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CS2-THT U-HARWARD Project: Final Assessment and Project Outcomes Evaluation

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The paper summarizes the research activities and the results obtained in the framework of CS2 U-HARWARD EU project, focused on the high aspect ratio wing technologies. The project started May 2020 and finished October 31, 2023. Comprehensive numerical analysis was performed to explore the optimum design for three high aspect ratio wing aircraft configurations: cantilever wing, strut braced wing (SBW) and folding wingtips (FWT). Whereas the increased wingspan causes significant aircraft weight penalties, resulting in a compromised overall aircraft performance, the studies show that there is a "sweet spot" of an optimal AR where the performance (fuel burn or Breguet Range) is maximized and this point is greater than current designs. Further benefits can be achieved through the use of Gust Load Alleviation and Manouevre Load Alleviation. The U-HARWARD project also included four main experimental wind tunnel campaigns：i. An aero-acoustic model to investigate the combination of the strut and wing wakes in the generation of the airframe noise, ii. An aeroelastic model composed of a wing plus strut to investigate static aeroelastic and flutter characteristics, iii. An aerodynamic model of the complete SBW configuration to identify the low speed aerodynamic characteristics and related stability derivatives, and iv. a large aeroelastic half model with a wing equipped with a folding wingtip mechanism to explore the gust load alleviation characteristics. A summary of the results, as well as the most relevant lessons learned, are included.

I. Introduction

The impacts of climate changes are clear and evident in our everyday life and justifies and explains the world effort in trying to reduce the most relevant cause of these changes universally recognized as the use of carbon-based fuels for all the energy related societal activities, including transports. The aviation world is well aware of these climate targets and since many years there are lots of activities to improve fuel-efficient and environmentally friendly aircraft designs; however, the rate of improvement in performance of conventional aircraft configurations (via improved aerodynamics, composite structures and better engines) is not fast enough to achieve net zero aviation by 2050. As a consequence, the need to explore the benefits of novel aircraft architectures to provide a step-change in fuel efficiency is evident. This need has been identified by ICAO, FLIGHTPATH2050 and Clean Sky 2 initiatives in Europe and also NASA, with challenging goals set for reductions in CO_2, NOX and noise by the year 2050 [1] [2] [3]. At EU level, the biggest part of the research funding in the field of aerospace are directed to programs having the clear object to significantly impact on the so called Destination 5, that is looking for "Disruptive gains by 2035, with up to 30% reduction in fuel burn and CO_2 between the existing aircraft in service and the next generation, compared to 12-15%

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in previous replacement cycles (when not explicitly defined, baselines refer to the best available aircraft of the same category with entry into service prior to year 2020)."

The path towards a completely carbon neutral air transport will certainly take many years and will require several intermediate steps. Although the recent announcement by Airbus of the zero-emission program, with the promise of flying the first fully hydrogen-powered aircraft by 2035, it is clear that there will be a transition through more traditional architectures but with a higher level of efficiency, certainly possible even with the technologies already available at the moment. Targeting this intermediate goal, the CS2-U-HARWARD project started in May 2020 in response to the call JTI-CS2-2019-CFP10-THT-07: Ultra-High Aspect ratio wings, aiming at the use of innovative aerodynamic and aeroelastic designs in a multi-fidelity multi-disciplinary optimal design approach to facilitate the development of Ultra-High aspect ratio wings for medium and large transport aircraft.

Historically, the most significant improvements in jet aircraft efficiency have been related to improvements in propulsion associated with the development of high-bypass-ratio turbofan engines. More recently, the extended use of high-strength composites enabled the reduction in airframe weight. Finally, configuration changes such as increased wingspan and optimized wing geometries have led to improving L/D. However, it must be pointed out that the integrated nature of the aircraft design means that few substantive configuration changes can be made without incurring some multidisciplinary trade-offs. For example, increasing the wingspan can lead to an increase in wing weight due to the higher bending moment.

However, the same integrated nature of aircraft design represents a great opportunity: indeed, significant improvements can come from optimized configurations that simultaneously exploit aerodynamic, control, and structural advances to improve efficiency. In most cases, a multidisciplinary approach is the only one that guarantees a net improvement in global efficiency. Aiming to achieve Natural Laminar Flow (NLF) from advanced wing designs combined with an aggressive combination of (passive or active) Maneuver (MLA) and Gust Load Alleviation (GLA) technologies and the use of tailored composite designs (to unlock the full potential of composites) provide the root to achieve greatly improved weight and aerodynamic terms in the Breguet equation.
The consortium of U-HARWARD is composed of six partners: Politecnico di Milano, the coordinator, IBK-Innovation GmbH & Co. KG, University of Bristol, Office National d'Etudes et de Recherches Aérospatiales, Institut Supérieur de l'Aéronautique et de l'Espace and Siemens Industry Software SAS. The main idea of U-HARWARD project is to combine the modern design and manufacturing technologies to extend the actual span limit of conventional configurations, together with a deep investigation on a new, promising configuration, i.e. The Strut-Braced Wing (SBW) and finally with the feasibility studies of a new disrupting technology based on the active folding wingtip concept. To this aim, the design activities range from the conceptual up to the high fidelity level and are managed by three teams focusing on three different concepts. Team 1, composed by Politecnico di Milano and IBK, is focused on traditional cantilever wing configurations with extended aspect ratio. Team 2, composed of ONERA and ISAE, is focused on the Strut-Braced Wing configuration. Finally, Team 3 represented by the University of Bristol and Siemens, is mainly focused on folding wing tip configuration.

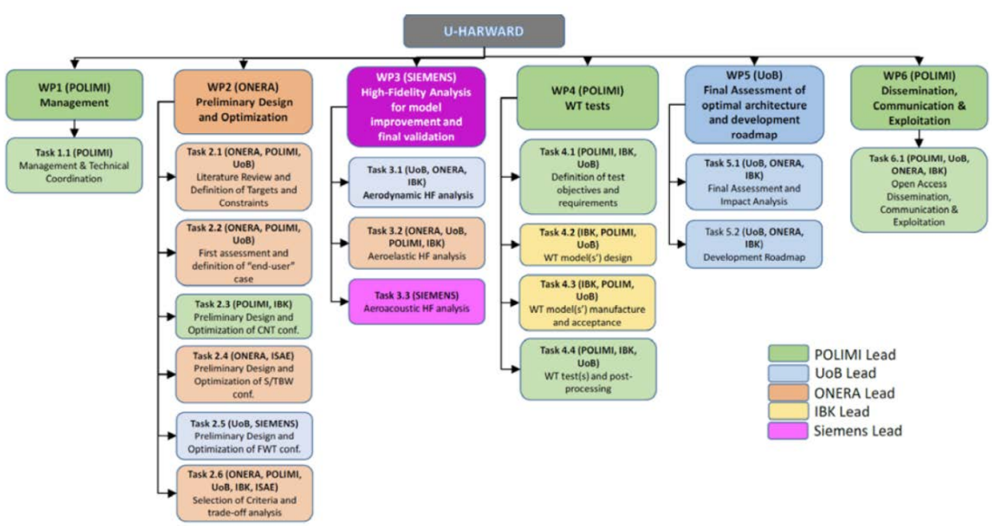


Figure 1: Project plan

Figure 1 shows the project plan divided in six work packages four of them dedicated to the research activity. In particular, WP2 focused on the conceptual and preliminary analysis of the reference and innovative configurations, WP 3 focused on high fidelity analyses in terms of aerodynamic, aeroelastic and noise impact verification, WP4 on the different experimental campaign for concept validation and WP5 the final assessment.

