thus minimizing the loads and the influence on plane aerodynamics during the cleaning operation.

A generic research has been conducted on various means of cleaning, from dry ice cleaning to scrapers with glycol solutions. These solutions include: thermal, chemical and mechanical cleaning. For most of the non-dry solutions, the system weight tends to discriminate any use of liquid.
The Fraunhofer Institute for Manufacturing Engineering and Applied Material Research (Fraunhaufer IFAM) has lead a study on anti-contamination coatings and developed tests to assess insect debris adhesion and clean-ability.
An input from the sailplane industry was also considered: the bugwiper from PAS (Pirker&Storka, Austria). However the system needs a complete rework as it uses aerodynamic forces and wires as

guidance system, which is not sufficient for the airliner application due to safety issues and aerodynamic loads.

2.2 Work breakdown in an academic environment

The initial project was run over 18 months as a series of 3 semester bachelor/master mechanical engineering curriculum project work. 3 levels of project were run: group project of 8-15 students as a design space exercise at bachelor level, representing 1.5 days a week over a semester, individual or small group (2-3) master level semester work representing 20hours a week per student over a semester, and master diploma thesis project representing an individual contribution full-time over a whole semester.
For the first category, typically a group of students were divided into a task force of 4-5 smaller groups, organised to be complementary. The tasks included two main groups:

Group Re-design

- Task 1.1: Documentation about existing concepts
  - Exhaustive documentation gathering and selection of potentially extrapolable existing concepts
  - Reverse engineering
  - Re-design

This included firstly: documentation gathering and summary, industrial actors identification, cleaning mechanisms identification, cinematic mechanisms identification, trade-offs, solutions selection process. Secondly performing relevant reverse engineering, measuring and CATIA drawing of selected solutions, dimensioning, re-design loop with modifications to lead to final design.

Innovative designs HOMOFABER group

- Task 1.2: Investigation for alternate and innovative concepts
  - Identification and definition of innovative designs
  - Trade-offs
  - Design

This included firstly: Cleaning physical principles, Implementation constraints, study of typical layouts for wither civil transport passenger aircraft wings or smaller business jet wings, evaluation of implementation difficulties and propositions for innovative solutions

All projects included usage of course knowledge of mechanical systems design, statics, dynamics, reverse engineering with metrology, and computer aided design tools of CAD using CATIA V5R20 and Matlab. The layout of the logic is within the following figure. Each sub-project contained a personal research on existing tools and methods.

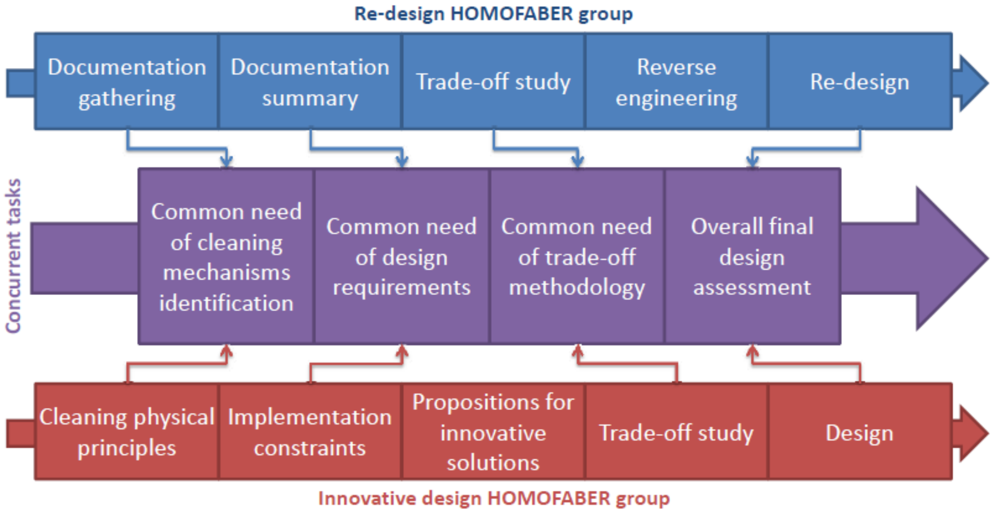

Figure1: Implementation of EPFL Bachelor Design Project Bachelor level Mechanical Engineering.

