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Next steps towards future medium-range electric/hybrid aircraft

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Abstract

Recent studies and forecasts suggest that to achieve the reduction of greenhouse emissions, the aeronautical industry must evolve to achieve more efficient solutions based on electric/hybrid technologies. However, there are several technical gaps which need to be solved around these areas, such as: new cooling systems, electrical power generation systems, systems around the batteries or new solutions for the use of boundary layer, among others. This paper is focused on the development of new solutions for the use of boundary layer in tail cones, regarding future electric and hybrid medium range aircraft.

1. Introduction

Nowadays there is a growing interest in the reduction of greenhouse gas emissions into the atmosphere in the world of aviation. Many institutions around the world, are pushing in that direction and asking for a big leap to achieve low emission levels in the next 20 years. Indeed, new European standards are promoting research in this line, for the near future of the European Sky.

In the current context, recent studies and forecasts suggest that to achieve this goal, the aeronautical industry must evolve to achieve more efficient solutions based on electric and hybrid technologies. However, there are several technical gaps which need to be solved before those goals can be achieved.

Concretely, if the main requirement is to increase the electric power on board, different challenges need to be addressed from a technical standpoint, such as how to safely store such a significant amount of energy on board, to develop batteries that have enough energy density or to include some other type of electrical power generation technology; how to manage a high voltage electrical network on board; how to cool all the new components that need to be added or how to manage the heat and the gases that may be produced in the batteries. However, hybrid/electrical aircraft also present opportunities to reduce the drag and build more efficient propulsion solutions such as a BLI system. This paper is focused on research that Altran has carried out in this regard.

2. Background

In relation to the future electrification of aircraft, Altran is developing innovative internal projects certified as R&D which encompass both completely electric aircraft and future hybrid aircraft, as well as developing a multitude of on board systems related to these technologies and its future required systems.
In order to carry out several of these researches, Altran has joined the Spanish consortium ESCAPHIB which is led by Airbus Spain, supported by CIEN program granted by CDTI IDI-20181069. Altran takes the concept of Boundary Layer Ingestion and develops it further by incorporating an adaptive FOD protection subsystem for the propulsion system.

BLI is not a new concept, it has been known to aerospace industry experts since the 60s, when NASA made some preliminary studies that demonstrated that this technology could theoretically improve efficiency in aircraft by reducing the drag caused by the fuselage and increasing the overall thrust. The concept has not been fully developed yet due to the practical challenges of integrating such a system in a real aircraft, challenges that are more easily overcome nowadays thanks to advancements in power electronics, electric motors, structural design and the development of an innovative active FOD protection system for the landing and take-off phases that is being developed by Altran.

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One of the main problems that the integration of a BLI system entails in a near transonic transport jet-propelled by turbofans is the intake of highly distorted flow in the fan. Since this research has been developed for a regional aircraft that wouldn't fly at such high speeds a propeller approach has been applied. By ingesting the lower velocity flow coming from the fuselage boundary layer the operational range of this propeller is extended in terms of flight Mach number.

The research is divided into 3 main tasks: An aerodynamic and propulsive analysis to design the propellers and quantify the benefits of including this type of system in the reference aircraft, the design of a structure capable of holding the propeller, motors and other subsystems in a modified tail cone and lastly the development of an innovative active FOD protection subsystem to ensure the safety and operational availability of the system.

3. Aerodynamic and propulsive analysis

3.1 Theoretical background

One of the main objectives in the aerospace industry is to design aircraft that are as efficient as possible, aerodynamic design and propulsion are the two main ways to achieve this goal. The Boundary Layer Ingestion system(BLI) here proposed affects both by including a propulsive solution that energizes the fuselage boundary layer to obtain a uniform velocity profile downstream of the aircraft, as can be seen in Fig. 1. Electric and hybrid aircraft offer the unique opportunity to include these types of devices by using electric motors to generate the required torque to move the propellers, which offer a great advantage compared to thermal motors due to their compactness, scalability and simplicity.

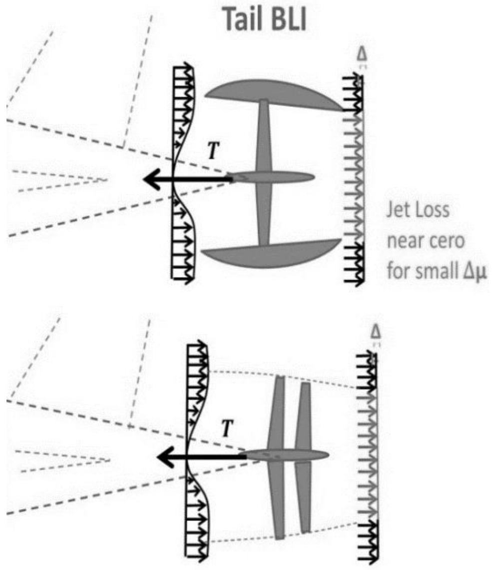

Figure 1: Effect of BLI on the velocity distribution of an aircraft's fuselage.

From a theoretical standpoint and assuming a control volume where the downstream and upstream pressures coincide, the thrust generated by a propeller is given by:

$$T = (\dot{m}\, u)_j - (\dot{m}\, u)_\infty \qquad (1)$$

Where u_j is the propeller's exit velocity and u_∞ the free stream velocity. In cruise conditions the generated thrust must be equal to the aerodynamic drag generated by the aircraft, therefore:

$$T = D \rightarrow (\dot{m}\, u)_j - (\dot{m}\, u)_\infty = (\dot{m}\, u)_\infty - (\dot{m}\, u)_w \qquad (2)$$

Where u_w is the ingested wake velocity. Assuming cruise conditions, the potential energy variation is equal to 0, the mechanical energy variation is:

$$E_m = \frac{1}{2} m\left(u_j{}^2 - u_\infty{}^2\right) \qquad (3)$$

Which can be expressed in terms of power as:

$$P_{added,noBLI} = \frac{1}{2}\dot{m}\left(u_j{}^2 - u_\infty{}^2\right) = \frac{T}{2}(u_j + u_\infty) \qquad (4)$$

On the other hand, the required power is defined as follows:

$$P_{required} = D \cdot u_\infty = \dot{m}\left(u_j - u_\infty\right)u_\infty \qquad (5)$$

If the BLI is added to this case:

$$T = (\dot{m} \cdot u)_\infty - (\dot{m} \cdot u)_w = D \qquad (6)$$

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Taking into account that in cruise conditions the variation in potential energy can be considered null, the added mechanical energy is:

$$E_m = \frac{1}{2} m({u_\infty}^2 - {u_w}^2) \tag{7}$$

Which can be expressed in terms of propulsive power as:

$$P_{added,BLI} = \frac{1}{2} \dot{m}({u_\infty}^2 - {u_w}^2) = \frac{T}{2}(u_w + u_\infty) \tag{8}$$

On the other hand, the required propulsive power is defined as follows:

$$P_{required} = D \cdot u_\infty = \dot{m}(u_\infty - u_w)u_\infty \tag{9}$$

Comparing the required propulsive power in both cases, taking into account that $u_w \leq u_j$, the following result is obtained. The benefits that a BLI system introduces are enumerated in the Table 1, along with the challenges that must be solved to take full advantage of them.

$$P_{required,BLI} < P_{required,noBLI} \tag{10}$$

Benefit	*Challenges*
Increase of the propulsive efficiency	Added weight
More thrust for kW consumed	Installations and operations cost
Reduction of the specific fuel consumption at cruise	Structure and other systems modifications
Increase of the total maximum thrust	Maintainability and reliability
	Tail strike and FODs at take-off/landing

Table 1: Benefits of adding a BLI system to an aircraft and challenges presented by it.