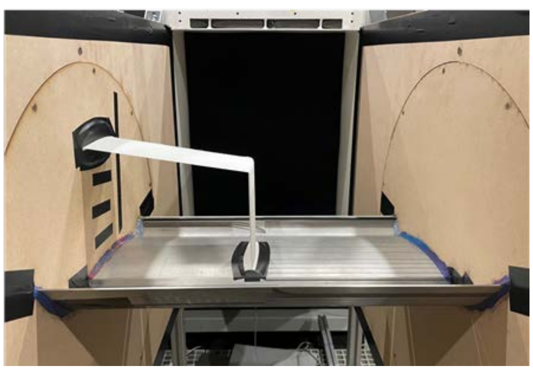
The research activities of U-HARWARD project also included four main experimental campaigns：

1. An aero-acoustic wind tunnel campaign to investigate the combination of the strut and wing wakes in the generation of the airframe noise. This test campaign was carried out at the aero-acoustic wind tunnel facility of University of Bristol with the support of SIEMENS. A portion of the wing including the strut and the TE flap was adopted. The model was derived by an already available model previously tested at Bristol (30P30N wing) equipped with both LE and TE flap see (Figure 2 (a))

2. An aeroelastic model (AE1) composed by wing plus strut model was tested at the large wind tunnel of POLIMI to identify the static aeroelastic and flutter characteristics of SBW configuration and their sensitivity with respect to type and position of the connection between the strut and the wing (see (Figure 2 (b)).

3. An aerodynamic model (AA) of the complete SBW configuration proposed by ONERA, scaled 1:22, was tested at the large wind tunnel of POLIMI to identify the low speed aerodynamic characteristics and related stability derivatives (see (Figure 2 (c)).

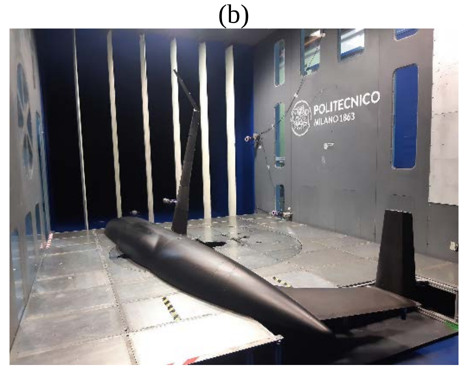
4. Finally, at the end of third year of the project, a large aeroelastic half model with a wing equipped with the folding wingtip mechanism was conducted at the large wind tunnel of POLIMI to investigate potential benefits and implementation issues aiming at load alleviation under discrete and continuous gust excitation. This test takes advantage of previous experience and already available setup already adopted for this kind of test during previous CS1-GLAMOUR and CS2-AIRGREEN2 EU projects (see (Figure 2 (d)).



(a)

(b)

(c)



(d)

Figure 2: The 30P30N wing model available at University of Bristol for aeroacoustics test (a); the cantilever+strut SBW AE1 model for flutter identification (b); the aerodynamic model AA (c); the large aeroelastic half model with folding wingtip for GLA validation (d).

II. Reference Aircraft

U-HARWARD design activities have been organized in a parallel way: 3 teams evaluated separately the 3 design options mentioned above, and results will be gathered and compared at the end of the OAD studies, to derive common conclusions and requirements for WP3 and WP4 design activities. Therefore, there was a need for a common reference among the teams to calibrate design tools and enable direct comparison of results. This reference aircraft is also used to position the results of the project and communicate on them. Defining a reference aircraft relies on 2 separate aspects: the mission to be completed by the aircraft, which often relies on some market segments in the aeronautics industry: regional, short-medium range, long range; the technology level and detailed features to be implemented on this reference aircraft: copy-paste of an existing one, redesign of a new aircraft, targeted EIS and associated technology levels. As no market segment is explicitly specified in the U-HARWARD targets, a broad analysis has been conducted to choose the most relevant mission definition, both from the benefits we can expect for a future commercialized aircraft, and from the more general lessons we could derive with the studies conducted in U-HARWARD.

Schematically, the main aircraft families can be identified as follows:

- Regional mission (~ 50 PAX, DR < 1000 NM, M~0.5)
- SMR mission (~150 PAX, DR < 2500 NM, M~0.78, typical 800 NM)
- Extended SMR mission (~200 PAX, DR < 4000 NM, M~0.78)
- Long range mission (~300 PAX, DR > 7000 NM, M~0.84, typical 5000 NM)

The regional mission, and especially its low flight Mach number, would make it suitable for the design of a UHAR, laminar wing. However, it has to be kept in mind that the target of CS2 studies is a massive reduction of CO2 emissions, for which the regional segment is only a minor contributor. Therefore, although it is relevant from the technical point of view, the regional segment has not been retained for U-HARWARD.

On the opposite side, the main benefits of UHARW lie in the reduction of induced drag and significant improvement of L/D at cruise conditions. The longer the cruise segment, the higher the relative benefits of this technology on fuel burn evaluation. However, this makes the design exercise more difficult: the high flight Mach number (and more severe associated transonic phenomena), the larger scale, the higher flexibility leading to flutter issues will make the transposition of numerical and experimental studies more difficult. Additionally, there is a lack of publicly available data for the reconstruction of a LR reference aircraft. These considerations oriented the work to the SMR mission.

The A320 family is well known by the research community, especially through the numerical model CeRAS CSR-01, and serves as a basis for comparison for a lot of CS2 studies. However, the typical mission of such an aircraft has a very short cruise segment and the benefits of a UHARW might not be maximal. Therefore, it was decided to go for the extended SMR segment, which is the one of the A321, to combine the demonstration of high benefits in this "middle of the market" segment, and the possible transposition to smaller (eg. SMR and even regional) or bigger aircraft. Therefore, the choice was oriented towards the A321neo aircraft.

This reference aircraft has been re-designed by the teams by first taking benefit of the existing database of CeRAS CSR-01, then stretching the results to the A321 neo results with modified fuselage and engine, upon the specific TLAR. Finally, 2035 technology options could be introduced at the end of the project for comparison with other CS2 studies.

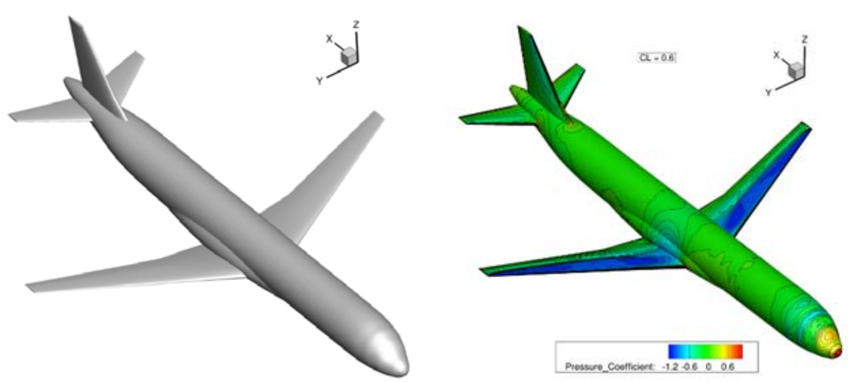


Figure 3: Reference aircraft geometry for RANS computations (left) and RANS surface pressure coefficients for CL=0.6 (right) computed by ONERA

III. Summary of Results

This section summaries the results of numerical and experimental work performed in the work packages to assess the performance of three aircraft configurations i.e. cantilever wing, strut-braced wing and folding wingtips as shown in Figure 4. For each configuration a sizing process was undertaken considering a range of different loading conditions in order to determine the structural weight and L/D from which the range could be computed.

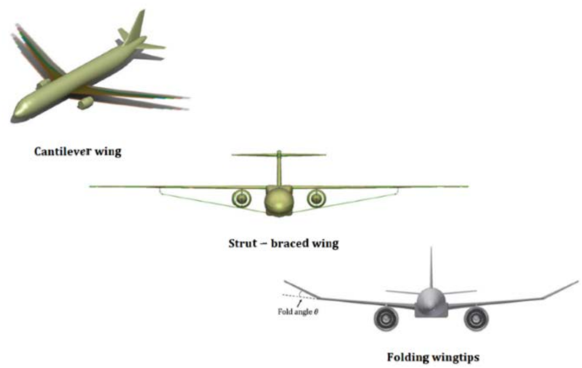


Figure 4: Schematic drawing three aircraft configurations.