The second and third category of projects allowed much deeper analyses into specific problems; typically the following topics were addressed: Numerical investigations of the airflow around the leading edge cleaning device, "CleanLE", in various configurations (near fuselage, near wingtip, centred), design modifications of the device to improve its aerodynamic performance and limitations (use of an inverted aileron on the device, localised wing flow perturbations), as well as design mechanisms shear and strain evaluations, with again iterative design modifications using thermal and CSM methods coupled to CATIA design. Also, studies of the use of magnets to move the CleanLE were made to demonstrate the size and dimension of the magnets to keep the system CleanLe fixed on the wing as it moves on the wing after the takeoff. These projects involved for example 2D and 3D computational fluid dynamics with state of the art RANS solvers running in both laminar and inviscid modes, (with the corresponding mesh generation issues), and subsequent turbulence level evaluations. Also shear, friction, drag force evaluations and requirements on the devices together with magnetic field estimations with FEM /COMSOL and re-design effects, defined another topic.
Finally a fulltime master project is conducted to design and perform test benches for prototype mechanical testing.

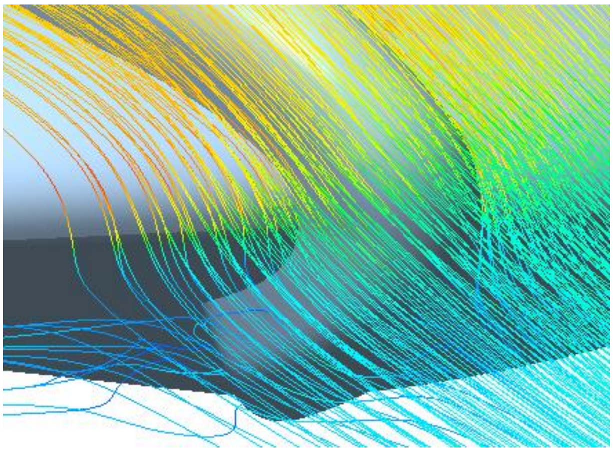

Figure 2: Numerical investigation of the airflow around a CleanLE device concept : full 3D calculations

These projects introduced the students to team design studies integrating their course work and progressing their level of knowledge in CAD design and tools, computational techniques and also to pursue innovative concepts from A-Z with evaluation and re-design iteration.

3. Two main concepts

Two main concepts could be extracted for the retained mechanical cleaning solution. They mostly vary on the way the device is guided on the wing surface. Both concepts could be divided in communal subsystem, allowing parallel engineering:

- A movable subsystem: composed of two modules, this system is located on the wing skin. It contains a shuttle whose main functions are to ensure the link between the external system and the wing structure, allow its displacement along the wing span and minimize the aerodynamic loads. It accommodates the cleaning module, composed of sponges and/or wires.
- A driver and guidance subsystem: its function is to ensure the displacement of the movable subsystem from wing root to wing tip and backwards. It also has the function to absorb some of the loads applied on the movable subsystem and avoid his separation with the aircraft structure. This subsystem is located inside the wing structure.
- A storage subsystem: defined to ensure a minimal impact of the system on the aerodynamic performances before and after the cleaning operations. The retained solution consists of a storage area inside the fuselage structure located at wing root. It will not be treated in this paper as it requires a deeper examination of each aircraft architecture.

One main possibility included an opening along the wingspan on the pressure side, allowing a driving system with a direct contact with the cleaning system to be implemented. A rail on the pressure side directly drives the whole system. It contains two articulated aerodynamic parts embracing the leading edge profile. Inside lies the cleaning system with scrapers and liquid tank. This will be further discussed in the next chapters. The solution is presented in the figure below at about half the wingspan.

