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Clean Sky

Aeroelastic Optimization of High Aspect Ratio Wings for Environmentally Friendly Aircraft

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Abstract

The paper deals with the aeroelastic optimization of a high aspect ratio wing, in the framework of the EU funded project CS2-U-HARWARD, aiming at the use of innovative aerodynamic and aeroelastic designs in a multi-fidelity multi-disciplinary optimal design approach to facilitate the development of high and ultra-high aspect ratio wings for medium and large transport aircraft. The optimization tool here adopted, called NeOpt represents a new module of the well know NeoCASS suite, an open source founded by POLIMI project for quick analysis and optimization of aerostructures ad conceptual and preliminary levels. The suite is linked to a dedicated module developed by IBK for the estimation of aircraft emissions so to quick assess the optimized aerostructural configurations in terms of global impact targets. Details of the adopted tools as well as the preliminary results obtained are reported in the paper.

I. Introduction

There is a worldwide need for improved fuel-efficient and environmentally friendly aircraft designs; however, the rate of improvement in the performance of conventional aircraft configurations (via improved aerodynamics, composite structures, and better engines) is reducing to a marginal level. Consequently, there is a need to explore the benefits of novel aircraft architectures to provide a step-change in fuel efficiency; this need has been identified by ICAO, FLIGHTPATH2050, and CLEANSKY2 initiatives in Europe and also NASA, with challenging goals set for reductions in CO2, NOX and noise by the year 2050 [1-3].

Historically, the most significant improvements in jet aircraft efficiency have been related to improvements in the propulsive term associated with the development of high-bypass-ratio turbofan engines. Most recently, the extending use of high-strength composites promises so to increase the weight fraction. Finally, configuration changes such as increased wingspan can lead 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.

Luckily, the same integrated nature of aircraft design could represent a great opportunity: indeed, significant improvements can come from configurations that can simultaneously exploit aerodynamic, control, and structural advances to improve efficiency. Furthermore, in most cases, the multidisciplinary approach is the only one that could guarantee a net improvement in global efficiency. It is the case of Natural Laminar Flow (NLF) that could be obtained by an aggressive combination of Manoeuvre (MLA) and Gust Load Alleviation (GLA) technologies that hold the potential to greatly improve both the weight and aerodynamic terms in the Breguet equation.

II. The U-HARWARD Project

U-HARWARD project, in response to the call JTI-CS2-2019-CFP10-THT-07: Ultra-High Aspect ratio wings, will consider 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. A conceptual design study, building on the current state of the art, will perform trade-off studies to determine the

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potential gains of different wing configurations, including strut-braced and folding wingtip wings, and loads alleviation concepts, in terms of aerodynamics, weight, noise, fuel-burn and range. Scaled model wind tunnel tests will be used to validate parametric variations in the aerodynamic and acoustic characteristics. Starting from a reference aircraft, the preliminary design of the best candidate configuration will be completed and the estimated gains validated using high fidelity tools and a larger scale aeroelastic test. The consortium is composed by six partners, i.e. 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 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. Team 2, composed of ONERA and ISAE, is focused on the Strut-Braced Wing configuration. Finally, Team 3 represented by the University of Bristol, is mainly focused on folding wing tip configuration.

This paper summarizes the activity carried out by Team 1 concerning the CNT configuration, together with the first available results. At first, the aeroelastic design and optimization framework is described then the results obtained in the first optimization exercise on increased aspect ratio wings are reported.

III. The Aeroelastic Optimization Framework

One of the difficulties in investigating non-conventional aircraft wing configurations is due to the unavailability of previous results on which to base statistically-based predictions in terms of global performances. On the other hand, the typical tools adopted during the conceptual design are not able to fully capture phenomena that are typically investigated later in the design loop, such as the impact on structural weight due to the use of advanced materials or of the active control for loads alleviation. In few words, any trade-off study at the conceptual level when the configuration is extreme, like in the case of high and ultra-high aspect ratio wings, appears as inaccurate. For this reason, the activity of Team 1 aiming at the investigation of maximum aspect ratio wing in classical cantilever configuration thanks to the most advanced current and future technologies, is based on a blend of available and specifically developed tools.

The core of the framework is represented by NeoCASS, an open-source code introduced about 10 years ago from POLIMI [4-7]. The main goal on the basis of NeoCASS development was to bring aeroelasticity up to the conceptual design phase, giving to the user the capability to investigate the aeroelastic behavior and its impact on the design loads and the global performances since the beginning of the design loop.

NeoCASS is a conceptual and preliminary design environment suitable for the generation of low order, medium-fidelity models for structural sizing, aero-servo-elastic analysis, and optimization [8] [9] [10]. It is not the only product available on the market for this purpose, TU-Delft developed an in-house tool named PROTEUS, the procedure used by Bombardier is described in [9] and the one used by Gulfstream (ATLASS) is described in [10]. All the sizing tools start from a geometrical, possibly parametric, representation of the aircraft which is used to generate the analysis model, which can be different and with increasing level of detail. The distinctive feature of NeoCASS with respect to the other conceptual design tool and methodologies is the fact that it sizes and works directly on an aeroelastic stick model: the properties of the structural beams are obtained through analytical computation of the sized skins thickness and stringers areas. The sizing loads are computed performing aeroelastic analysis with the same model. Some industrial approaches, like the aforementioned ATLASS, create a global FEM model (GFEM) starting from the parametric geometrical representation of the aircraft. In this case, the problem is the computation of the loads for the sizing, which is done by reducing the GFEM into a stick model for aeroelastic simulations that are used for the evaluation of the load envelope.