Firstly, CFD simulations have been run to quantify the benefits in efficiency that the BLI system may provide. After that, the modifications needed to the airframe are studied through structural analysis and finally the proposed FOD protection system is discussed, along with a study of foreign object trajectories.

3.2 Main activities and studies

The first step taken to analyse the impact in the propulsive efficiency of the BLI system has been to run CFD simulations on a version of the reference aircraft that has had its tail cone modified to house the propulsive solution. Tanks to this analysis a baseline can be established to which the performance of the propeller can be compared. This simulation has also given important insight into the state of the fuselage boundary layer at the point on which the BLI would be installed. The effect the wing has on the velocity profile has also been analysed. This helps size and choose a suitable location, as well as to obtain a preliminary design of the propeller. The first tasks were focused on developing a geometry of the new tail cone that could hold the propeller and all the necessary subsystems. A comparison between the original tail cone and the modified one can be seen in Fig.2.

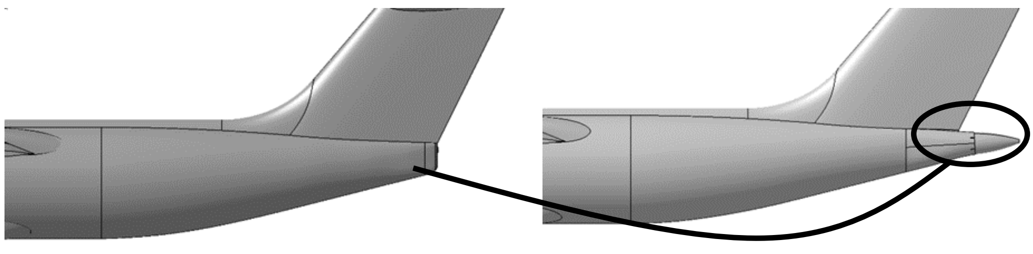

Figure 2: Comparison between the original tail cone and the modified version

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Thanks to all the analysis that have been carried out, a significant flow disturbance induced by the wings has been found in the flow over the tail cone. This is one of the main flow features that, if corrected, could lead to an important improvement in the aerodynamic efficiency of the aircraft. It is hypothesized that this can be achieved thanks to BLI. Currently more simulations are being run in order to discern how this can be done, although some elements have been developed that might manage it.

The proposed solution for the BLI System consists of a couple of contra-rotating propellers driven by two electric engines. These propellers are used to increase the boundary layer velocity to improve the aircraft's overall efficiency. The propellers are integrated into the airframe thanks to a structure that must be able to handle the loads that appear as a result of its operation as well as a subsystem that is tasked with protecting the blades form foreign object damage (FOD) in take-off and landing phases. Figure 3 shows the design of the propellers, (a) shows the location and dimensions of the propeller relative to the fuselage of the aircraft, (b) shows a single propeller version of the system that has also been used to do some preliminary studies and figure (c) shows the contra-rotating propellers.

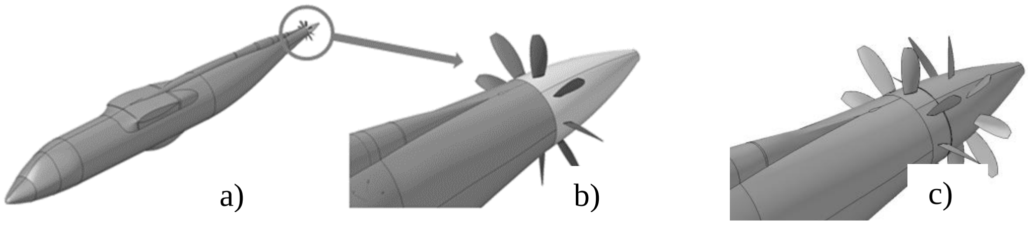

Figure 3: Location and geometry of the propellers.

The Propulsive subsystem is composed of two parts:

- Engines
- Propellers

Concerning propeller design, the essential part of the group is the blade. These blades have been designed with specific features for the required performance.

Propeller 8 blade D 1600mm first v1 cruise				
r/R	c/R	β	r	Airfoil
[-]	[-]	[°]	[mm]	[-]
0.00	Spinner			
0.40	Spinner			
0.45	0.1506	74.9	360.0	NACA 16-512
0.50	0.1685	73.3	400.0	interpolated
0.55	0.1827	71.7	440.0	interpolated
0.60	0.1923	70.2	480.0	interpolated
0.65	0.1969	68.7	520.0	NACA 16-506
0.70	0.1992	67.2	560.0	interpolated
0.75	0.1980	65.7	600.0	interpolated
0.80	0.1912	64.3	640.0	interpolated
0.85	0.1781	62.9	680.0	interpolated
0.90	0.1566	61.6	720.0	interpolated
0.95	0.1203	60.3	760.0	interpolated
1.00	0.0818	59.0	800.0	NACA 16-104

v/(nD)	η	v	rpm	Power	Thrust	Torque
[-]	[%]	[m/s]	[1/min]	[kW]	[kN]	[kNm]
1.420	45.79	68.16	1800	336	2.260	1.785
1.620	48.86	77.76	1800	347	2.185	1.845
1.820	51.91	87.36	1800	357	2.123	1.895
2.020	54.37	96.96	1800	365	2.050	1.939
2.220	56.17	106.56	1800	373	1.968	1.981
2.420	58.53	116.16	1800	385	1.943	2.046
2.620	60.85	125.76	1800	397	1.922	2.108
2.820	62.54	135.36	1800	401	1.855	2.130
3.020	64.01	144.96	1800	403	1.781	2.140
3.220	65.63	154.56	1800	406	1.727	2.158
3.420	67.77	164.16	1800	416	1.718	2.208
3.620	70.39	173.76	1800	430	1.741	2.281
3.820	72.45	183.36	1800	432	1.709	2.295
4.020	73.98	192.96	1800	424	1.626	2.251
4.220	74.98	202.56	1800	407	1.508	2.162
4.420	75.51	212.16	1800	386	1.374	2.048