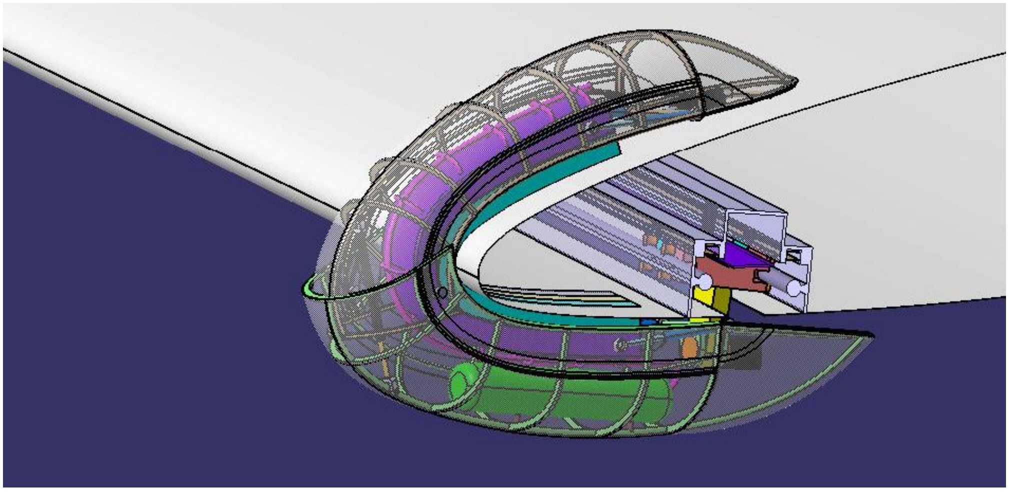

Figure 3: Cut of the C-shape solution

Another possibility leaves the wing skin unaltered, the guidance system has thus to be designed with no-contact between the driving and cleaning part. Magnetic force appears to be the most suitable solution to ensure transmission and aerodynamic resistance. Permanent magnets on both sides of the wing skin are used to fulfil this issue.
Two rails on both pressure and suction side of the wing guide the driving magnets, while on the wing the magnet system with scrapers and wires follows.

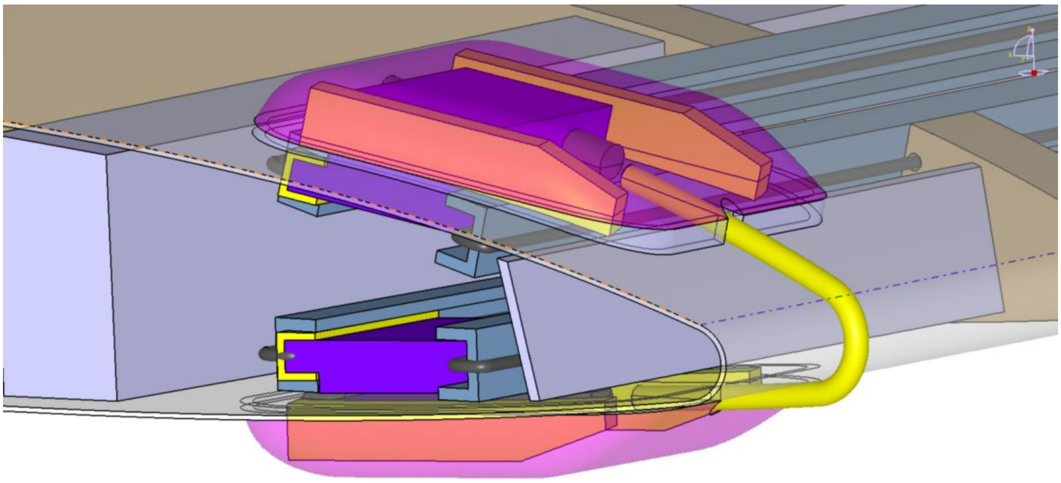

Figure 4: Cut off magnetic solution

4. Three subsystems

The following part presents the state of the art solution implemented for both concepts.
The “movable subsystem” has been again split in two distinct entities corresponding to their function: the module responsible for cleaning and the one for aerodynamic loads. As aforementioned, the storage subsystem is not included in this paper.

