Aeroelastic design and optimization of strut-braced high aspect ratio wings

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Abstract. To improve aircraft aerodynamic efficiency, a possible solution is to increase the wing aspect ratio to reduce the induced drag term. As a drawback, the span increase introduces an increment of the wing loads, specially of the wing root bending moment that drives the sizing of the wing. Structural mass must be added to withstand higher loads, reducing the aerodynamic advantage from a fuel consumption point of view, as it can be instinctively seen in the Breguet's range equation. To limit the load increment due to the increased span, a possible solution is the usage of a strut: this kind of structure modifies the load path spanwise, diminishing the wing internal forces and reducing the wing penalty mass. In this framework, a lot of research is done studying Ultra-High Aspect Ratio Strut-Braced Wing, where the aspect ratio of such configuration is exasperated above 15, and the resulting wing is extremely flexible and may experience large deformation under loading. Moreover, the over determined structure realized by the fuselage-wing-strut connections deserves particular attention to fully characterize the aeroelastic interaction among the structural elements. For this reason, a two-step design approach that exploits NeoCASS (GUESS + NeOPT) is used to provide a sizing of the wing and of the strut considering several structural and aeroelastic constraints (e.g. flutter and ailerons effectiveness).

Introduction

In the framework of the Clean Aviation program, the HERWINGT project studies new wing configurations for a future regional aircraft carrying 80 passengers. In the project, alongside with innovative powertrain solutions, Ultra High Aspect Ratio Wings (UHARWs) are studied to improve the aerodynamic performance thanks to the reduction of the induced drag. As a drawback, the increase of the aspect ratio introduces higher bending moment for the wing sizing, that starts a snowball effect on the structural mass needed to withstand the loads. Therefore, the design becomes multidisciplinary and it's a trade-off between the aerodynamic performance advantages and the structural mass penalty. A possible solution to limit the structural mass is the Strut-Braced Wing (SBW) configuration, that redistributes the loads between the wing and the strut. This solution is becoming popular in the aviation industry, and it is proved by many project and programs focused on such configuration, for example [1]-[5]. This new configuration introduces new challenges since the conceptual design phases, where statistical approaches like [6][7] are no more valid for the wing structural mass estimation due to the lack of statistical sample for such configuration. Moreover, to fully exploit the benefits of using composite materials and their higher strength to weight ratio, novel physical based approaches must be adopted since the early design phases.

For this reason, in the WP1 of the HERWINGT project, Polimi is involved in the identification of the best wing configuration to be developed in the following of the project, using its in-house developed code NeoCASS [8][11] and its optimization module NeOPT [13][14] (Figure 1).

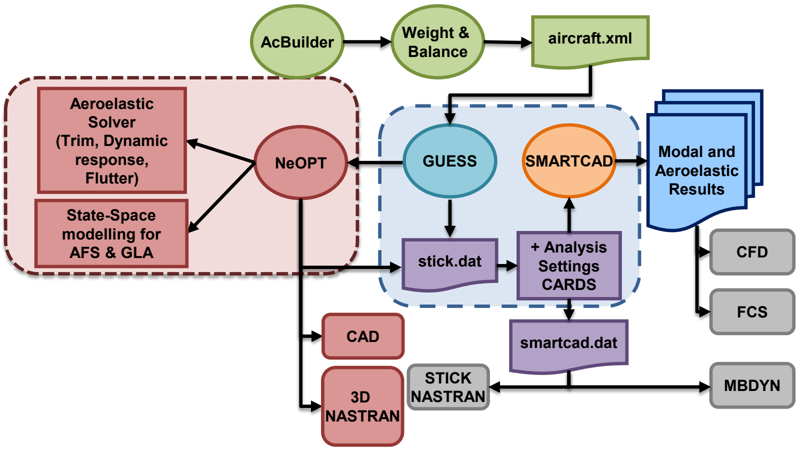

Figure 1: NeoCASS environment from [15]

When dealing with UHARWs, classical fully-stressed approaches may miss some important aeroelastic aspect of such configurations, for example the wing deformation, the divergence and control surfaces effectiveness. For this reason, an approach like the one adopted by NeOPT is convenient: in addition to classical stress and buckling criteria, whichever aeroelastic response can be accounted during the optimization, e.g. flutter or control surface efficiency.