A. Cantilever wing configuration

The top level objective of the activity done in WP2 and WP3 was to investigate the overall performances by increasing the aspect ratio of the wing, which was made by keeping fixed the wing planar surface. Among the infinite combinations available, the taper ratio distribution of the wing was kept constant, defining a unique law for the wing shape scaling. In addition to the Reference Aircraft four increased aspect ratio in cantilever (CNT) configuration are considered, which wing characteristics are presented in the following Figure 5:

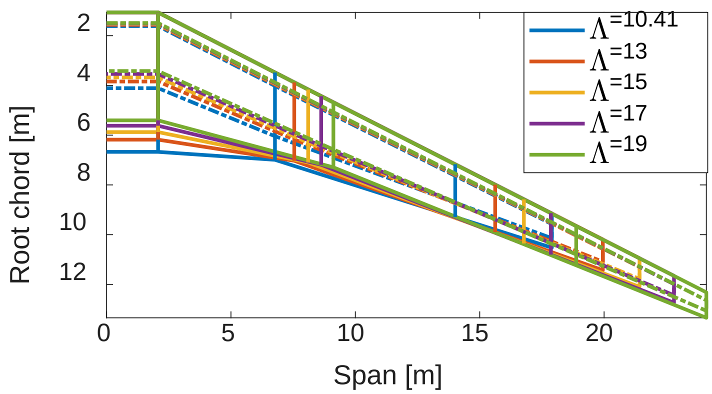


Figure 5: Wing planform shape and wingbox position with different AR with constant taper ratio and surface.

Table 1 shows the sized wingbox structural masses for the 5 Aspect Ratios that were considered for high strength composite and aluminium construction using the NEOCASS package. A safety factor SF=1.5 was used for the nominal load obtained during the optimization, hence no stress related failure nor buckling are expected up to ultimate loads. The structural mass and wing weight (see Figure 6) increases with the aspect ratio as does the aerodynamic performance and thus the optimal AR is a trade-off between wing structural penalty mass and induced drag reduction. To complete the foreseen trade-off studies of the novel environmentally friendly configurations for increasing aspect ratio it is necessary to implement into the design framework the capability to estimate fuel burned and NOx and CO2 emissions. In the following some details about the adopted computational models.

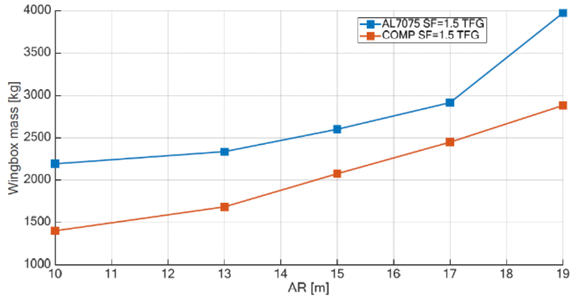


Figure 6: Cantilever Wing. Sized wing weight for each wing aspect ratio

Table 1. Wing weight for different materials and aspect ratio

AR	10	13	15	17	19
AL-7075	2193.5	2337.7	2601.4	2916.5	3975.5
Composite	1402.4	1685.2	2076.4	2449.3	2882.4

The methodology adopted to correctly estimate the fuel burned during a pre-defined mission proposed by IBK is based upon the well-known Breguet range equation, where Q_{jet} is the fuel-flow, $TSFC$ is the engine thrust specific fuel consumption, D and L are the global drag and lift respectively, E is the aerodynamic efficiency, T is the total engine thrust and W is the aircraft weight. Knowing the engine $TSFC$ and the aircraft thrust, we can immediately compute the fuel flow as

$$Q_{jet} = TSFC\frac{D}{L}W = TSFC \times T$$

Alternatively, knowing the aircraft weight and the aerodynamic efficiency in each point of the mission, the aircraft thrust could be computed through the well-known Breguet formula:

$$\text{Range} = \frac{V}{TSFC\ g}\left(\frac{L}{D}\right)\ln\left(\frac{W_i}{W_f}\right)$$

where V is the cruise speed, W_i is the initial aircraft weight and W_f is the final aircraft weight. Defining ΔT as the global mission time, the fuel burned FB is computed knowing the fuel-flow Q_{jet} in each point of the mission by a simple integration over the whole mission.

$$FB = \int_0^{\Delta T} Q_{Jet}\,dt$$

The described methodology provides a reliable result for the cruise phase only but is not sufficiently accurate for the climb and descent phases. For this reason, it has been necessary to develop a different approach to be able to compute a reliable value of aircraft thrust and subsequently fuel flow in each flight phase of the mission. A simple correction has been applied consider the climb phase also, using the climb flight equations instead of the Breguet formulation.

The common ICAO certification procedure [4] of the aeronautical engines foresees the generation of a public engines' emission databank. The certification process involves running the engine on a test bed at various thrust settings in order to simulate the so-called LTO cycle (Landing Take-Off cycle). The NOX and CO2 indices (grams/ kilograms of NOX and CO2 emitted for each kg of fuel burned) are stored for each sub-phase of the LTO cycle, but unfortunately, no information is reported in the ICAO public databank about the other flight phases. For this reason, it was necessary to adopt a different strategy to correctly estimate the amount of NOX and CO2 emitted during the selected mission, depending on the amount of fuel burned in each flight phase.

Concerning the estimation of NOX emitted during a typical mission, a semi-empirical methodology has been developed. Thanks to the data reported in [5] dealing with emissions during aircraft operations it was possible to quantify the amount of NOX emitted by two reference aircraft (Boeing B737-800 and B767-300) during a typical mission. The missions described are subdivided into the following mission phases:

- Segment 0-1: LTO (Landing Take-Off) cycle.
- Segment 1-2: Climb from 3000 ft to cruise altitude.
- Segment 2-3: Cruise.
- Segment 3-4: Descent from cruise altitude to 3000 ft.

Table 2. shows the fuel burn for the above mission for different aspect ratio aluminium wings where it can be seen that an increasing AR results in less fuel burn. Furthermore, reference [6] reports the average fuel consumption of, among others, the above two aircraft. Combining the two data (NOX emitted w.r.t. time and fuel consumption) it was possible to estimate, for each mission phase, an emission index for the two-reference aircraft describing the amount of NOX emitted per each kg of fuel burned. Known the emission indices of the two-reference aircraft, for each mission phase, it has been assumed that interpolation can be performed on the emission indices with respect to the aircraft's maximum take-off weight to obtain the emission indices of a generic aircraft. It is clear that to improve the fidelity of the interpolated emission indices, a larger database of reference aircraft with more reliable values of fuel consumption per hour would be required. The validation of the developed methodology has been performed by the use of the same public technical report used for the validation of the fuel burned estimation methodology, i.e. the CeRAS report [4]. As seen before, these two data can be combined to obtain a NOX emission index describing the amount of NOX emitted per kg of fuel burned, for each flight phase. Literature research has been conducted to investigate the current state of the art on the estimation of the amount of CO2 emitted by aircraft during typical missions. As demonstrated in [7], it is possible to estimate the emissions of CO2 by simply scaling the amount of fuel burned, considering a variable emission factor depending on the type of fuel used.

Table 2. Fuel consumption for Aluminium Wing vs AR for 4 segment mission

Wing	AR	Trip Fuel (kg)	Delta Trip Fuel	Nox Flight (kg)	CO2 Flight (kg)
Al 7076 -T6	10.47	14534	-	153	43367
Al 7076 -T6	13	13215	-9%	139	39213
Al 7076 -T6	15	12478	-14%	131	36891
Al 7076 -T6	17	11888	-18%	125	35031
Al 7076 -T6	19	11427	-21%	121	33580

The results obtained are based on the calculation of Fuel Burn using the classical Breguet formulas, valid for cruise phase only, and estimating the drag using statistical methods. What happens in case of more sophisticated aerodynamic calculations, together with the modified Breguet approach as explained in previous section, is summarized in Table 3 where the results concerning all the analyzed configurations, based on aluminum and optimized composites, under limit and ultimate loads are shown. The drag is computed by an enhanced panel method with boundary layer correction. Trip fuel and NOX/CO2 emissions have been computed for each aircraft configuration.

Table 3. Results for all the analyzed configurations, with CFD based aerodynamic results and modified Breguet formula.