4.1 Cleaning module

Investigations lead to discuss two main concepts which are adapted to each manufacturer specifications. One consists on sponge-brush system with additional fluids; the second one is a composite of Teflon wires and scrapers.

The first solution relies on a combination of chemical and mechanical cleaning. Investigations on the efficiency of that type of cleaning system have been undertaken at the Frauenhofer IFAM institute, allowing a systematic characterisation of friction coefficient and pressure required.

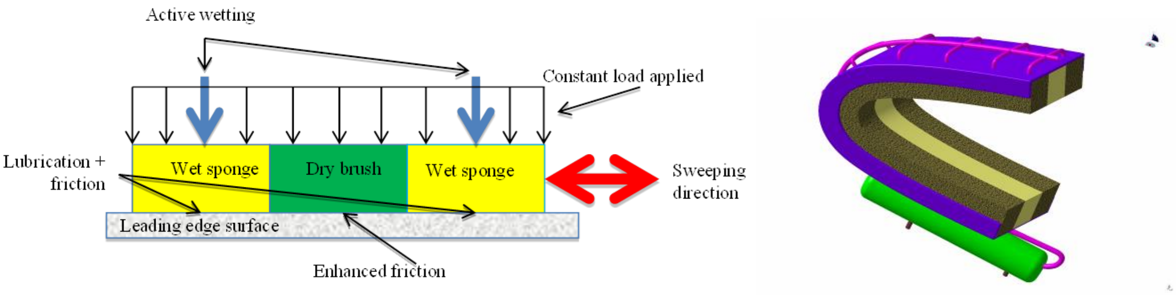

Figure 5: Mechanical and chemical cleaning solution

Conclusions of these investigations pointed out the following drawbacks and uncertainties:

- The system, as defined in figure 5, does not ensure cleaning of the wing leading edge while achieving all the technical requirements defined for this project. A pressure of 350 g/cm^2 is required to reach the cleaning requirements in only two passes, which is not achievable. For wing skin structural purposes a maximum pressure of 175 g/cm^2 has been set for the cleaning system and further investigation will provide the number of passes needed to achieve the cleaning requirements.

- Uncertainties concerning the necessity and the feasibility of a wetting system have pointed out that the low temperatures reached at the cleaning altitude implies risks of icing of the wetting liquid which could lead to a loss of the cleaning efficiency. The idea of a constantly wetted sponge-brush-sponge system is then avoided and investigation will be made on the efficiency of a dry, or lubricated only brush-sponge-brush and/or wire system.

The second solution relies on an already existing device (bugwiper from PAS) and is still in development (pre-design is shown in figure 4). A brush-sponge system is adapted to the casing around the magnetic drivers, but would not contain any wetted part for volume consideration. The front part consists of Teflon wires, as per PAS bugwiper presented in figure 6. The wire system from figure 4 is not the actual solution which is still in the process to be designed for optimized cleaning efficiency.