Table 2: Geometry of the blades obtained with Javaprop

The engines are electrically driven with axial configuration. This is possible thanks to a significant advancement in electrical motor technology in the latest years. This development allows a size reduction which has an effect in weight with an acceptable power to weight ratio.
Estimations show that the power needed is around 600-1200 kW for each of the 2 motors (1200-2400 kW total) and the percentage of added thrust is 15-20% of the aircraft's total thrust. The main reason to use an engine of this kind is due to the very considerably efficiency and power density they offer compared to other solutions based on thermal

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engines. The reduced dimensions, scalability, modularity and the reduced fabrication and maintenance costs make this kind of engine very attractive as an option to power the BLI system.
Multiples studies have been done to find an engine which fits in the best way in the BLI System. There are multiple options to choose from according to power to weight ratio, size, configuration, etc. As a result, there are two different approaches that being taken into consideration, a low rpm electrical motor or a high rpm model, this latter one would necessitate the installation of a gearbox to reduce the rpm from 6000-15000 rpm to a maximum regime of 2000 rpm, which is the maximum that the propeller of around 1.6-1.8m of diameter can handle both for structural and aerodynamic reasons.

The main research done regarding the propulsive system has been the propeller study. The objective of this study is the analysis of different blade configurations in order to optimize the boundary layer ingestion system for the desired flight conditions. As a starting point, the influence of the freestream velocity on the thrust generated by the system as well as the reduction of the resistance, the torque on the blades and the efficiency of the system has been studied. The initial geometry will be formed by a propeller group composed of eight blades. Future studies will include a second contra-rotating helix. This contra-rotating configuration will allow the use of a smaller propeller diameter in order to solve the tail strike problem – see Fig. 4 – and avoid the resistance produced by the swirl of the first helix, thus increasing efficiency.

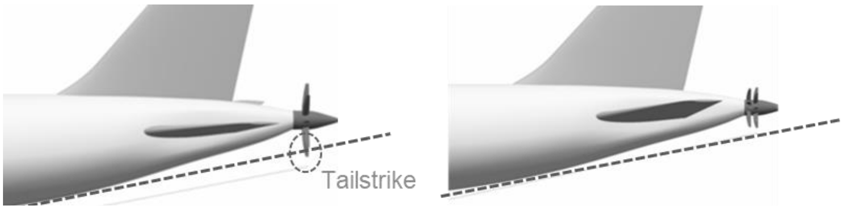

Figure 4: The contra-rotating blades solve the tail strike problem

Firstly, to validate the propeller data obtained in Javaprop a simplified model was created formed by the blades, a spherical pod to substitute the rest of the aircraft and the spinner which would be connected to the electrical motor. The simulations run on this model were made on incompressible regime to obtain the propulsive efficiency curve as a function of the advance ratio. After these analysis more simulations were carried out increasing the freestream velocity and rotation speed to check that this efficiency does not vary for compressible flow.

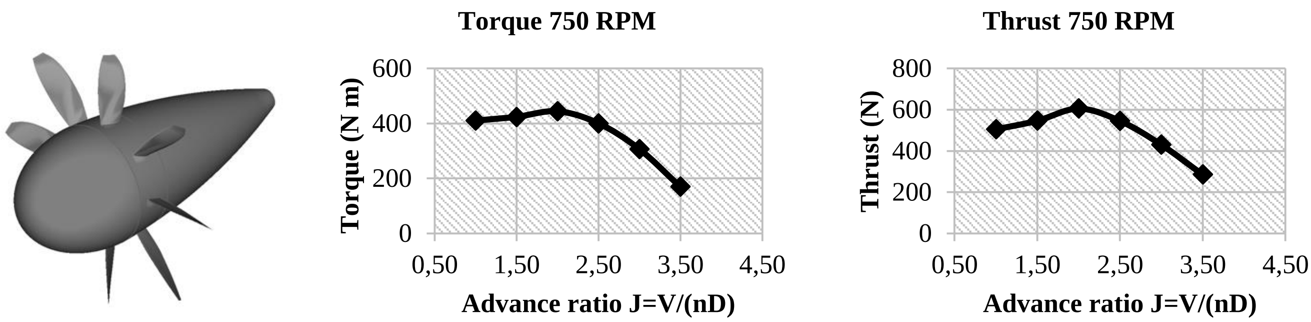

Figure 5: Thrust and torque as a function of advance ratio of the propeller at 750 RPM.

These results show that the thrust and torque presented a maximum that coincided with the maximum efficiency point for a certain advance ratio, therefore for future analysis on the complete model the advance ratio will be kept as close as possible to this optimum.

$$J = \frac{V_\infty}{nD} \rightarrow J_{max} D = \frac{V_\infty}{n} \quad (11)$$

Where J_{max} is the optimum advance ratio that maximizes efficiency, D the diameter of the propeller V_∞ the freestream velocity and n the revolutions per second of the propeller. Table 3 summarizes the cases that have been run to analyse a model of the fuselage of a regional aircraft with a single propeller BLI system integrated into it (see Fig. 3(a) (b) for the single rotor geometry and (c) for the 2 rotor geometry). Another simulation has been run

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V_∞	Number of rotors	RPM	J	Max Mach (tip)
100	1	1600	2,344	0,492
100	1	1800	2,083	0,532
120	1	1600	2,813	0,529
120	1	1800	2,500	0,567
140	1	1600	3,281	0,570
140	1	1800	2,917	0,605
140	2	1600/1550	3.281	0.570

Table 3: Summary of the cases that have been run.

The convergence strategy followed in the simulations is shown in Fig. 6. Initially the calculations have been solved assuming the condition of incompressible fluid with constant density for later, in compressible regime cases, use that solution as the initial condition of the nodes for the compressible flow simulations by using the ideal gas equation for density. All these simulations have been carried out by applying a reference frame to the rotating parts of the system and the fluid that surrounds them to simulate the rotation of the system in a stationary state to, finally, perform the simulations with transitory flow for the most promising cases by using a moving mesh.

For both simulations, steady state and transient, it is necessary to divide the fluid volume into two regions: a volume whose mesh will be fixed, and a second volume around the propeller whose mesh will be rotating or part of the reference frame. Additionally, a refinement zone has been added after the propeller with the aim of improving the accuracy of the results.