Aluminium, SF=1.5					
Aspect ratio	10	13	15	17	19
Half Wingbox Mass (kg)	2070	2273	2461	2689	3014
Trip Fuel (kg)	22969	21081	20924	21522	21558
NOX flight (kg)	306	282	280	288	289
CO2 flight (kg)	69938	63990	63496	65381	65492
Delta Trip Fuel	0.00%	-8.20%	**-8.90%**	-6.30%	-6.10%
High Strength Composites (CFUD), SF=1.5					
Aspect ratio	10	13	15	17	19
Half Wingbox Mass (kg)	1378	1692	2056	2423	2813
Trip Fuel (kg)	22566	20761	20701	21384	21456
NOX flight (kg)	300	277	277	286	287
CO2 flight (kg)	68668	62983	62793	64944	65171
Delta Trip Fuel	-1.80%	-9.60%	**-9.90%**	-6.90%	-6.60%

Interestingly, the most efficient configuration does not correspond to the highest aspect ratio (AR 19) but to the AR 15 configuration. Considering the AR 15 configuration as baseline, the trip fuel has been computed considering all the 4 combinations of polar curves and take off weights for AR 15 and AR 19 configurations. If compared to AR 15 configuration, the polar curves of the AR 19 imply only a 1% fuel saving, however, the TOW of the AR 19 case implies 5% more fuel burned. Consequently, the biggest impact of the higher TOW w.r.t. the improved aerodynamic efficiency is the reason why the fuel burned by the AR 19 configuration is higher by 3% than AR 15 configuration.

B. Strut braced wing configuration

The ONERA-ISAE FAST-OAD aircraft conceptual design framework is used in the U-HARWARD project to perform the overall aircraft design of the SBW configuration. FAST-OAD is implementing a multi-disciplinary sizing process of the aircraft that allows easy addition or replacement of disciplinary models, as illustrated in Figure 7.

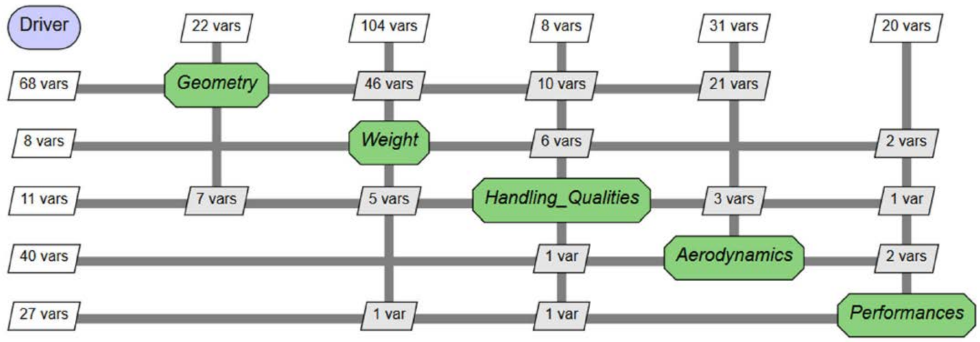


Figure 7: FAST-OAD process (XDSM).

This process is adapted to the design of strut braced wing configurations through additional modules accounting for the strut viscous drag and estimate the wing weight. These modules were detailed in [8]. To start from reference, FAST-OAD has first been used to render the characteristics of the A321LR-like aircraft. Taking advantage of the ability for quick evaluations of aircraft designs, an iterative approach was deployed. The idea is to gradually modify the geometry of the reference to converge toward the ONERA ALBATROS configuration (selected as the SBW reference configuration since it aerodynamic performances have been investigated previously by ONERA) and then realize a study on the influence of the aspect ratio of the wing on the aircraft performance. This effect is illustrated in Figure 9.

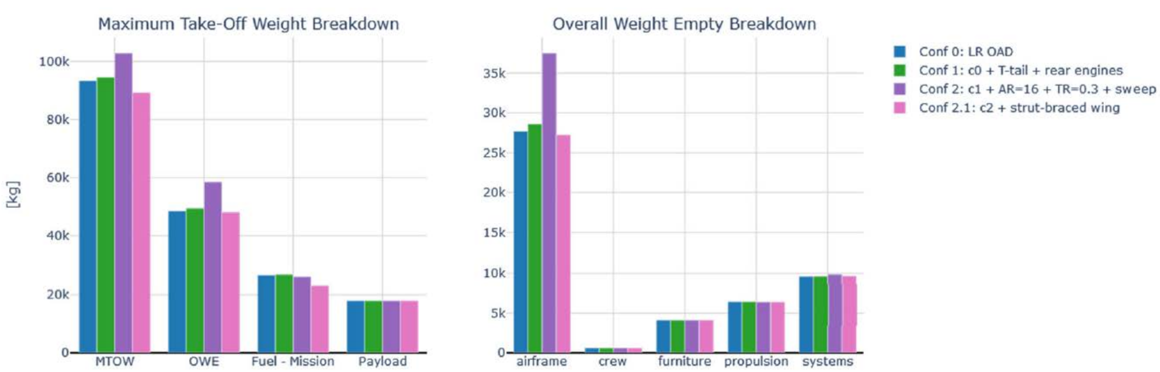


Figure 8: Mass breakdown comparison of the ALBATROS configuration.

The first modification (going from configuration 0 to 1) consists in moving the engines to a rear position on the fuselage and modelling a T-tail shape, ensuring the effectiveness of the HTP. From this configuration, the aspect ratio of the wing, the taper ratio and the leading-edge sweep angle are modified to match the ALBATROS wing geometry (configuration 2). Finally, the strut is modelled to define the configuration 2.1. *Note: for all configurations, including the reference one, the wing area is fixed to the ALBATROS value of 160m². It is significantly larger than the A321LR.* A Breguet-Leduc equation is considered to estimate the fuel weight gains that the strut-braced wing configurations would allow. An estimation of the impact of each modification of the aircraft geometry on its performances is detailed in Figure 9.

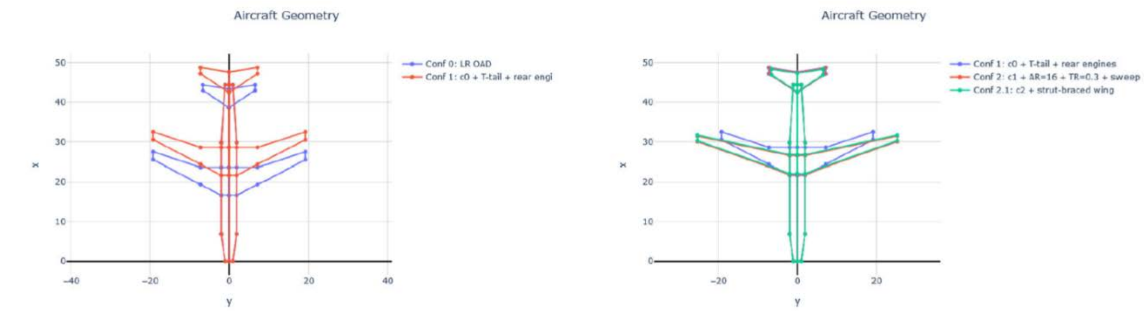


Figure 9: (a) Reproduction of the A321-LR configuration (in blue) and modification of the Tail geometry and engines position (in red). (b) Modification of the tail geometry and engines position (in blue), increase of the wing aspect ratio, modification of the taper ratio and sweep angle (in red) and modelling of the strut (in cyan)

Note: the mass presented in the breakdown are currently under investigation as it seems that the OAD process tends to underestimate the wing mass. From this first evaluation, the strut-braced wing configuration would allow a fuel reduction of 12% compared to the initial cantilever configuration which is mainly due to the reduction of the induced drag induced by the increase of the aspect ratio of the wing. The airframe mass is almost the same between configuration 0 and 2.1 thanks to the presence of the strut which allows alleviating the wing while the aspect ratio is increased from 10 to 16. The next step consists in studying the influence of the aspect ratio of the wing and the position of the junction between the strut and the wing on the overall aircraft performance.