It is a sequential optimization process where the GFEM is sized using the loads obtained with the stick model which is not sensitive to the variation of the design variables: after each sizing, the GFEM is reduced again and the loads computed once more until a convergence criterion is satisfied. Both paths lead to a sized stick model which can be used for the aeroelastic simulation, the advantage of the NeoCASS approach is that it avoids the condensation of the GFEM into a stick model, which can be hard-working and some information may be lost during the procedure.

Figure 1 shows a diagram with the key features of NeoCASS vs. industrial approach at the conceptual design level.

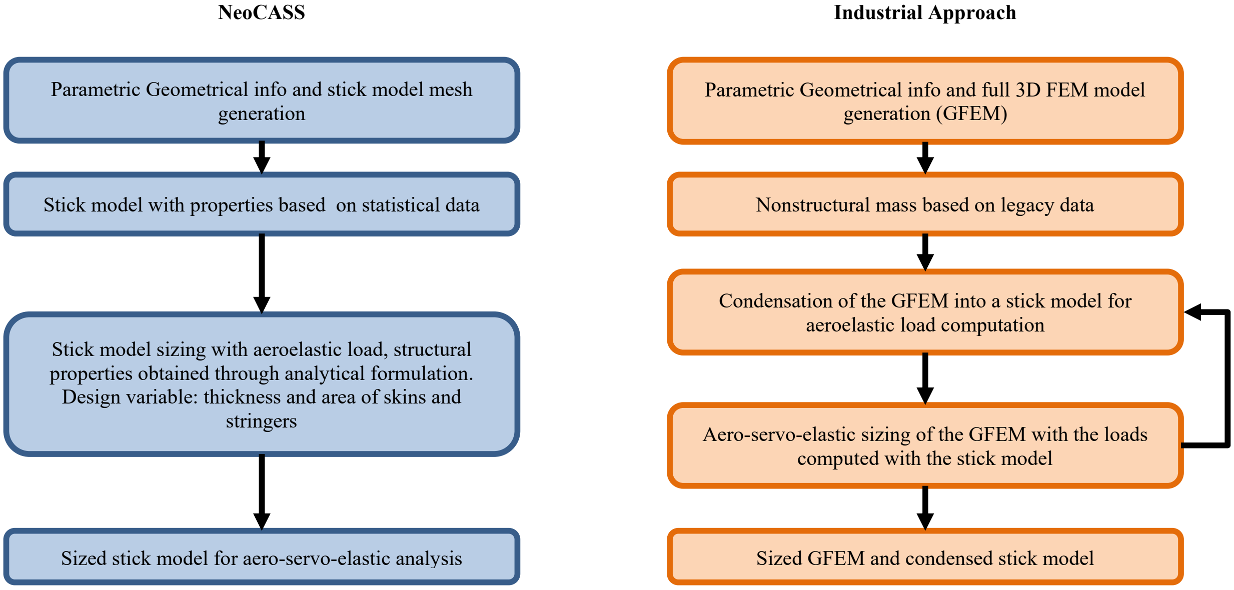


Figure 1: Schematic comparison between NeoCASS and industrial approach.

To improve the capabilities of the original NeoCASS suite as to be suitable for the investigations foreseen in the U-HARWARD project focused on very high aspect ratio wings for environmentally friendly aircraft three are the key capabilities that must be included in the design framework:

1. To enhance the structural modeling capabilities as to fully exploit the adoption of advanced composites
2. To introduce a dedicated module for the evaluation of aircraft emissions
3. To include a dedicated non-linear aeroelastic module

While the first two goals have been successfully achieved and will be described in the following sections, the third one completed by the end of 2021.

A. NeOpt a module for semi-analytical medium fidelity structural analysis

Each philosophy has its own pro and cons: for example, NeoCASS is not able to consider three-dimensional effects like coupling terms introduced with the composite materials and the realization of detailed 3D FEM and CAD models of the structural components. This chapter highlights the shortcomings of the current NeoCASS version and the solution adopted to partially bridge the gap with higher fidelity tools.