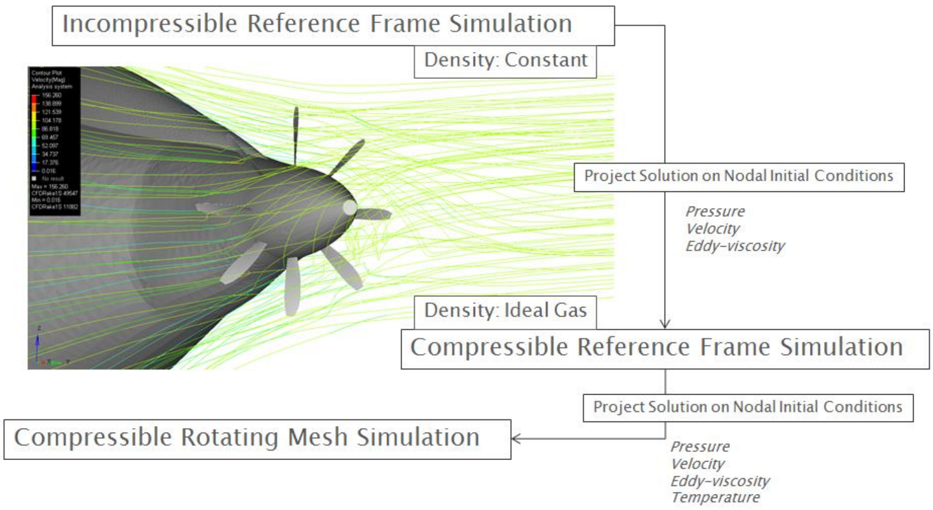

Fig 6: Convergence strategy

3.3 Preliminary Results

The propulsive efficiency of the propellers is plotted in Fig. 7. The reason for the maximum efficiency now corresponding to a higher value of J is the fact that by including the fuselage in this study, which was not included in the simplified pod used for the previous analysis, the boundary layer now affects the intake velocity of the propeller and the actual advance ratio is lower. This is also why the efficiency is higher than 1 in the case of 2 rotors, the reference velocity is the freestream velocity but the air that the propeller receives is lower. Fig. 8 shows the power requirements for the electrical motor for a single propeller and shows that the integration of the BLI system in an aircraft is energetically possible.

Even though the overall force is reduced on the fuselage + BLI ensemble thanks to the effect of the propeller’s thrust on the tail cone, if the forces are analysed separately the drag on the fuselage increases (see Fig. 9 and 10). Furthermore, if the drag on the fuselage is divided into its components, the friction drag stays practically the same (see Fig. 11) but the pressure drag increases (see Fig. 12), which indicates that there is room to improve the system. This increase comes from an early detachment of the boundary layer in the tail cone surface upstream of the propeller and it can be solved by redesigning the tail cone or by including vortex generation devices to prolong the attachment of the boundary layer to the fuselage. The counter rotating case shows a reduction in this drag with respect to the single rotor case, however, it does not approach the case with no BLI, this means further work needs to be done to bring this value further down.

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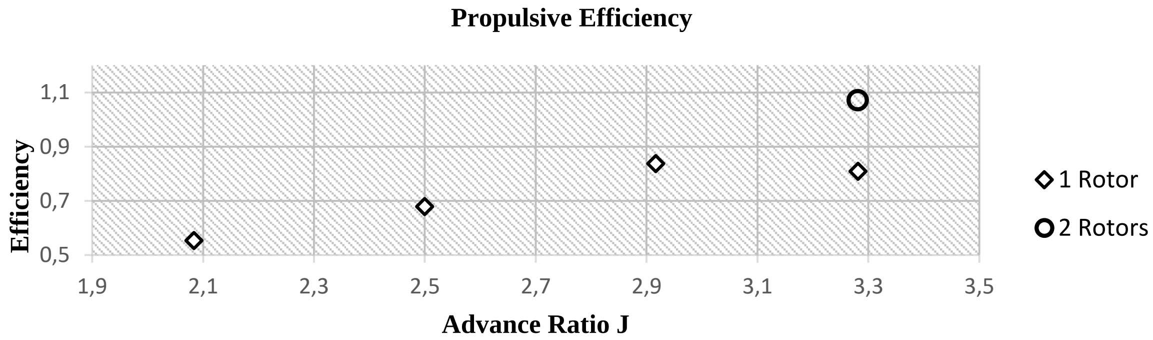

Figure 7: Propulsive efficiency as a function of the advance ratio

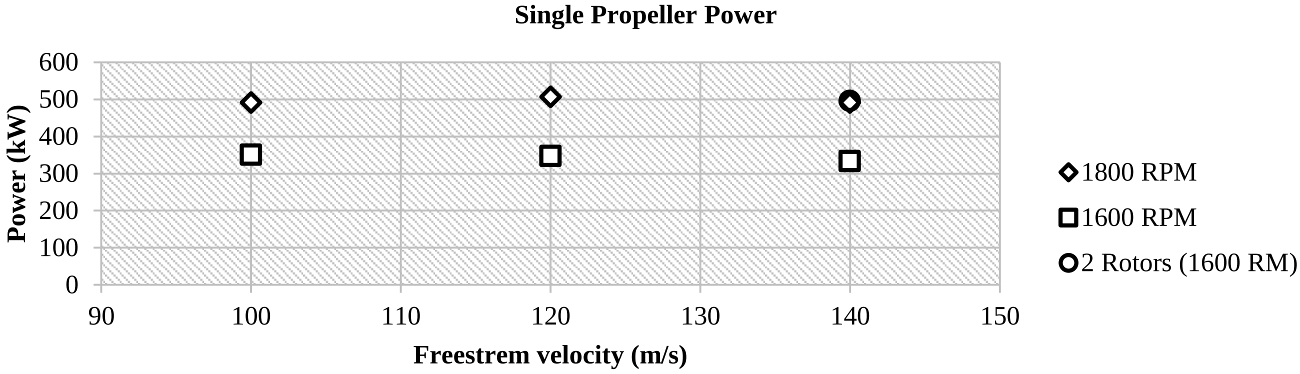

Figure 8: Power required for a single propeller

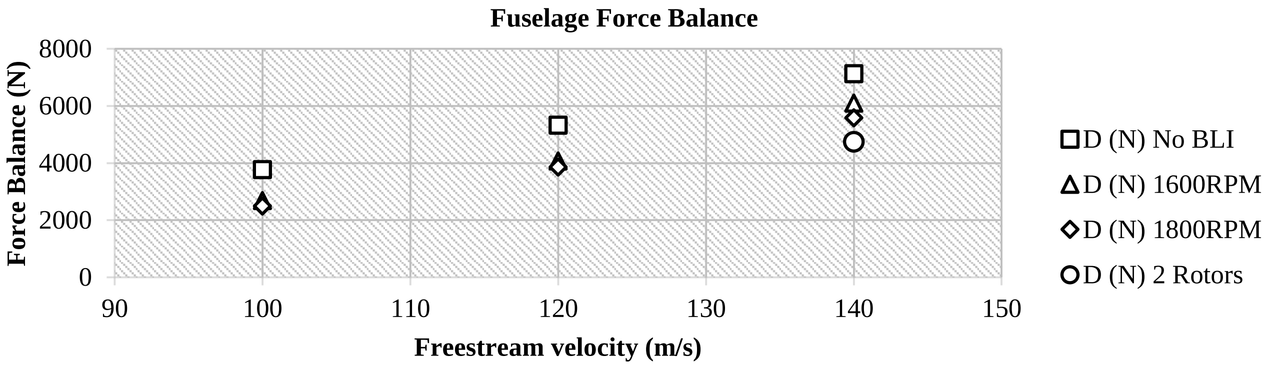

Figure 9: Overall force balance on the fuselage.