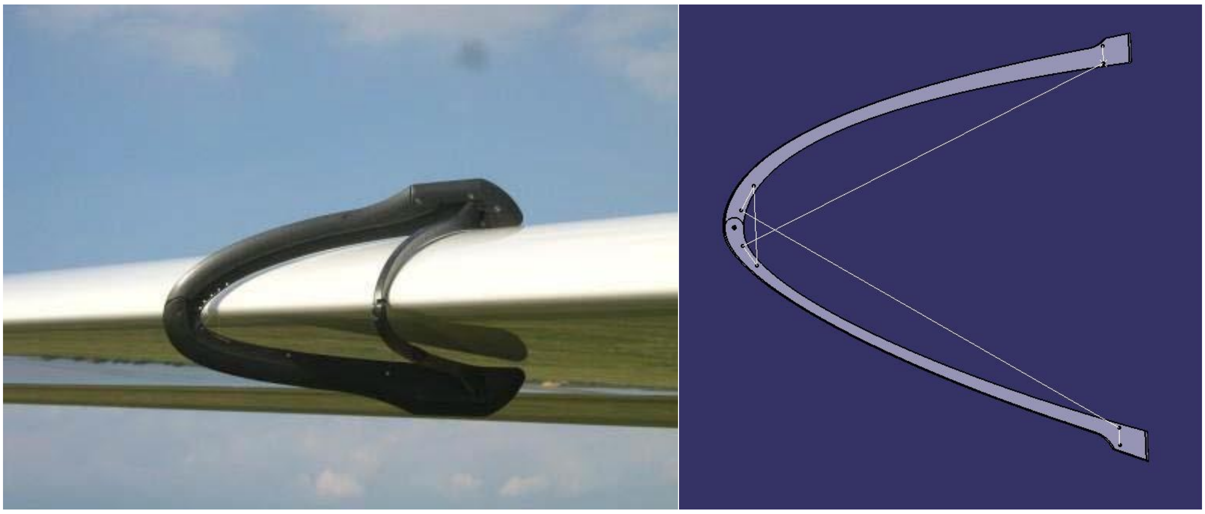

Figure 6: Bugwiper from PAS (http://www.storka.at/)

4.2 Shuttle

The shuttle is the sweeping element of the movable subsystem. It hosts the cleaning module and ensures the internal as well as the external kinematics of the so called subsystem. The first one corresponds to the motion required to ensure the contact of the cleaning module on the complex leading edge surface and is ensured by a shuttles' deformation along the wing span. The second corresponds to a movement of the subsystem through the wing span and is ensured by its link to the guidance and driving subsystem.

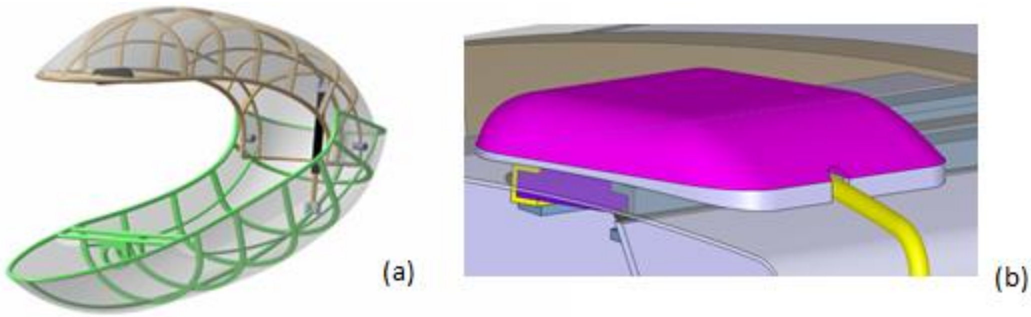

Figure 7: Shuttles

The main challenge of the shuttle is to withstand the aerodynamic forces and protect the cleaning and driving subsystem from the impinging air (up to Mach 0.4 as the device is considered used after takeoff and before acceleration to cruise speed).

Computational Fluid Dynamics (CFD) studies showed that the shuttle is exposed to non-negligible aerodynamic forces. As a first approximation, the pressure distribution on the shuttle can be considered the one on the wing at shuttle location in absence of cleaning device, allowing a first design to be generated. Further calculation then leads to the optimal solution.

In the first case (C-shape shuttle, figure 7(a)), this leads to a strong normal force on the shuttle upper side which tends to generate an opening hinge torque as well as to separate the shuttle from the wing suction side. This effect is especially critical for the cleaning efficiency since friction force directly depends on the pressure applied on the scrapers. This issue can be counteracted by adding some passive aerodynamic control surface. CFD results from the first system (C-shape shuttle) are presented below and show the possibility of reducing the suction force experienced by the upper side of the shuttle.