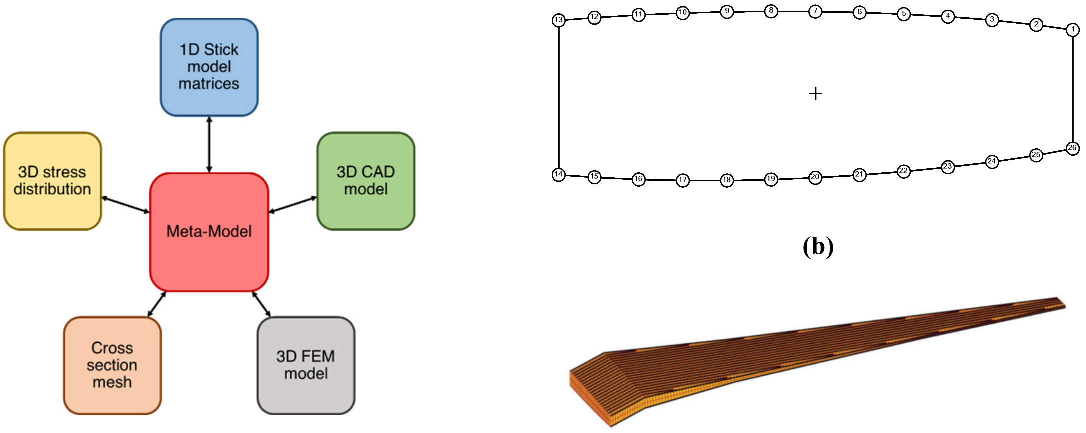
NeoCASS computes the stiffness and mass matrices with classical mechanic's formulation, i.e. the stiffness terms are obtained by multiplying the cross-section inertial properties by the elastic modulus. The beam formulation implemented in NeoCASS [7] allows to use the full 6x6 stiffness matrix of the beam element, hence all the coupling can be modeled. However, at the moment, the calculation of the coupling terms due to the use of composites is not implemented. The wing box designed with GUESS, the module devoted to the initial structural sizing, is rectangular and symmetric i.e. it is described by its width, height, upper skin thickness, upper stringer area, and front web thickness. The aft web thickness and lower elements are equal to the upper and front ones. This representation of the wing box is simplified and it is valid in early design phases when stiffness and mass are not well defined yet. This limits the design space and leads to a non-optimal solution because the wing box stress distribution is not symmetric, for example, the ones obtained with a *2.5g* pull up and *-1g* push down manoeuvre. It is possible to find an analytical solution for non-symmetric and multiple cell structures, but this approach is not able to catch the coupling terms due to the composite materials. This aspect cannot be neglected anymore at the conceptual design level for two main reasons: the first one is that the coupling terms, especially the bending-torsion one, have a huge impact on the load distribution and dynamic stability (flutter) of the aircraft. The second reason is the aeroelastic tailoring, which allows a wider design space to optimize the structural components by acting on the coupling terms itself. To fully exploit the potential of the composite materials it is needed a tool for the correct evaluation of all the components of the stiffness matrix.

The composite wing box modeling is not the only missing item of NeoCASS, one of the limitations of the current sizing procedure is the sequential optimization process implemented in GUESS, which uses only the static trim maneuvers to size the structure. The trim loads are a part of the sizing envelope, the dynamic loads are not accounted and they may play a relevant role in the load envelope. Structural constraints like failure and buckling are not the only constraints that must be considered in the wing design, aeroelastic constraint must be considered as well: the aircraft has to be dynamically stable in all its flight envelope i.e. there is no flutter and the handling qualities must meet the prescribed value without losing their effectiveness with the increasing wing flexibility.

In this environment, a new module has been implemented, called NeOPT [8][9] positioned in the design loop right after GUESS for two reasons: the first one is because thanks to a dedicated cross-section modeler it is possible to refine the description of stiffness and mass matrices of the stick model before running further analyses, the second one is because the preliminary sizing performed by GUESS can be used as starting point for the more complex optimization of the wing box.

The meta-model is an analytical three-dimensional representation of the wing box containing both geometrical and structural information. The concept recalls the approach proposed and further develops the idea leading to higher fidelity and single-environment application. The stick model realized by GUESS describes the wing box only with 1D the cross-sectional stresses which are expanded in 3D to obtain the wing box stress state.

A geometry module processes the geometrical information of the beam elements, hence all the information about the structural components (geometry, thickness...) is not used anymore. The meta-model creates a database of the wing box properties which is used to store and preserve its physical properties, this information allows to expand the 1D beam element in the correspondent analytical representation of the wing box's chunk. Finally, it is used to elaborate the information necessary to realize an analysis model or to post-process analysis results. Figure 2 illustrates the pivotal role of the meta-model with respect to all the models available as an output, its information is used to realized different analysis model (stick model, cross-section model, or 3D FEM model) and to post-process the results of each analysis, typically the internal forces coming from the stick model are used to recover wing and produces a database where are stored the intersection between the ribs and the stringers. Once obtained the 3D points it is possible to connect them in different ways to obtain different elements and models. Connectivity across the chordwise direction creates the 2D representation of the cross-section for each rib, a global connectivity creates a 3D mesh of the wing box suitable to realize a CAD or FEM model. The geometrical information alone is useless from the structural point of view, the properties of the structural elements (area and thickness) and the material characteristics are associated with the connectivity in order to identify each element of the wing box in terms of position and properties.



(a)

(b)

(c)

Figure 2: Schematic representation of the Metamodel (a), section representation inside NeoANBA module (b) and the high fidelity fully analytical representation of the wingbox.

The meta-model is more than a simple database of nodes, connections, and properties. It preserves the coherence among the different models, this means that whichever modification of a property in one domain is automatically transmitted to the others models. The analysis model that can be obtained through the meta-model are:

- A cross-section 2D FEM model, which is used by a dedicated section analyzer, called NeoANBA to obtain the beam stiffness and mass matrices.
- The aircraft stick model with the updated stiffness properties.
- The 3D FEM detailed model of the wing box.