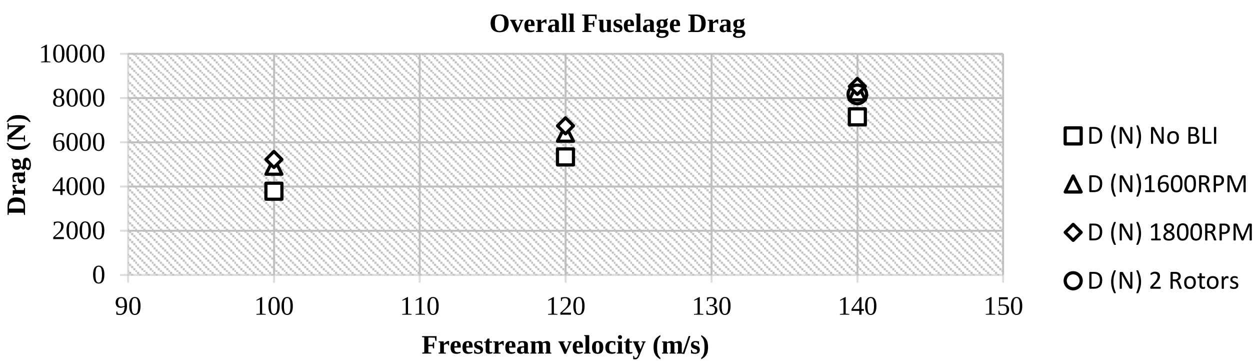

Figure 10: Overall drag on the fuselage

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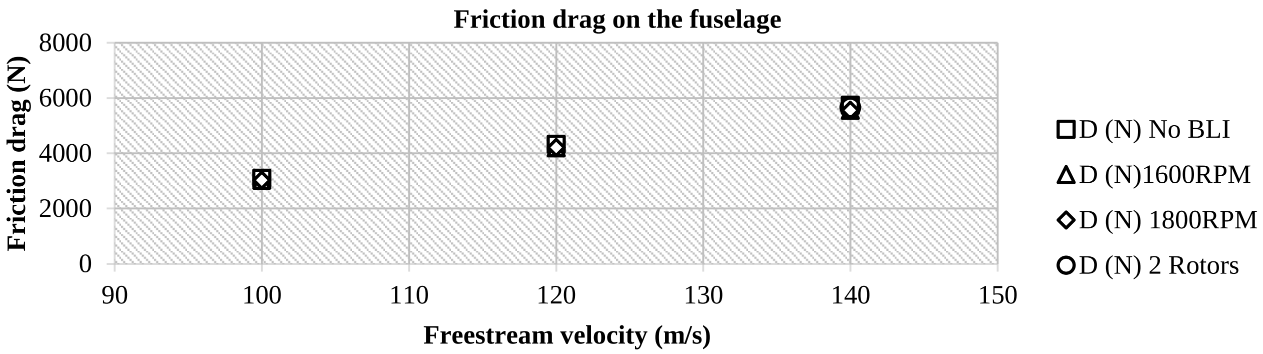

Figure 11: Friction drag forces on the fuselage

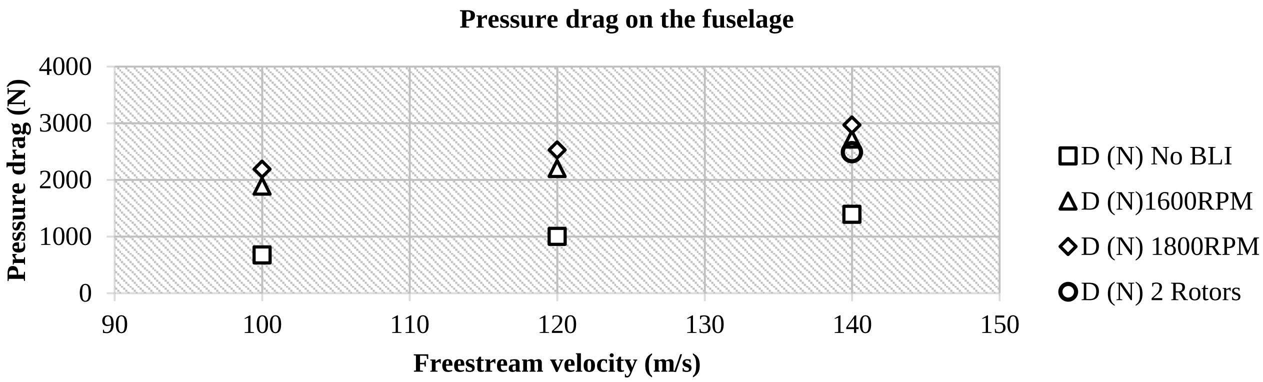

Figure 12: Pressure drag forces on the fuselage

The velocity profiles have also been obtained and can be seen in Fig.13 for 4 different cases. The coloured parts correspond to areas with a velocity lower than 95% of the freestream velocity.Fig.14 depicts the velocity profile just downstream of the first rotor, for the counter rotating case the plane is located just ahead of the second propeller. Fig.15 corresponds to a plane downstream of the airplane. The top right image corresponds to a rotating speed of the rotor of 1600RPM while the bottom left corresponds to a rotating speed of 1800RPM.