The reconstruction of the ALBATROS configuration (with AR = 16) is considered as the reference point of the study. Strut-braced wing configurations with $AR \in [10, 12, 14, 16, 18, 20, 22]$ are evaluated using the FASTOAD process for different positions of the junction between the strut and the wing (defined as $\eta_{strut} = \frac{y_{junction}}{b}$) in the spanwise direction. The fixed main geometrical parameters of the SBW configuration are the strut wetted surface and the aspect ratio while the variables of interest are the wingspan and the wing planform area. The main quantities of interest determined in the end by the FAST-OAD process are the MTOW, block fuel and wing mass, which are expected to decrease if compared with a classical cantilever configuration. The evolutions of these quantities are illustrated in Figure 10, where the values plotted for η_{strut}=0 corresponds to the cantilever configuration of the airplane.

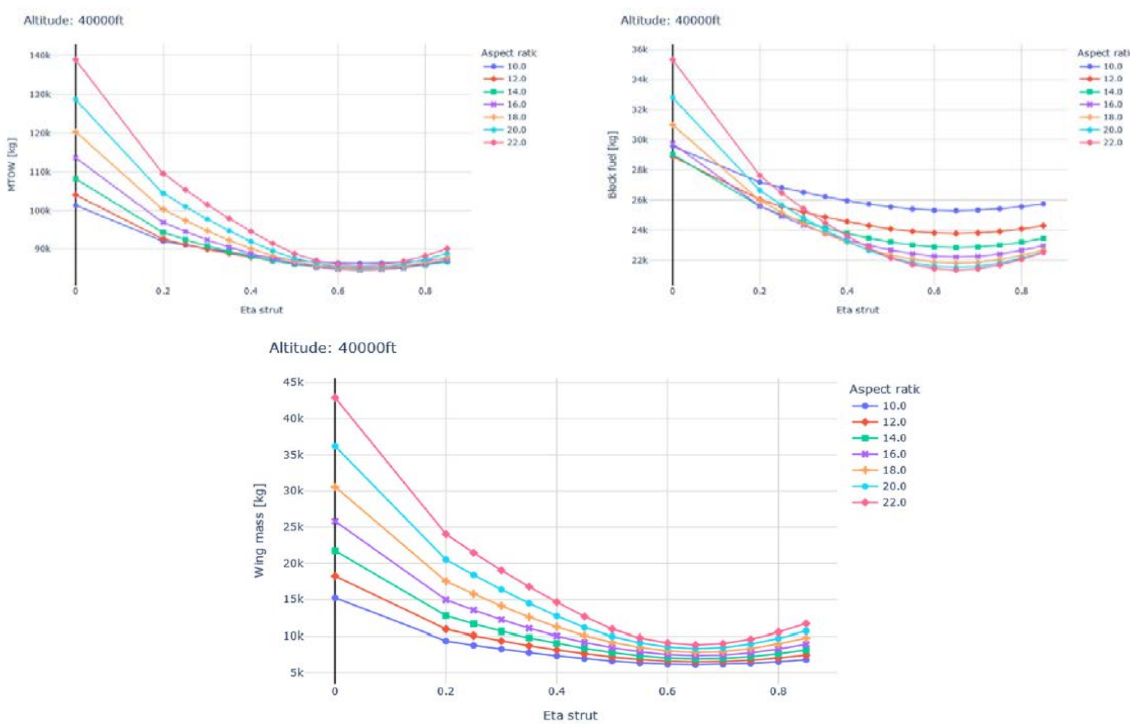


Figure 10: Influence of the Aspect ratio and the junction position on the SBW configuration performance.

From this preliminary study, it appears that the strut induces a direct advantage over the cantilever configurations for all the aspect ratio considered. The trends of the masses plotted in the figures decrease until it reaches a minimum between 60 and 70% of the wingspan which can be identified as an optimum position for the junction between the strut and the wing. A dedicated study in this interval, not shown here, demonstrated that the optimum position of the junction should be located at η = 65%, for all the aspect ratio considered.

Analysis has performed to evaluate the influence of the strut on drag. Two different joint positions are considered and illustrated Figure 11. The SU² CFD computations are achieved in the aircraft cruise conditions, at a Mach number M = 0.78 and an altitude of 11 000 m. The FFD post-processing of the computations allows determining the influence of the strut/fuselage junction position on the wave drag, as illustrated in Figure 12.

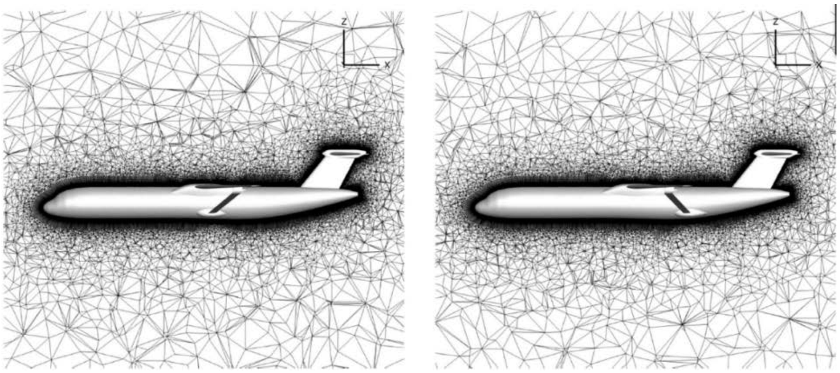


Figure 11: Aircraft with two different position of strut.

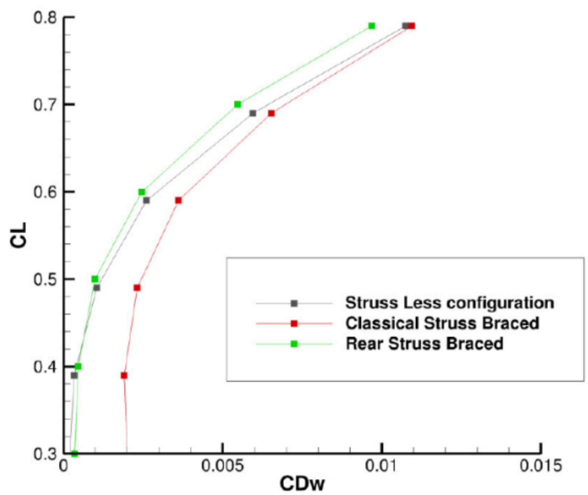


Figure 12: Influence of the strut position on the wave drag component.

Furthermore, an in-depth experimental noise investigation of strut-braced 30P30N high-lift aerofoils is conducted to evaluate the impact of the strut on noise, where the new contribution from strut system is identified as a mechanism for reducing noise. A detailed comparison is made between strut-braced aerofoils of varying strut height and baseline model with no strut, as shown in Figure 11, for a wide range of chord-based Reynolds numbers and angles of attack. The present study examines three strut configurations, namely small height, medium height, and large height (the Albatros). All struts are mounted on the midspan of the main element aerofoil and two chordwise mounting positions are studied for each strut, namely the mid-chord and trailing-edge locations. Under the inertia-dominated high Reynolds number flow regime, far-field noise assessments are first carried out, followed by detailed near-field flow characterisation.

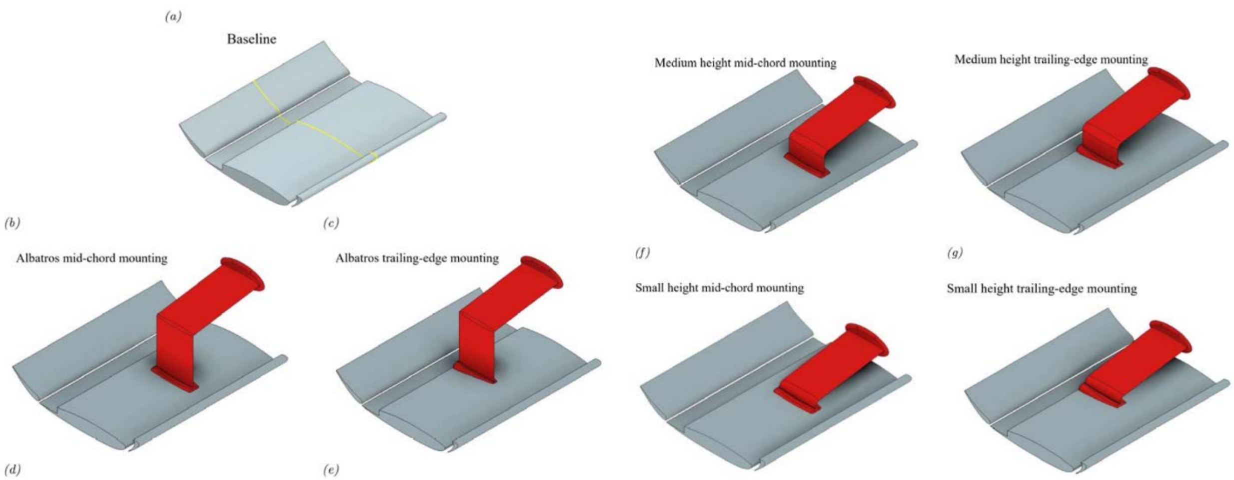


Figure 13: Various strut-braced wing configuration considered for aeroacoustics test.