The inclusion of the NeOPT module into the original NeoCASS architecture (see Figure 3) allows for a powerful tool with all the necessary capabilities and level of details to be used for trade-off studies of advanced aircraft configurations such as the ones investigated in the framework of U-HARWARD project.

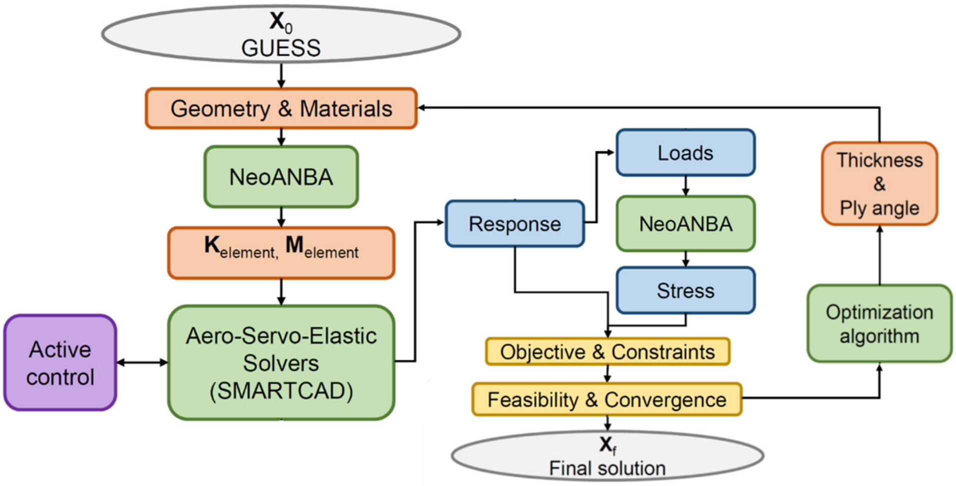


Figure 3: Architecture of NeOpt module inside the NeoCASS suite.

B. Fuel Burned and Emissions Calculation

To complete the foreseen trade-off studies of novel environmentally friendly configurations with increased aspect ratio 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.

Fuel Burned Estimation

The methodology adopted to correctly estimate the fuel burned during a pre-defined mission is based on 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 respectively the global drag and lift, E is the aerodynamic efficiency, T is the total engines' thrust and *W* is the aircraft weight. In other words, knowing the engines' *TSFC* and the aircraft thrust it is immediate to compute the fuel flow. On the other hand, the aircraft thrust can be computed knowing the aircraft weight and the aerodynamic efficiency in each point of the mission through the well-known Breguet formula:

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

Taking into account that **ΔT** is 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.

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

Nevertheless, the described methodology provides a reliable result for the cruise phase only, resulting to be 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.

For what concerns the climb phase, the aircraft thrust has been computed by the use of the climb flight equations instead of the Breguet formulation. Being the rate-of-climb (RC) one input of the mission, it is possible to compute the trajectory angle θ:

$$RC \equiv V_\infty sin\theta$$

Once the trajectory angle is known, by the use of the climb equation previously reported it is possible to compute the required lift and subsequently, knowing the aerodynamic efficiency, the drag.

$$L = Wcos\theta$$

As the last step, knowing rate-of-climb, weight, drag, and aircraft velocity as mission inputs, by the use of the climb flight power balance equation it is possible to compute the required thrust.

$$RC = \frac{TV_\infty - DV_\infty}{W}$$

Once the aircraft thrust is known it is immediate to compute the fuel flow.

The corrected gliding flight equations have been then used to estimate the aircraft thrust for the descent phase instead of the Breguet formulation. The main hypothesis for this flight phase is to consider a descent at the maximum efficiency, necessary to estimate lift and drag in each point of the descent phase. Being the difference of altitude during descent (Δh) and the descent range (ΔR), two mission inputs, it is possible to compute the descent efficiency (E^*) as the ratio between Δh and ΔR. Exploiting the descent efficiency computed at the previous step and correcting the gliding flight equations by taking into account the thrust, it is possible to compute the required thrust:

$$E^* = \frac{L_{Max\,E}}{D_{Max\,E} - T}$$

Emissions

The common ICAO certification procedure [11] 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.

For what concerns the estimation of NOX emitted during a typical mission, a semi-empirical methodology has been developed. Thanks to the data reported in [12] 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.

Furthermore, in [13] where are reported the average fuel consumption of, among others, those 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 [15]. 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 [14], 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.

IV. Application example: high aspect ratio SMR Aircraft

One of the first steps in U-HARWARD development was the definition of the Reference Aircraft, which is based on two different 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, and the technology level and detailed features to be implemented on this reference aircraft. Since no market segment was explicitly specified in the U-HARWARD targets, an extended 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. The decision was to investigate the extended Short Medium-Range segment (SMR, meaning ~200 PAX, Design Range < 4000 NM, M~0.78) which is the same as 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. Finally, once the segment is chosen, there are 3 possible choices for the reference aircraft:

- An existing, currently flying aircraft, with known geometry and features,
- A redesigned aircraft upon chosen TLAR,
- A projected aircraft with technology improvements associated with some target EIS (eg. 2035 in most CS2 studies).