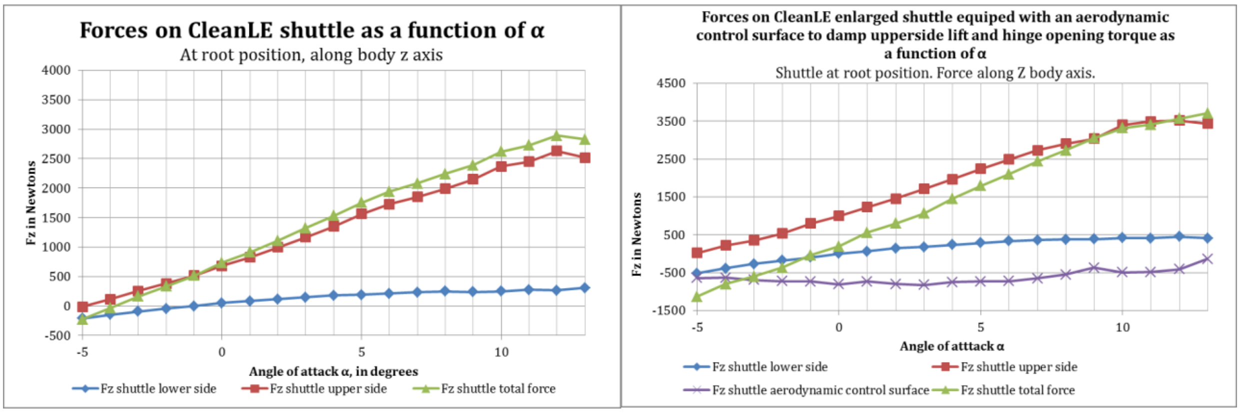

Figure 8: CFD analysis of enhanced solutions

In the second case (figure 7 (b)), the suction forces tends to pull off the shuttle from the wing. This effect can only be reduced by reducing the surface exposed to lift. However, reducing the shuttle size also decrease the space available for the permanent magnets, whose forces depends on their surface (as a rough approximation). As part of a semester project undertaken by an EPFL student, a deeper CFD analysis shows reduced aerodynamic forces compared to the first case. A cut-view of the wing with the device for a 5° angle of attack is presented in figure 9. This simulation has been validated by two other numerical simulations run by a CFD expert at EPFL. Trade off and optimization loops have to be undertaken to improve the geometrical characteristics and are the purpose of on-going investigations.

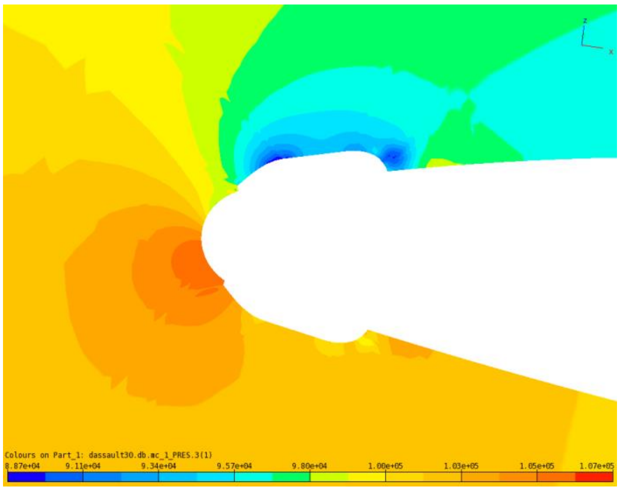

Figure 9: Leading edge pressure plot

It should also be noted that a structural issue can emerge from the contact between the shuttle and wing skin. Taking a safety coefficient into account in the design leads to a force applied through the aluminium skin, which may require reinforced areas.

4.3 Driver and guidance system

The housing of the driver and guidance subsystems is placed inside the wing frame and lies on the internal wing skin. Its twisted shape follows the one of wing ensuring guidance at constant distance of the leading edge. It is designed in order to allow the storage of:

- A rail ensuring the guidance of the driver element,
- A cart linked to the shuttle and lying on the internal rail providing the sweeping movement of the shuttle at a constant distance of the wing leading edge (requirement ensuring the constant contact of the cleaning module with leading edges' shape),
- The driver mechanism that will drive the cart on the rails.
- In case of an opening on the pressure side, a system allowing the opening and the filling of the crack that allows the direct link between the driver element and the shuttle should be implemented.