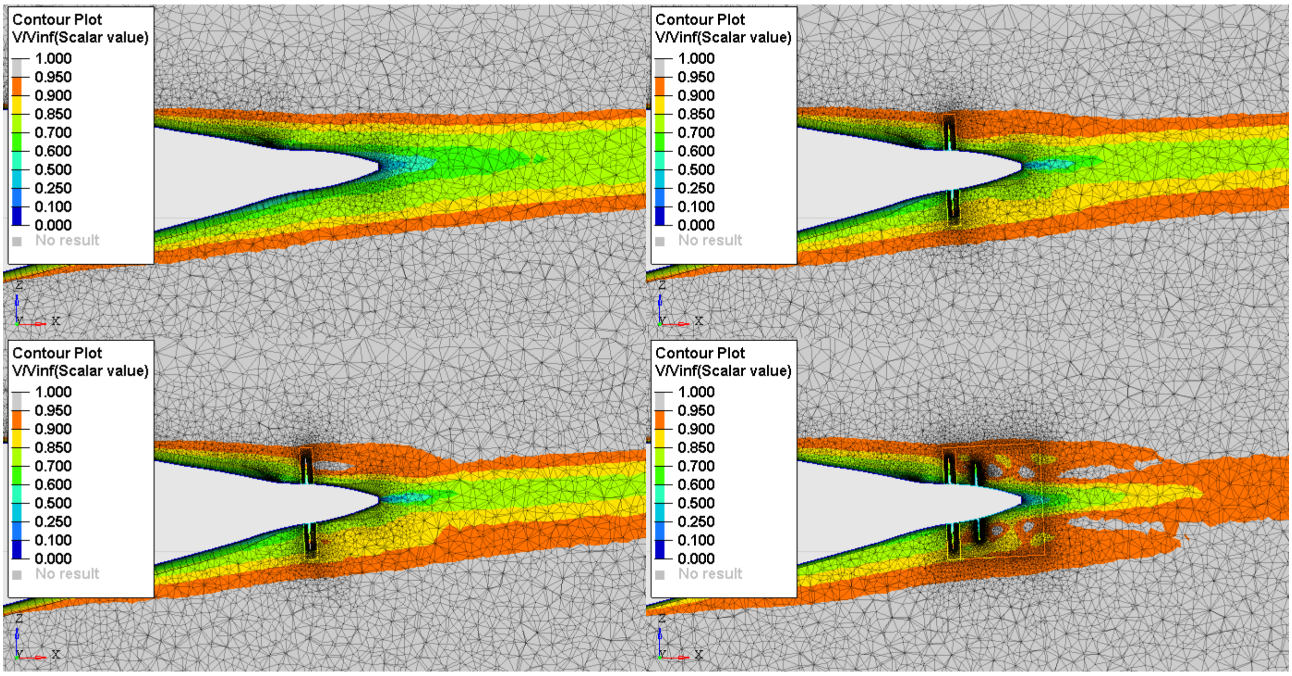

Figure 13: Velocity profile for different propeller configurations.

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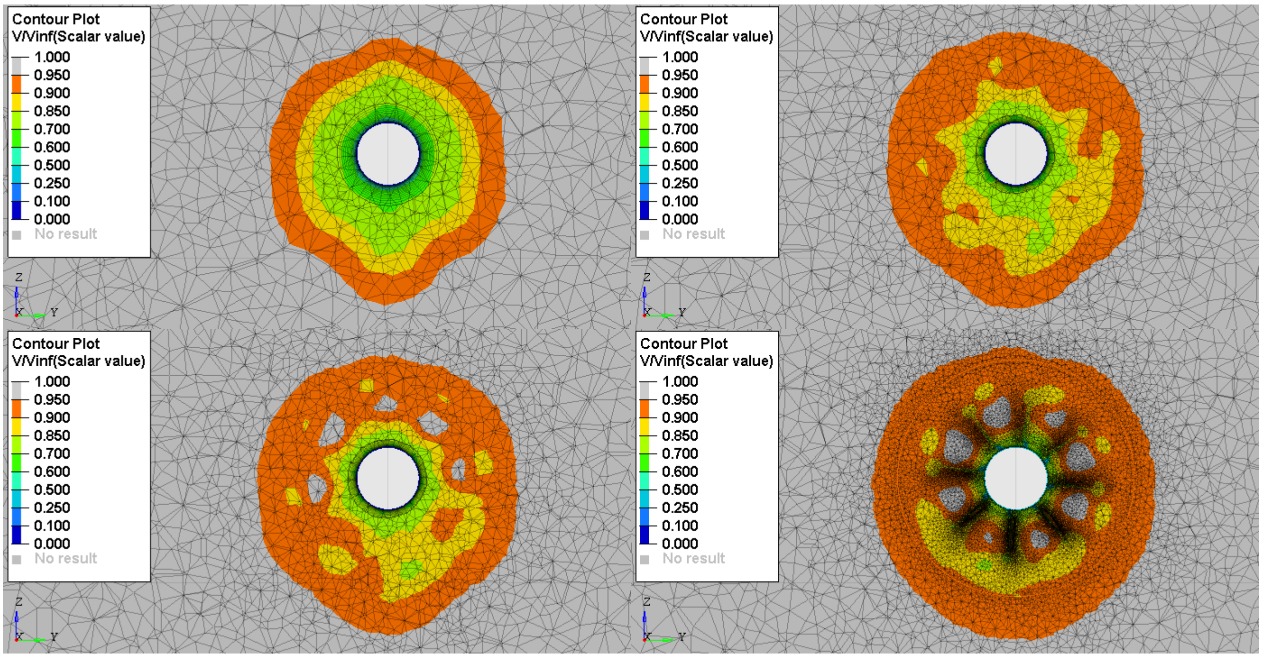

Figure 14: Velocity profiles for different propeller configurations just downstream of the first propeller.

It is clearly shown that the BLI system has an effect on the reduction of the velocity profile gradient downstream of the aircraft, as theorized. The effect is much more clear in the case of contra-rotating propellers.