In order to avoid the biases from the design procedure (which might be different from one team to another), the choice was made to start from the reconstruction of an existing, flying aircraft, with the most recent technology level (especially engine option). Therefore, the choice is oriented towards the A321neo aircraft.
This reference aircraft has been re-designed by each project team and then stretching the results for the A321 neo it was possible to start the investigation on new high aspect ratio configurations.

Stretched Reference Aircraft

In a first exercise, a wing stretching has been applied to the original wing of the Reference Aircraft, based on the geometry of A321 Neo. In particular, keeping the same wing area a span increasing has been applied by keeping the engine position fixed, so to increase the aspect ratio from the original value of 10.41 up to 19. Using the Aeroelastic Optimization framework a wing structural sizing has been carried out by including the set of maneuvers (trim and dynamic gust) requested by the CS25 certification rules plus the flutter constraint. A total of 41 maneuvers across the flight envelope, 40 gusts in two different flight points (cruise at sea level and at cruise altitude) and three altitudes (z=0m, z=7357m, z=10668m) for flutter computation were considered in the constraints evaluation. For each of the two flightpoitnts selected, 10 positive and 10 negative gusts, with an equally spaced gust gradient between 9m and 107m, are simulated following the CS25 regulation. The model used for the aero-elastic analyses in NeoCASS is represented in Figure 4.

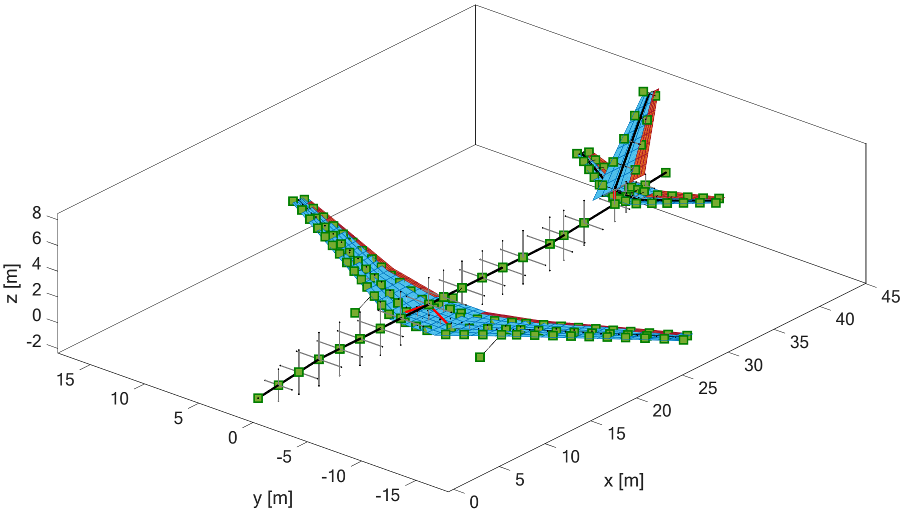
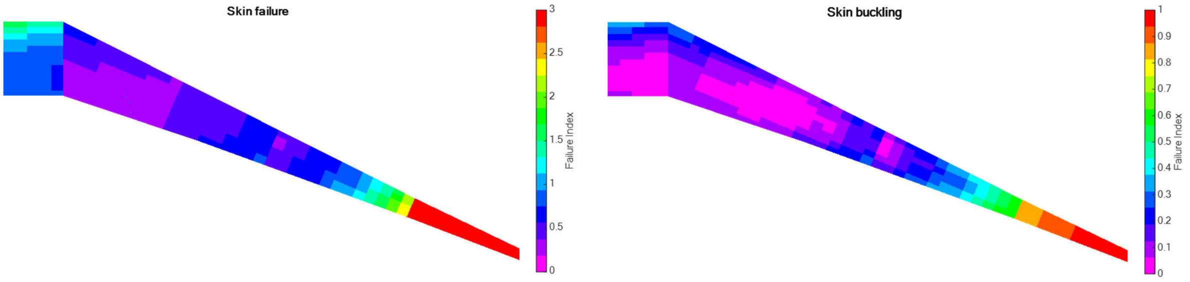


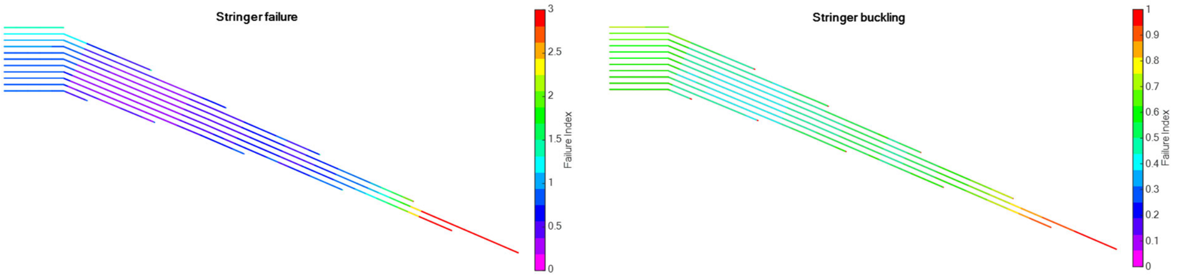
Figure 4: Stick model used in NeoCASS

The constraints used in the sizing process are the aero-elastic stability of the system i.e. no flutter, and the structural integrity in term of strength (no component failure below the ultimate loads, safety margin computed with Von Mises's criterion for isotropic and Tsai-Hill for orthotropic) and several buckling mechanisms (single skin panel, stiffened skin panel, stringer webs, spar webs) [17][18]. An example of the structural constraints obtained is presented in Figure 5 and Figure 6.