Wing conceptual design in the HERWING project

In the framework of the HERWING project, a reference aircraft carrying 80 passengers is studied. The wing is high-mounted and equipped with two propellers. An initial wing layout was used as starting point for the study of the most promising solution, and its main characteristics are reported in Table 1. It is a trapezoidal wing that is rectangular up to the kink, then a constant tapering is applied. The wing is completely flat, i.e. no dihedral is present. From the material point of view, the wing is required to be in composite material with a symmetric and balanced layup, with at least 10% of ply oriented in the three main directions (0°-45°-90°).

Table 1: Reference wing geometry

Area [m2]	Span [m]	Root Chord [m]	Tip Chord [m]	Aspect Ratio [-]	Engine Span [m]	Kink [m]	Outboard Sweep [°]
73.3	29.65	2.92	1.48	12	5.555	5.555	2.62

Starting from this configuration, the wing was stretched increasing the aspect ratio and keeping the same wing surface, to have the same wetted area, associate to the viscous drag, but increasing the aspect ratio so reducing the induced drag term. The constraints accounted in the wing stretching are: the maximum span achievable remaining in the same Aerodrome Reference Code (ARC= C), that is 36m; the wing tip minimum chord that must be guaranteed to fit the actuation systems, that is 1.4m; the kink position is kept fixed as well as the LE sweep angle.

This approach resulted in a reduction of the root and tip chords, while the LE position was kept constant.

Performing a full geometry optimization would take too much time in this design phases, where it is way more important to understand the sensitivity of the design to the macro parameters rather than finding the optimal solution. For this reason, a parametric study increasing the aspect ratio was performed, considering AR=12,13,15,17. The wings considered for the analysis are illustrated in Figure 2. Despite the maximum span allowed is 36m, the wing is stretched to a maximum of 35m to leave 0.5m for each side to eventually install wing tip device like winglets.

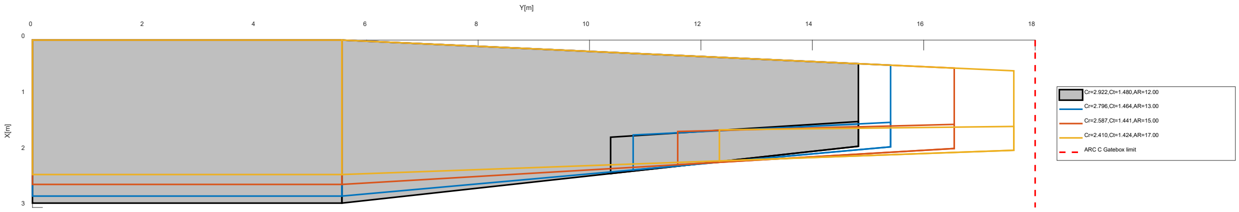

Figure 2: Wing layout selected for the conceptual parametric study.

The design strategy adopted was to perform an initial screening of the solution with the GUESS module, the module of NeoCASS dedicated to the quick and simplified structural sizing, and then to perform a refined optimization of some configuration with NeOPT able to consider a 3D wingbox and different aeroelastic constraints.

Initially, the wing was studied for all the aspect ratio in both cantilevered (CNT) and strut braced (SBW) configurations. The SBW with AR17 immediately showed a considerable weight reduction w.r.t. the CNT wing, for this reason only the AR17 was considered for the SBW configuration.

All the wings were designed with a maneuver envelope compliant with EASA CS25 regulations [16], that results in 45 maneuvers (pull-up, push-down, high lift, roll, sideslip, etc,…), in different flight points (VA,VS,VMO,VD,…). The structural masses of the wingbox and strut-wingbox (spar, stringers, caps, skins) are reported in Table 2 and plotted in Figure 3. Wing group it is intended as the sum of the wing and the strut items.

Table 2: GUESS sizing results for the considered configuration, wing and strut structural masses

Item	CNT AR=12	CNT AR=13	CNT AR=15	CNT AR=17	SBW AR=17
Wing [kg]	1145	1255	1516	1821	828
Strut [kg]	0	0	0	0	615
Wing + Strut [kg]	1145	1255	1516	1821	1211