Aeroacoustics measurements indicate that 30P30N aerofoils with struts can result in significant reductions in leading-edge slat noise levels, and even up to 9dB when Albatros is mounted at the trailing edge location. The nearfield pressure coefficient and hot-wire measurements were additionally conducted to characterise the aeroacoustic quantities of the aerofoils. An attempt has been made to gain insight into noise reduction mechanisms by linking near-field hydrodynamic quantities with far-field noise signature of the high lift device. A systematic investigation of this phenomenon revealed that the excitation mechanism, that is, the unsteady shear layer in the cove cavity, can easily be suppressed through a strut structure. It was anticipated that the flow channelling effect due to the installation of strut structure drives the mechanisms of noise reduction in high-lift aerofoils. This is the first time the noise suppression mechanisms from a wing supported by a strut structure have been investigated.

C. Folding wingtip configuration

In-flight floating folding wingtips improves aircraft performance by enabling high aspect ratio wing to be designed at lower weight, owing to its effective load alleviation capability for gust and manoeuvre loads. The aerodynamic loads are computed at a range of design points in which the aircraft is expected to experience the worst-case loads such as manoeuvres and severe gust encounters, as shown in Table 4.

Table 4. Load cases considered in the folding wingtip preliminary design process.

Load cases	Load factor	Gust length (m)	Mach number	Altitude (ft)	Fuel fraction	Hinge condition
1	2.5	NA	0.48	3000	1	Free
2	2.5	NA	0.78	36000	1	Free
3	-1	NA	0.48	3000	1	Free
4	1	18 - 214	0.48	3000	1	Free
5	1	18 - 214	0.6	20000	1	Free
6	1	18 - 214	0.78	36000	1	Free
7	2.5	NA	0.78	36000	0	Free
8	-1	NA	0.48	3000	0	Free
9	1	30% worst case amp	0.48	3000	1	Fixed
10	1	18 - 214	0.48	3000	1	Fixed

Note that the load case 9 considered the worst load case for cruise condition (fixed hinge + 30% of the worst gust amplitude for each gust length), whereas the load case 10 was the hinge failure case where the safety factor of 1 was used. The worse-case loads during manoeuvre (2.5g pull up) and cruise (1g level flight) are compared between three hinge configurations: (i) fixed hinge (ii) free hinge with the relative FWT span, η, of 20% (iii) free hinge with η of 30% as shown in Figure 14. Approximately 15% of root bending moment is found to be mitigated when the relative FWT span, η = 20%, and more load alleviation was achieved by increasing, η, to 30%, where 25% reduction in bending moment was seen at the wing root. A similar trend in the vertical shear forces were observed, however, the reduction of the shear forces appeared at the outboard of the wing, whereas the value was almost constant at the wing root for all hinge conditions. The torque distribution is zigzagged towards the inboard sections, mainly attributed to the presence of the attachments (engine and pylon), leading to the negative (nose down) torques in the wing sections. Figure 15 shows the incremental gust loads computed for the three hinge configurations. The highest incremental bending moment appeared in the fixed hinge configuration. Whereas approximately 20% reduction of the incremental bending moment was achieved at the wing root, when the free hinge configuration (η = 30%) was used. A small reduction of the incremental shear force was seen because of the free hinge, whereas the influence of the FWT on the incremental torque is not obvious. A perturbed incremental torque distribution was seen near to the root, which was mainly caused by the engine motion.

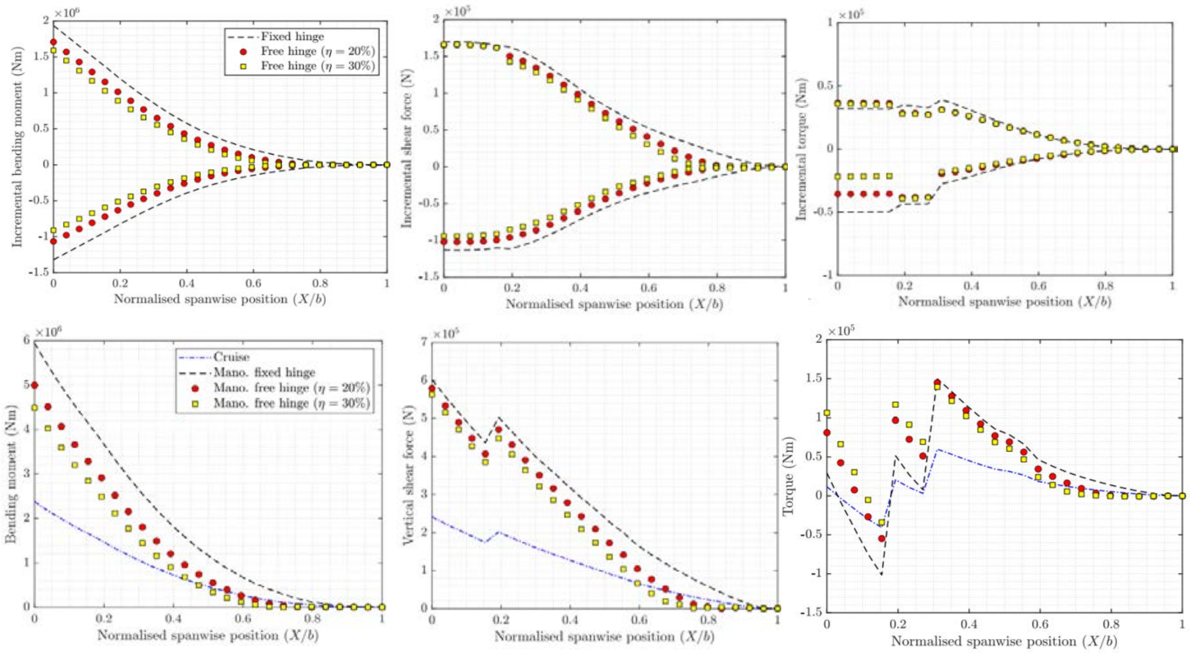


Figure 14: Comparison of manoeuvre and cruising loads between fixed hinge and free hinge configurations for AR = 16.

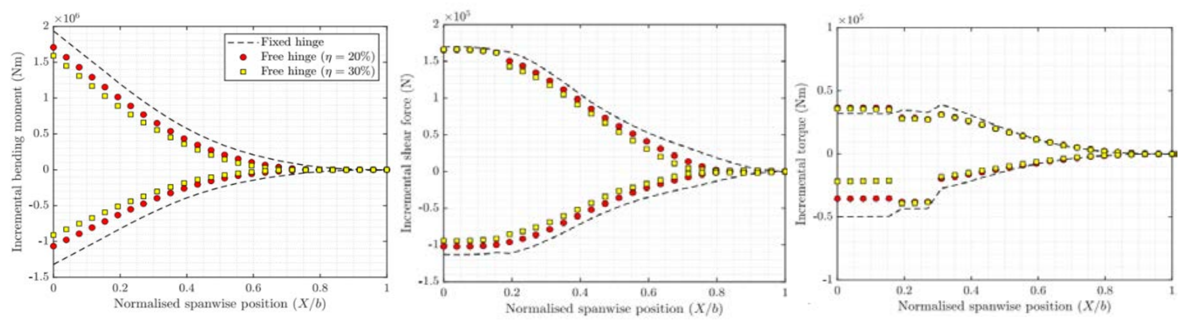


Figure 15: Comparison of gust loads between fixed hinge and free hinge configurations for AR =16.