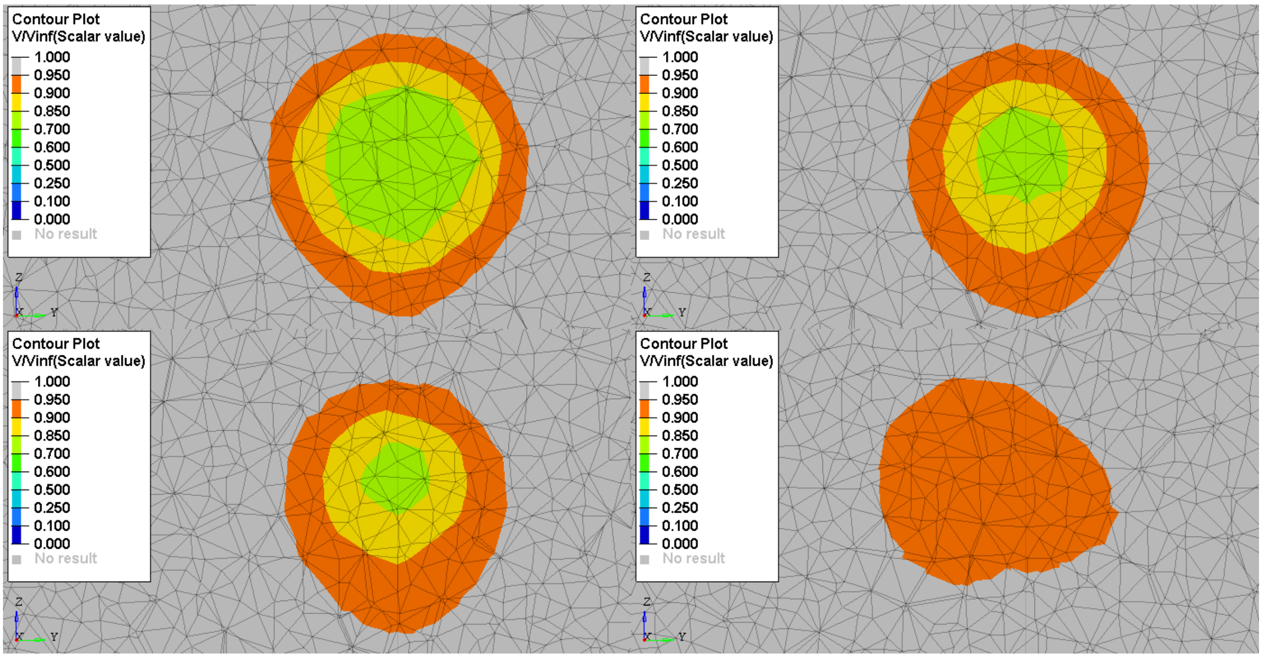

Figure 15: Velocity profiles for different propeller configurations downstream of the aircraft.

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4. New structure design and analysis

This new system requires the modification of the tail cone of the aircraft. For this purpose, a major part of the project is the generation, study and optimization of a structure that could both be applied to an already developed aircraft and also be able to support all the BLI structure as well as the impact protection system and respective loads.

Initially a tubular base structure was considered, similar to an engine bed, inside, and separated from the skin of the modified tail. However, due to the length of the structure required and limitations of the possible mounting locations as well as the need to have the maximum free volume available for the impact protection system this solution was not viable.

A new solution was devised that made use of a monocoque type structure. This structure was envisioned to make use of the air brake moorings of an already existing aircraft, to reduce cost of development and deployment. These constraints meant that the whole structure would be supported only in four singular points and therefore would require the use of four major structural elements, henceforth designated main stringers. The whole structure and engine configuration are represented in Fig: 16.

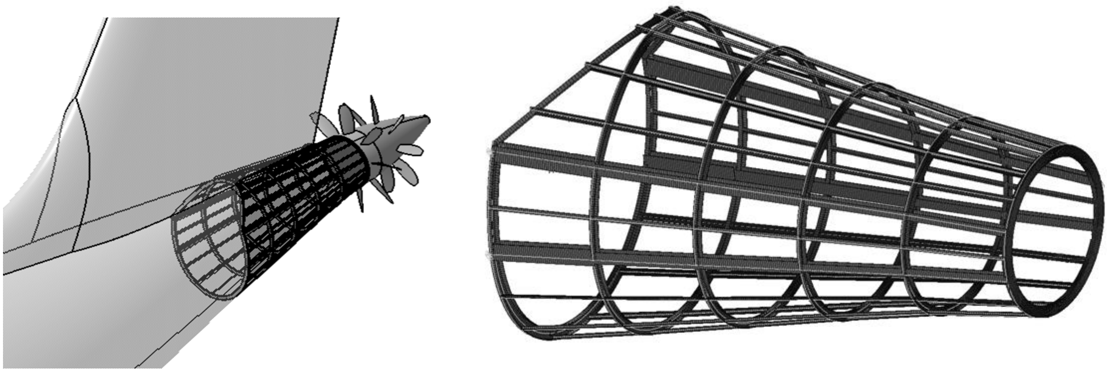

Figure 16: Proposed structure to hold the propeller and subsystems

Besides the main stringers, “I” shaped, the structure is composed of six “C” shaped frames and fifteen “Z” shaped small stringers. The structure should run a total length of 2.75 meters in order to ensure the BLI blades do not hit the aircraft’s rudder. The four points of support are highlighted in Fig 17. An estimation was made of the loads the structure would have to resist taking into account both engines and their respective mountings and blades. At this point there was not a concrete design for the protection system and therefore an estimation of its weight was not possible, meaning that the structural analysis was run without this information and therefore, will need to be adjusted at a later stage.

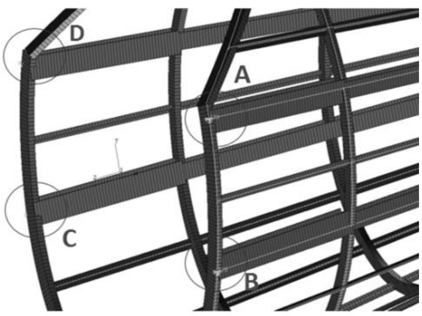

Figure 17: Support points

CRITICAL F O R C E S ON SUPPORT FITTING

SUPPORT	Fx	Fy	Fz
A	-53598	-8003	-1474
B	32749	2934	7378
C	52893	-7886	6805
D	-32045	2984	3246

Table 4: Forces on support fitting (*N*)

A process of structural optimization was conducted in order to try and obtain the lightest possible structure that would be able to support a limit load of all the weights multiplied by 4G and 2.5 G in the downward vertical direction and lateral direction respectively as well as the engine torques to simulate the worst possible scenario. The forces applied in the supports of the optimized structure are summarized in Table 4.

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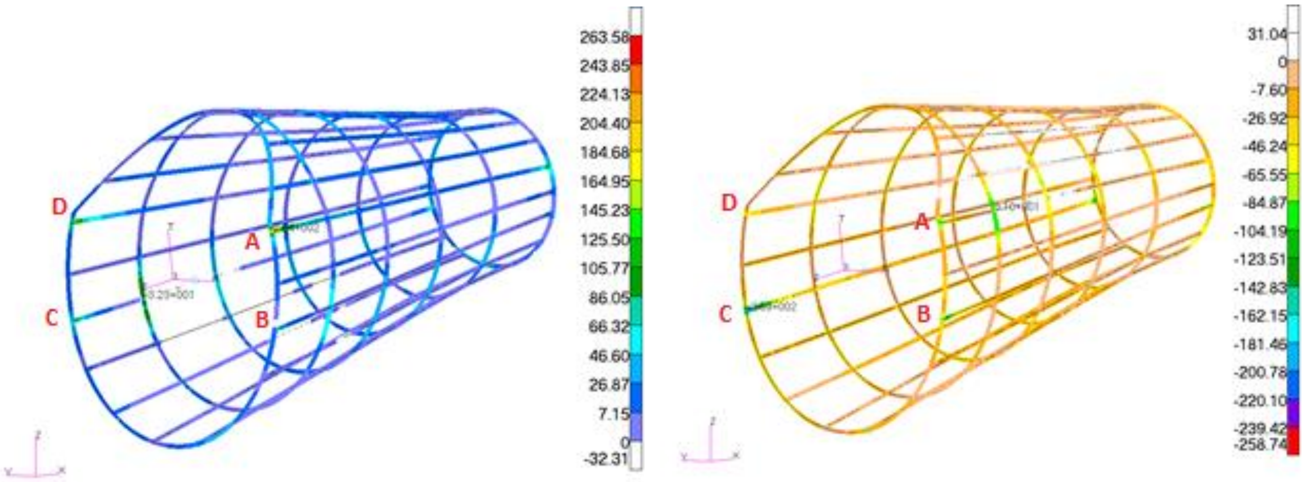

Figure 18: Tension and Compression stress (MPa)

Analysing Table 4 it is clear that, as expected, the top two supports stand in tension, while the bottom two deal mainly with compression. It is also support A that is subjected to the highest force followed by support C. However, the forces alone are not enough to judge if the structure can hold the loads or not. Fig 18 shows the minimum and maximum stresses each bar element is subjected to. As the constraint forces indicated the maximum stresses are experienced by the main stringer A and the minimum in the main stringer C. Since the material chosen for the structural elements was 7075-T6 the gross limit margin of safety (MS) is estimated to be around 0.66. At this point, due to the relatively large sections of the main stringers, the buckling and crippling margin of safety was not taken into account and will be studied in future analysis.