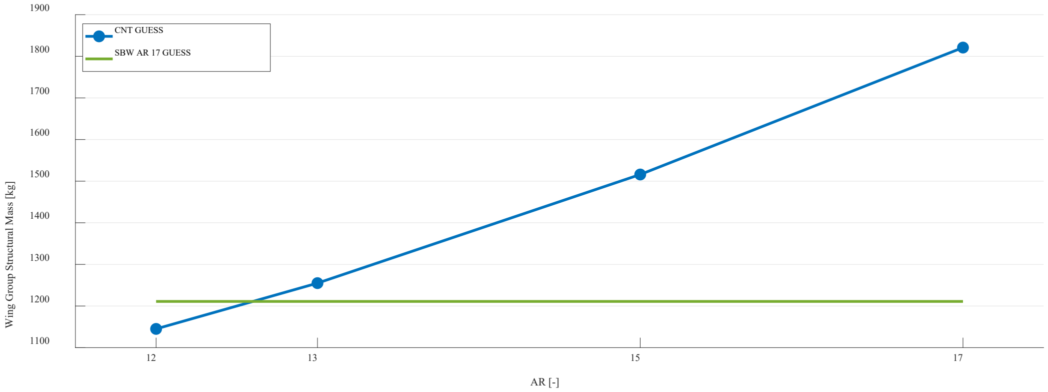

Figure 3: Wing group structural mass evolution with AR

The results obtained show that the SBW wing group with AR=17 has the same weight of the CNT with AR = 12.5. Despite CNT AR = 12 is lighter than the SBW AR=17 solution, the induced drag is term is around 40% higher for the CNT solution. For this reason, the focus is moved on the SBW configuration only, which design was refined with NeOPT considering different structural layout.

The refinement performed with NeOPT considered the same load conditions (45 maneuvers). In addition to the structural constraints, a minimum aileron efficiency must be guaranteed to preserve the aircraft handling qualities. The aileron efficiency is expressed as the ration between the flexible and rigid roll moment derivative w.r.t. the aileron deflection $C_{L,\delta}$ (Eq.(1)).

$$\frac{C_{L,\delta\ flexible}}{C_{L,\delta\ rigid}} > 0.5 \tag{1}$$

The internal structure layouts considered are listed in Table 3.

Table 3: Structural configuration considered for the NeOPT refinement.

SBW ID	η, Wing Strut Connection [Span %]	Rib Pitch [m]	Stringer Pitch [m]	Spar Number
1	50	0.5	0.16	2
2	50	0.5	0.16	3
3	50	1.0	0.16	3
4	50	0.5	No stringer	3
5	50	1.0	0.16	4
6	66	0.5	0.16	2
7	31	0.5	0.16	2

The results of the sizing are reported in Table 4

*Table 4: NeOPT Sizing results. * Not converged*

SBW ID	1	2	3	4	5	6	7
Wing Mass [kg]	1108	1181	3686*	1700	3355	992	1499
Strut Mass [kg]	383	383	383	383	383	536	386
Wing Group Mass [kg]	1491	1564	4069	2083	3738	1528	1885

From the optimization results, the most convenient layout is a conventional 2 spar with 0.5m rib pitch. Three and four spar configurations were considered to increase the rib pitch, but this solution was not effective for the SBW configuration. Indeed, the strut introduces relevant compression load on the inboard portion of the wing and the increased rib pitch makes the buckling of the stiffened panels critical.

The sensitivity w.r.t. the connection point between the wing and the strut is studied for the two-spar configuration in three different section spanwise, which are 31% 50% and 66%. The firs value is studied to evaluate a possible configuration were the engine and the strut are connected to the wing in the same span location, having a single reinforced wing rib for both the items. The second point is exactly the mid wing, while the last one is the optimal point found in previous studies [17]. The obtained data were fitted with a 2nd order polynomial function and a minimum in the structural mass was found for an η=0.56, as shown in Figure 4.

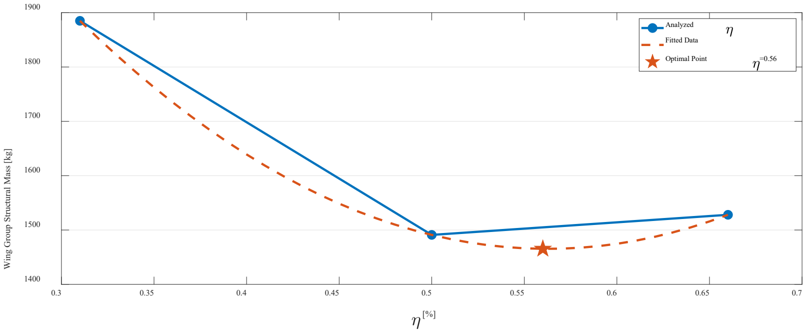

Figure 4: Wing group structural mass evolution w.r.t. the strut-wing connection point.

Conclusion

In the HERWINGT project different SBW configuration were sized, investigating the different structural layout options and connection point for the strut. The most promising solution in terms of wing structural mass was not directly considered, but it was identified with a parametric study: it is a 2 spar layout with 0.5m rib pitch and a connection between the wing and the strut placed at 56% of the span.

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