Figure 16 shows the calculated drag polar of the aircraft models with various wing aspect ratios, where a dramatic reduction in induced drag was achieved by increasing the aspect ratio. To assess the aircraft performance, a flight mission was set for the full fuel tank case with corresponding maximum payload. The range of each aircraft model was then predicted using the Breguet range equation,

$$Range = \frac{V}{SFC}\frac{L}{D}\ln(\frac{W_i}{W_f})$$

where the specific fuel consumption, SFC, is taken as 16.03 $(g/s)/kN$, V is the cruise speed which is taken as 0.78

Mach, Wi and Wf are the initial and final weight of the aircraft. For the fixed hinge condition, the range increases with respect to the aspect ratio (AR) until 18-20 and any further increase in AR results in a detrimental effect in the overall efficiency due to the increased weight penalty shown in Figure 16.

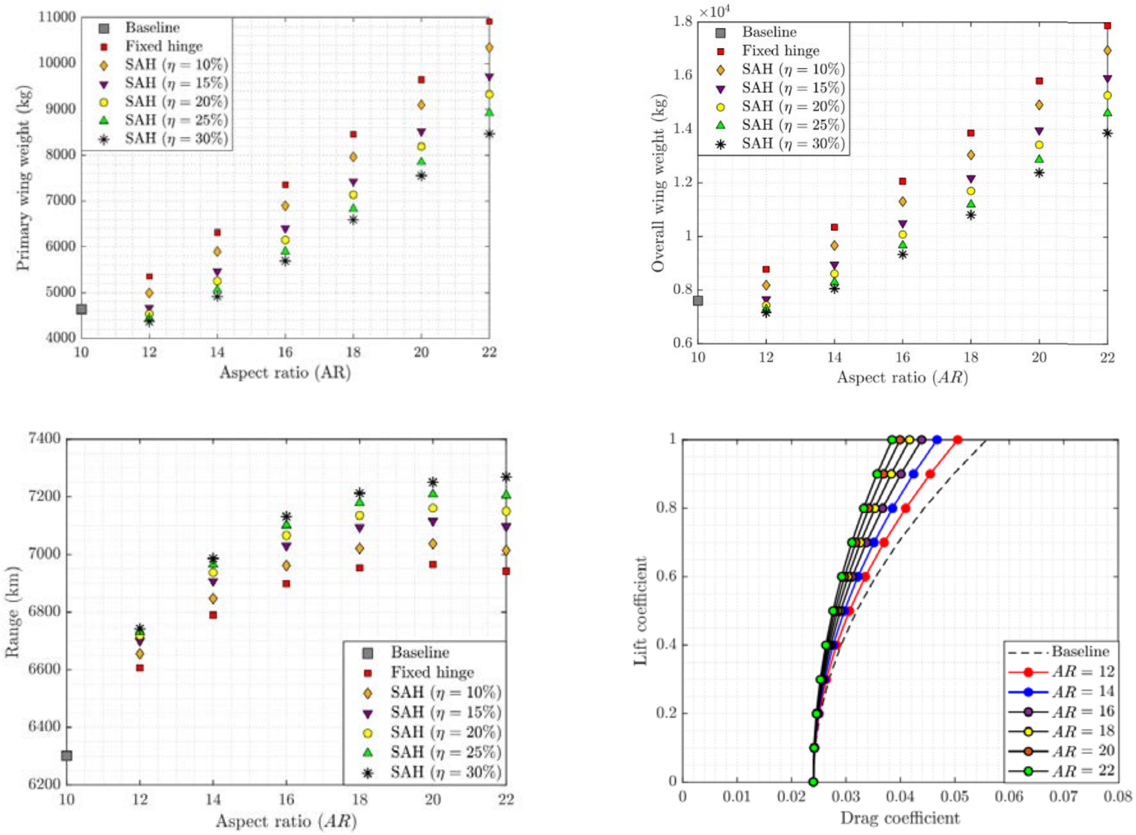


Figure 16: Sized primary wing weight (a), overall wing weight (b) of various wing aspect ratios and FWT configurations; Aircraft range (c) and Drag polar for various wing aspect ratios.

An obvious improvement in range was seen in each model when the SAH device was implemented. It was shown that more than 5% increase in range can be achieved in the model with a wing aspect ratio of 22. In addition, the ’sweet spot’ of the wing aspect ratio was appeared at the higher values when the SAH devices were incorporated into the models. For SAH with relative span, η, of 30%, the optimum wing aspect ratio was increased to above 22, where better aerodynamic efficiency can be attained.

High fidelity modelling of folding wingtip concept was performed to assess the gust load alleviation. The detailed wingbox was modelled using shell elements instead of a stick model as shown in Figure 17, where significant gust load reduction was seen with FWT device incorporated in the wing configuration compared to the conventional cantilever wing, and similar load reduction was able to achieve via an aileron control technique, as illustrated in Figure 19. Further work showed that by moving the elevator to the next trim condition after the hinge was released could improve load alleviation and that the time delay of the wingtip release in relation to the gust is very important. It was found that a 'sweep spot' for the delay in the hinge release exists for each gust length that enables the maximum gust load alleviation.

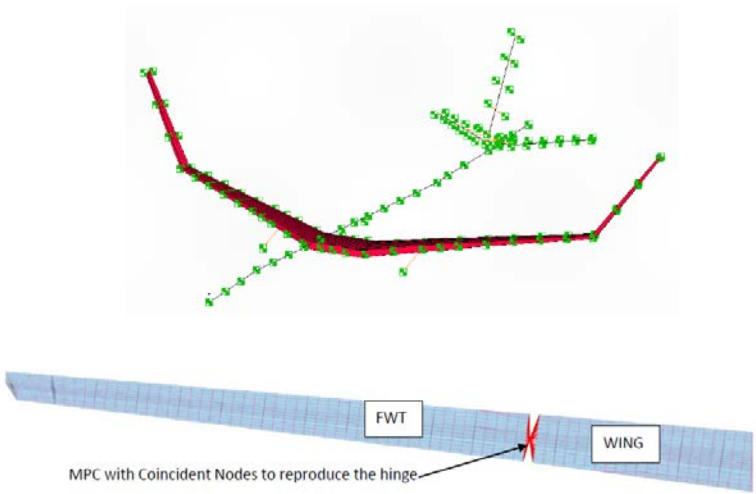


Figure 17: High fidelity model of folding wingtips.

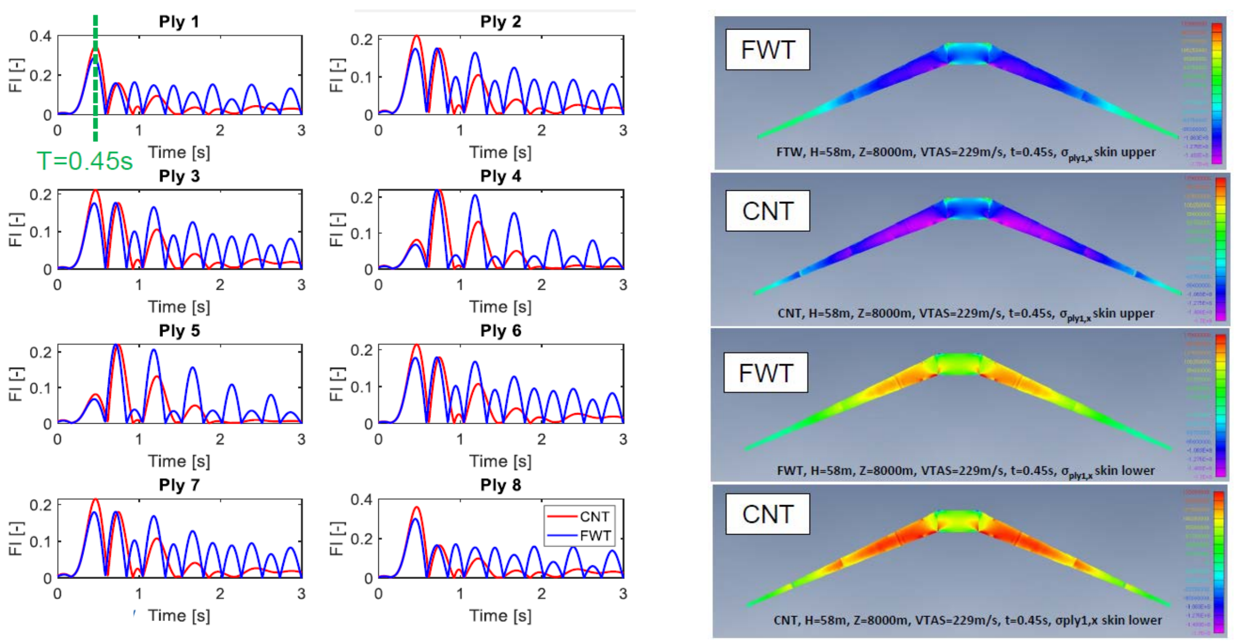


Figure 18: Comparison of the stress induced by gusts for the FWT model and CNT.