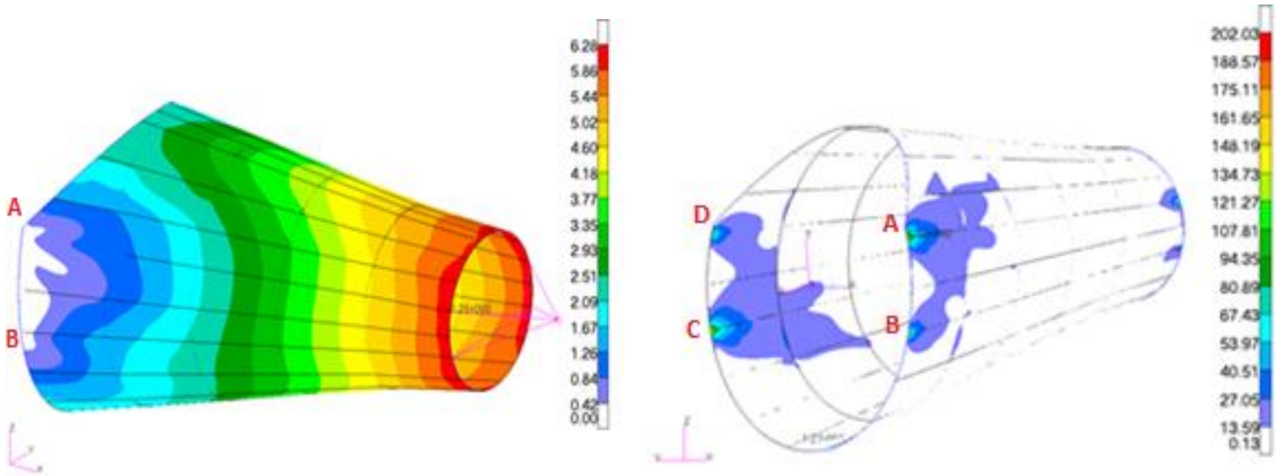

Figure 19: (a) Displacements (mm). (b)Max shear (MPa)

Fig 19 a) shows the limit deformations which reach a maximum value of 6.28 mm. This is a more than acceptable value taking into account the loads and length of the modification.

Fig 19 b) displays the distribution of the maximum shear loads. The distribution led to the reinforcement of the skin sections surrounding the area where the main stringers are braced with a 2.5 mm thick skin. The lateral sections of the skin are composed of 2 mm thick sections and the top and bottom sections, where the least amount of shear loads are expected, are composed of 1.6 mm thick segments. The material to be employed in the skin is Alclad 2024-T3 due to its mechanical properties and extensive use in the aeronautical sector.

Ultimately the whole structure comes in at a total of 58.14 kg, of which 8.20 kg are from the main stringers, 5.42 kg the stringers, 7.12 the frames and the skin weighs 37.40 kg.

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As a result of the analysis, the optimal configuration for the project development could be determined. The weight reduction, the simplicity of the structure among other factors show that this kind of structure is the best way to move forward.

5. FOD protection subsystem

The BLI protection system consists of several small supersonic nozzles of different sizes that are distributed along the rear part of the fuselage, some meters ahead of the propeller system. These nozzles would be activated in case that an object would collide against the BLI propellers during takeoff or landing, changing its trajectory and avoiding the possible impact.

This system can be divided into three parts:

- Pressure tanks.
- Connecting ducts.
- Convergent-divergent nozzles.

The different activities have been focused towards getting enough force to deviate from the initial trajectory any object that could impact the propeller system and the attachment of this system to the rest of the structure.

These are the different studies that have been carried out:

- CFD analysis of the supersonic nozzles.
- CFD analysis of the tank and nozzle junction ducts.
- Analytical study of possible trajectories and how to divert them.

Analyzing the results obtained, different models have been studied. Attending to the limitations that have been found, a good solution would be several rows of 4 or 5 nozzles that would encircle the lower and lateral parts of the fuselage, covering all possible collision trajectories.

This nozzle system could be a viable way to protect the BLI propellers from colliding objects. However, most parts of the system have only been conceptually designed, so it is a work in progress, especially on how to distribute the pressure tanks in order to avoid excessive pressure losses and having a homogeneous pressure in the different parts of the system as well as the location of the nozzles on the tail cone to optimize their performance.

3.4.3 Conclusions

Many pieces of evidence demonstrating a big step in an aircraft’s overall aerodynamic efficiency were found with the development of the BLI system. Nevertheless, it is still in the early phase of development, hence there are many parameters to set and details to finalise.

The improvements are mainly focused on thrust, drag and fuel consumption areas; an improvement in thrust and a drop in drag will lead to a reduction of fuel usage. Exact numbers of these facts cannot be provided yet due to the early development of the project but they indicate a very significant increase in overall efficiency.

This project shows the possible benefits of the hybridization/electrification of aircraft, showing real solutions to the current challenges. It also represents a milestone in Altran's commitment to innovation applied to a better world, committed to the environment and the next developments in green transport.

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Acronyms

CFD: Computational Fluid Dynamics
BL: Boundary Layer
BLI: Boundary Layer Ingestion
FOD: Foreign Object Damage

Nomenclature

T: $Thrust$
$\dot{m}$: $Mass\ flow$
u: $Velocity$
D: $Drag$
E_m: $Mechanical\ Energy\ variation$
$P_{added,noBLI}$: $Power\ added\ without\ BLI$
$P_{added,BLI}$: $Power\ added\ with\ BLI$
$P_{required,noBLI}$: $Power\ required\ without\ BLI$
$P_{required,BLI}$: $Power\ added\ with\ BLI$
∞: $Freestream$
j: $Before\ propeller$
w: $wake$

Keywords

Electrical, hybrid, aircraft, boundary layer propulsion, electric propulsion, green transport.

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