(a) (b)

Figure 5: Failure (a) and buckling (b) indexes for upper skins, AR=10.41 and most critical maneuver



(a) (b)

Figure 6: Failure (a) and buckling (b) indexes for upper stringers, AR=10.41 and most critical maneuver

Different material combinations have been evaluated, starting the classical full aluminum up to the carbon fiber with optimal fiber orientation. The optimal structural weight has been evaluated, and its impact on the MTOW and Final Range performance using the simplified Breguet approach (see Table 1), where W1, W2 and WCL are the initial weight, the initial weight minus the fuel weight, and the average value used to estimate the CL for the calculation of the range used the Breguet formulas, respectively. Finally, for the aluminum case only, the emissions have been computed (see Table 2).

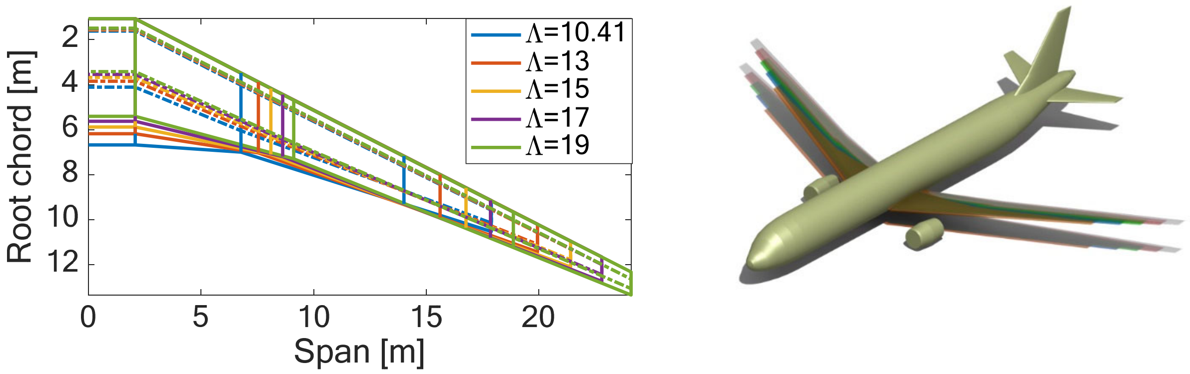


Figure 7: The stretched wing of Reference Aircraft. Dashed lines represent the wingbox.

Table 1: results of the aeroelastic optimization for different materials adopted and increased aspect ratio, together with their impact on general performances

	AR [-]	Half wingbox Mass [kg]	Full A/C Mass [kg]	W1 [kg]	W2 [kg]	WCL [kg]	CL [-]	CDi [-]	Range [km]
AL7075-T6 SF=1.5	10.41	2193.48	87526.05	8.75E+04	7.35E+04	8.05E+04	0.57	0.011101	3784.68
	13	2337.73	89365.53	8.94E+04	7.53E+04	8.23E+04	0.59	0.009354	4244.89
	15	2601.41	91305.23	9.13E+04	7.73E+04	8.43E+04	0.60	0.008493	4515.19
	17	2916.46	93492.07	9.35E+04	7.95E+04	8.65E+04	0.62	0.007888	4726.70
	19	3975.49	97251.43	9.73E+04	8.32E+04	9.02E+04	0.64	0.007685	4801.60
CFUD red LAM1 SF=1.5	10.41	1402.37	85943.81	8.59E+04	7.19E+04	7.89E+04	0.56	0.010669	3889.44
	13	1685.21	88060.50	8.81E+04	7.40E+04	8.10E+04	0.58	0.009060	4334.03
	15	2076.37	90255.13	9.03E+04	7.62E+04	8.32E+04	0.59	0.008283	4586.95
	17	2449.30	92557.75	9.26E+04	7.85E+04	8.55E+04	0.61	0.007718	4789.94
	19	2882.44	95065.32	9.51E+04	8.10E+04	8.80E+04	0.63	0.007317	4945.50