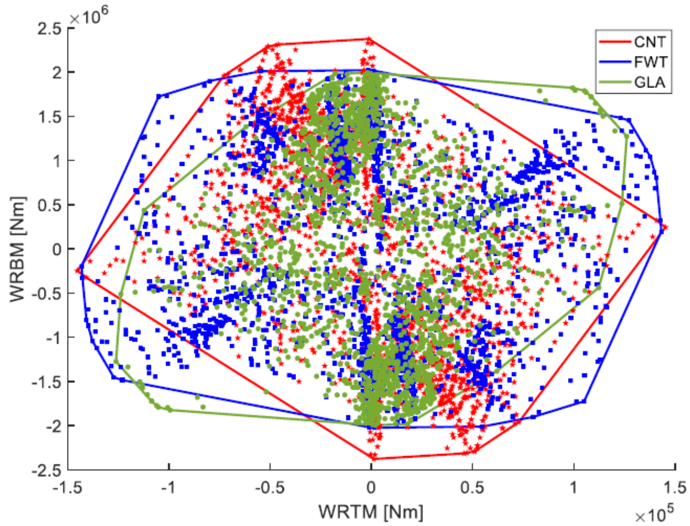


Figure 19: Comparison of the gust loads between folding wingtip concept and wingtip aileron control method.

IV. Summaries of environmental impact of optimized aircraft configurations

The optimal findings from the above design studies for the three configurations considered are now compared in terms of their environmental impact. Note that the exact load cases and optimization process considered were different between the parties concerned, so it is not possible to make a definitive decision as to whether then is an optimal configuration.
The optimum design of the cantilever wing configuration as expected depends upon wing aspect ratio (AR). For the cases considered, as seen in Figure 21 the optimum results were achieved at aspect ratio of 15, where the reduction of emissions was reduced by 10% compared to the conventional A321-like aircraft. The inclusion of Gust and Manouvre Loads alleviation enhanced the performance significantly. Note that these analyses do not include the requirement for a folding wing tip (to be used on the ground as opposed to the in-flight loads alleviation FWT concept considered) to meet airport gate and taxi limitations which will involve further weight and wing design considerations.

For the strut-braced wing concept, the optimum design is highly related to wing aspect ratio, strut joint position and strut sweep angle, and for the case of AR = 19, a 6% reduction of MTOW was achieved leading to 17% decrease in the fuel burn for a given mission compared to the cantilever wing. Again, the inclusion of some mechanism to facilitate meeting airport span restrictions should be considered in the future.

Whereas for the FWT concept, the optimum design associated with the hinge position. Based on the analysis conducted the highest load alleviation was seen when the FWT size is 30% of the semi wingspan, which lead to an approximately 25% reduction in the wing weight and additional 6.7% decrease in the fuel burn on top of the optimized conventional cantilever wing configuration. Further work is needed to include the effect (weight and power) of the mechanism to facilitate the folding wing tips.

V. Lessons Learned

All of the concepts investigated improved upon the performance of the baseline aircraft. The obtained results considered the wing redesign aiming at improved aerodynamics and aerostructures, without considering any improvement on propulsion efficiency due to better engines or radical propulsion architecture. Although such an approach is not sufficient to achieve the ambitious emissions reduction claimed in all new research programs, improving the aircraft performance (regardless of power source) is going to make a significant contribution towards meeting net zero aviation by 2050.

The global targets in terms of emission reductions cannot be obtained keeping the traditional cantilever wing architecture, even if using powerful MDO techniques coupled with aggressive active control technologies. The project identified AR=15 as a maximum possible aspect ratio achievable in cantilever configuration seems to be a hard limit. New and unconventional configurations appear as a must to achieve the expected significant emissions reduction with the SBW being the one with the most potential - including folding wingtips – and arguably a SBW configuration is less of a big step compared to more radical designs (Blended Wing Body, Forward Swept Wings, etc).

The aeroelastic behaviour of SBW configuration still represents a challenge and its impact to the expected aerodynamic benefits has to be carefully investigated. The results obtained on ONERA configuration are related to the initial hypothesis of a strut loaded only in tension and not in compression. Consequently, a very thin strut has been obtained that is very light.

Extended aeroelastic investigations, together with the experimental results demonstrated that this approach could be critical and, in some cases, not applicable, in case of curved strut. The aeroelastic coupling due to the closed structure typical of SBW architecture requires a detailed trade off among different approaches.

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The adoption of a lifting strut, taking advantage of unloading the wing to generate the same total lift, moving from a pure strut-braced to a truss-braced configuration must be further investigated.

The FWT approach could be a powerful mean to achieve significant load alleviation targets: however, several issues are still open concerning the approach from a system point of view, in terms of implementation, reliability, safety and certification.

From the noise point of view, the experimental results, quite new to this field, showed that the contribution to the total noise produced by the interaction between the trailing edge flap and the strut wakes is limited or negligible, however further investigations are necessary.

The development of a redesigned, A321-like aircraft to make final comparisons opens the door to a possible distribution of the model as an open-source test case to be shared with other researchers.

The integrated parametric HIFI approach adopted by ONERA seems a very powerful tool to investigate complex architectures.

The large experimental campaign allowed to validate the numerical results and investigate even in some cases resulted in many test challenges. Testing at more typical flight Reynolds numbers is essential to validate the different concepts.

The wind tunnel models realization and test resulted particularly difficult in case of SBW and FWT configurations, due to strong nonlinear phenomena (SBW) and practical limitations in implementing the folding wing tip release mechanism (FWT).

VI. Conclusions

Comprehensive analysis has been performed to explore the optimum design configuration for three aircraft configurations - cantilever wing, strut braced wing and folding wingtips. In general, higher wing aspect ratios provide enhanced aerodynamic performance which in turn lead to decreased trip fuel and emissions. Whereas the increased wingspan causes significant aircraft weight penalties resulting in a compromised overall aircraft performance, the studies show that there is a “sweet spot” of an optimal AR where the performance (fuel burn or Breguet Range) is maximized and this point is greater than current designs. Further benefits can be achieved through the use of Gust Load Alleviation and Manouevre Load Alleviation.

Both the strut braced wing and folding wingtip concepts were found to be efficient for the load reduction which resulted in reduced wing weight. The optimum design of the strut braced wing highly depends on the location of the connection between the strut and the wing and sweep angle of the strut. It was found that the rear braced strut provides significantly lower drag compared to the conventional strut braced wing. For an optimized strut braced wing configuration, a 17% reduction in the fuel burn was predicted compared to the conventional cantilever wing configuration (CNT). Furthermore, the load alleviation performance of the folding wingtip concept was found to be sensitive to the location of the hinge. For the cases considered in the study, the folding wingtip provides 25% reduction in the wing weight, leading to 6.7% lower fuel consumption than the CNT wing configuration.

All concepts are worthy of further investigation as part of a campaign to improve the fuel burn of future aircraft, regardless of power source.

VII. Disclaimer

The content of this document reflects only the author's view. The European Commission and Clean Sky 2 Joint Undertaking (CS2JU) are not responsible for any use that may be made of the information it contains.

VIII. Acknowledgments

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