In the case of a magnetic force being used, it is necessary to have two rails both on suction and pressure side of the wing to ensure the system integrity at this stage of development. This is especially true if no rigid connection is used to link the lower and upper side of the system (use of wire for example).

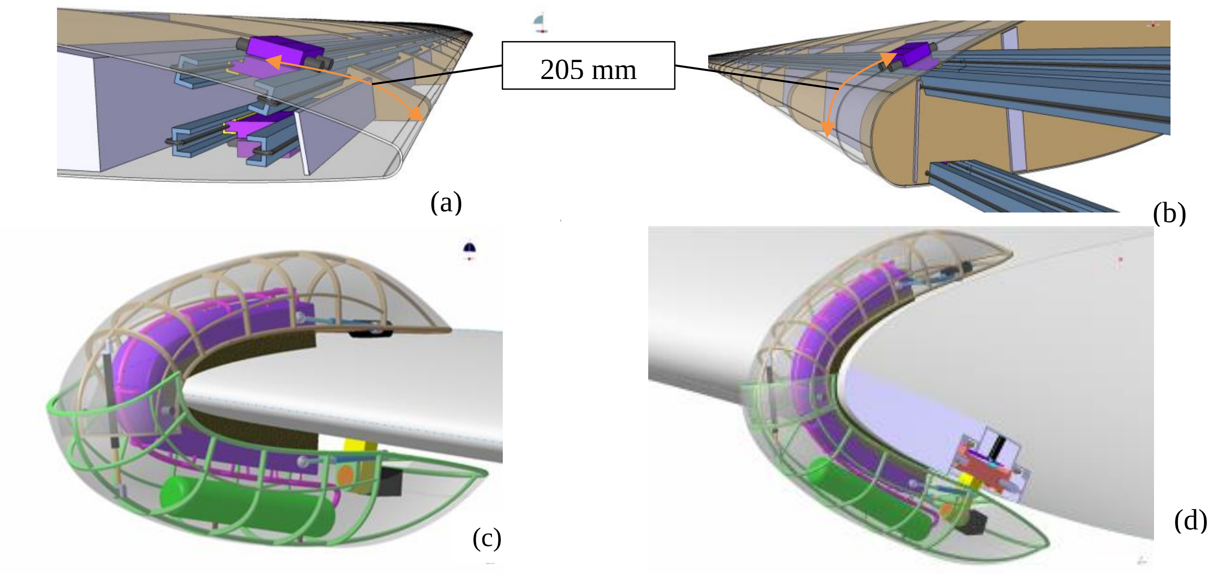

Figure 10: Driving and guidance systems

To allow guidance without contact, the force created by the offset between two facing permanent magnets is used. The use of steel plates around the magnets is still being numerically investigated, as it could actually reduce the total weight.
In both cases the inner cart is the leading object of the whole system and serves as position controller and active guidance system. This function will be assured either by cables or rack-and-pinions coupled to an electrical motor.

Conclusions

The two solutions that could be implemented on future NLF wings were presented. In terms of space, implementation and according to the sizing investigation, such solutions are feasible.
Some extra investigations on the cleaning systems are needed to ensure the reliability and the cleaning efficiency of the presented solutions.
As both solutions rely on the implementation of an inner rail placed inside the wing structure, a special focus on the modified wing structure analysis is required. Indeed, if the implementation of these rails is structurally not feasible, one can easily consider that the whole cleaning systems (as presented here) are not implementable for any type of wings and some major modification on the strategy applied for the definition of the solutions have to be conducted.
Furthermore, a deeper analysis on the magnetic guidance is being held at EPFL to fully capture the challenge of including magnetic fields in the aircraft airframe.

5. Acknowledgements

This project was partially supported by The JTI CLEANSKY Project of the FP7 Framework Programme of the European Commission under the project number: 270644; SP1-JTI-CS-2010-01.

5. References

[1] Parker and Storka, www.storka.at, 26.04.2013
[2] Erosion resistant coatings with anti-contamination property enabling natural laminar flow, Internal Report, *Frauenhofer IFAM Institute, 2011.*