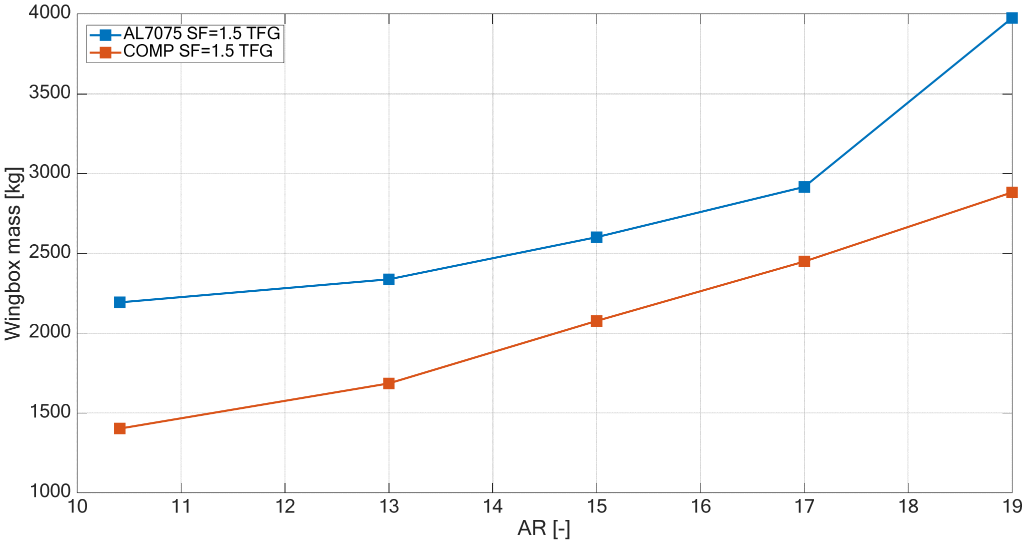


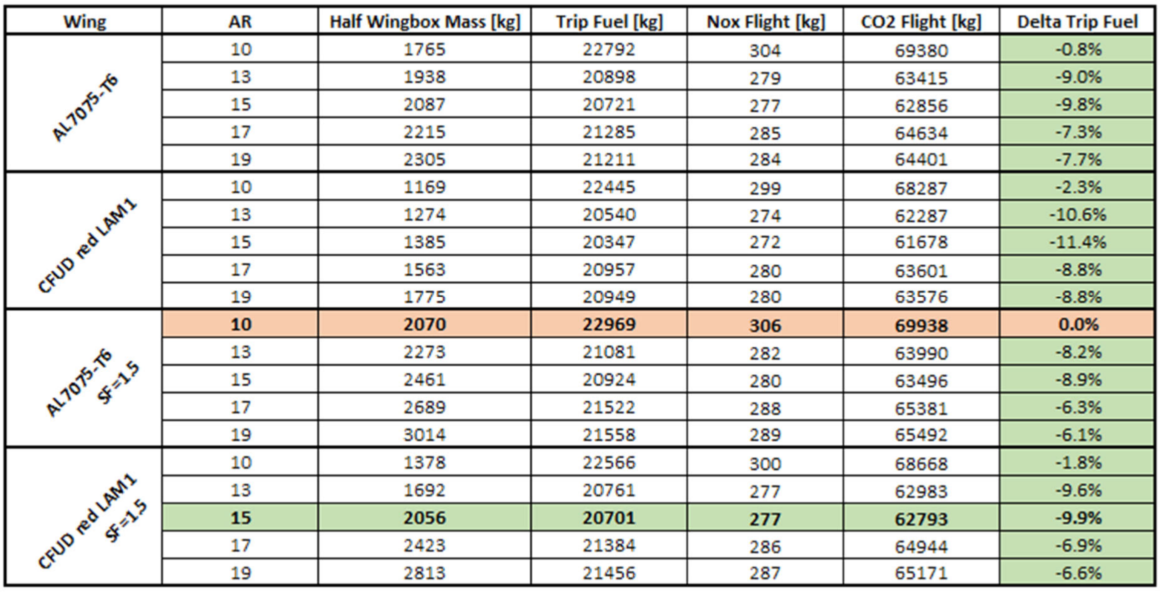
Figure 8: Wing box mass evolution with SF=1.5

Table 2: Emission results for the fully aluminum configurations.

Wing	Trip Fuel [ton]	Fuel saving [%]	NOX [kg]	CO2 [ton]
AL7075-T6 AR=**10.41**	14.534	-	153	43.467
AL7075-T6 AR=**13**	13.215	-9%	139	39.213
AL7075-T6 AR=**15**	12.478	-14%	131	36.891
AL7075-T6 AR=**17**	11.888	-18%	125	35.031
AL7075-T6 AR=**19**	11.427	-21%	121	33.580

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 the following. Table 3 reports the results concerning all the analyzed configurations, based on aluminum and optimized composites, under limit and ultimate loads. 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. 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 of 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. On the other hand, the TOW of the AR 19 implies 5% more fuel burned 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.

Table 3: Results for all the analyzed configurations, with CFD ased aerodynamic results and modified Breguet formulas.



Wing	AR	Half Wingbox Mass [kg]	Trip Fuel [kg]	Nox Flight [kg]	CO2 Flight [kg]	Delta Trip Fuel
AL7075-T6	10	1765	22792	304	69380	-0.8%
	13	1938	20898	279	63415	-9.0%
	15	2087	20721	277	62856	-9.8%
	17	2215	21285	285	64634	-7.3%
	19	2305	21211	284	64401	-7.7%
CFUD red LAM1	10	1169	22445	299	68287	-2.3%
	13	1274	20540	274	62287	-10.6%
	15	1385	20347	272	61678	-11.4%
	17	1563	20957	280	63601	-8.8%
	19	1775	20949	280	63576	-8.8%
AL7075-T6 SF=1.5	**10**	**2070**	**22969**	**306**	**69938**	**0.0%**
	13	2273	21081	282	63990	-8.2%
	15	2461	20924	280	63496	-8.9%
	17	2689	21522	288	65381	-6.3%
	19	3014	21558	289	65492	-6.1%
CFUD red LAM1 SF=1.5	10	1378	22566	300	68668	-1.8%
	13	1692	20761	277	62983	-9.6%
	15	**2056**	**20701**	**277**	**62793**	**-9.9%**
	17	2423	21384	286	64944	-6.9%
	19	2813	21456	287	65171	-6.6%

V. Conclusions

The paper introduces the scope and structure of the EU-CS2-U-HARWARD project aiming at the investigation of high and ultra-high aspect ratio wing configurations for future eco-friendly transport aircraft. Then, a description of the activities done to implement a general aeroelastic framework for the optimal design of such as aircraft configurations, combined with a module for the emissions evaluation, has been reported. Finally, an example of the obtainable results to be used for top-level trade-off studies is reported, concerning the stretched wing version of the reference aircraft considered in the project. The proposed framework appeared reliable to perform trade-off analysis, having the capability to quickly produce a optimal aerostructural configuration and at the same to assess it from the global emissions point of view.

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VII. Disclaimer

VIII. References

[1] Work programme 2013 Cooperation Theme 7 Transport (including Aeronautics), European Commission C(2012) 4536 of 9 July 2012..

[2] European Aeronautics: A Vision for 2020. Group of Personalities. 2001, ISBN 92-894-0559-7.

[3] ACARE Strategic, Research and Innovation Agenda Vol. 1, Realising Europe’s Vision for Aviation, September 2012.

[4] L. Cavagna, S. Ricci, and L. Travaglini, “Neocass: an integrated tool for structural sizing, aeroelastic analysis and mdo at conceptual design level,” Progress in Aerospace Sciences, vol. 47, no. 8, pp. 621–635, 2011.

[5] L. Cavagna, S. Ricci, and L. Travaglini, “Structural sizing and aeroelastic optimization in aircraft conceptual design using neocass suite,” in 13th AIAA/ISSMO Multidisciplinary Analysis Optimization Conference, p. 9076, 2010.

[6] L. Cavagna, S. Ricci, and L. Riccobene, “A fast tool for structural sizing, aeroelastic analysis and optimization in aircraft conceptual design,” in 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 17th AIAA/ASME/AHS Adaptive Structures Conference 11th AIAA No, p. 2571, 2009.

[7] L. Cavagna, S. Ricci, and L. Riccobene, “Structural sizing, aeroelastic analysis, and optimization in aircraft conceptual design,” Journal of Aircraft, vol. 48, no. 6, pp. 1840–1855, 2011.

[8] Toffol, F., & Ricci, S. (2019). “NeOPT: an Optimization Suite for the Aeroelastic Preliminary Design”. In 18th International Forum on Aeroelasticity and Structural Dynamics (IFASD 2019) (pp. 1-10).

[9] Toffol, F. (2021). “Aero-servo-elastic optimization in conceptual and preliminary design”. PhD Thesis (2021)

[10] N. Werter and R. De Breuker, “A novel dynamic aeroelastic framework for aeroelastic tailoring and structural optimisation,” Composite Structures, vol. 158, pp. 369–386, 2016.

[11] P. Piperni, A. DeBlois, and R. Henderson, “Development of a multilevel multidisciplinary optimization capability for an industrial environment,” AIAA journal, vol. 51, no. 10, pp. 2335–2352, 2013.

[12] B. A. Autry and D. Victorazzo, “Automated top level aircraft structural sizing tool (Atlass): A framework for preliminary aircraft design and optimization,” in AIAA Scitech 2019 Forum, p. 0550, 2019.

[13] https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank

[14] P. Glowacki, M. Kawalec, Quantitative Emissions of NOX, CO and CO2 During Aircraft Operations, 30th Congress of the International Council of the Aeronautical Sciences, ICAS 2016, https://www.airliners.net/forum/viewtopic.php?t=1355819

[15] https://www.verifavia.com/greenhouse-gas-verification/fq-how-are-aircraft-CO2-emissions-calculated-11.php

[16] K. Risse, K. Schäfer, F. Schültke and E. Stumpf, Central Reference Aircraft data System (CeRAS) for research community, CEAS Aeronautical Journal volume 7, pages121–133 (2016).

[17] P. M. Weaver and M. P. Nemeth, “Bounds on flexural properties and buckling response for symmetrically laminated composite plates,” Journal of engineering mechanics, vol. 133, no. 11, pp. 1178–1191, 2007.

[18] J. E. Herencia, P. M. Weaver, and M. I. Friswell, “Optimization of long anisotropic laminated fiber composite panels with t-shaped stiffeners,” AIAA journal, vol. 45, no. 10, pp. 2497–2509, 2007.