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Preliminary Design of Advanced Wing for an Ultra Efficient Regional Aircraft

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Abstract. Under the HERWINGT project, a comprehensive trade-off study was performed to assess advanced wing concepts for a next-generation regional aircraft, referred to as the Ultra Efficient Regional Aircraft (UERA). The investigation focused on aeroelastic implications of increasing wing aspect ratio up to 16, with the goal of reducing fuel burn, while limiting the structural weight growth driven by higher loads. Parametric analyses have been conducted along with the assessment of a load alleviation system. Study results provided wing structural and aero-servo-elastic requirements fundamental for the experimental demonstration phase, based on wing gust load alleviation system, to be tested inside POLIMI wind tunnel.

Introduction

Climate change has become a central rationale for disruptive technologies in the aviation field. In 2023, air transport was responsible for 2.5% of total CO_2 emissions [1]. The worsen scenario if contrails are kept into consideration, leading aircrafts to be responsible for 4% of global warming [2]. To mitigate the negative environmental impact of human-related activities, the European Union (EU) has settled an agreement - Green Deal - to reach net zero emissions by year 2050 [3]. The Clean Aviation Joint Undertaking was created to research new aviation technologies compliant with the climate crisis. In this context, the *Hybrid-Electric Regional Architecture* (HERA) project - coordinated by Leonardo (A/C Division), and the *Hybrid Electric Regional Wing Integration Novel Green Technologies* (HERWINGT) project - coordinated by Airbus Defence and Space, started in January 2023. The aim is to study a new regional aircraft configuration capable of reducing the emissions both flight-related and technology-based [4, 5]. Hybrid electric propulsion is introduced by batteries and Sustainable Aviation Fuels (SAFs). Aerodynamics efficiency is reached through high Aspect Ratio (AR) wing along with morphing control surfaces, to reduce drag. Since increasing wing AR leads to an increase in wing loads and, consequently, in wing structural mass, additional control surfaces with Load Alleviation (LA) purposes are considered.

The present work focuses on preliminary design of high AR wing for such aircraft, summarized in the following.

1. A reference aircraft - ATR72-600 - has been designed. The model is referenced throughout the work as ATR72-like.
2. The ATR72-like has been modified to account for the presence of batteries and lower fuel mass. The updated model is named UERA-like.

3. A parametric analysis has been computed on the UERA-like configuration, increasing wing AR and assessing its effect on sizing and loads. The set of obtained models are UERAAR, with AR substituted by its value (e.g. UERA16, for AR=16).

On such models, a LA system has been introduced through an additional wing control surface, here referenced as Load Control (LC) tab, along with the conventional aileron. Static aeroelastic analyses have been computed for different deflections - considered positive as the control surface goes downward - of LC tab, also coupled with ailerons, to quantify potential wing root load alleviations.

Models

The adopted tool to generate and analyze models in the current work is NeoCASS, an open-source code developed at POLIMI [6, 7, 8]. The procedure starts with the definition of geometry, maneuvers compliant with the certification regulations (EASA CS23, CS25) and mass configurations. Aerodynamics is modeled through Vortex Lattice Method (VLM), while structure is represented by beam elements. The sizing process leads to a stick model, whose inertia and stiffness distributions are evaluated through a physics-based approach. NeoCASS allows to compute trim, modal and flutter analyses, but also dynamic responses to gust or control deflections.

ATR72-like model. Starting from ATR72-600 public data, the ATR72-like model has been sized. The analyzed configuration considers a 72 passengers cabin arrangement, total fuel mass of 5000 [kg] - entirely stored in wing tanks - and aluminum alloy as material. Table 1 presents some data concerning the wing. The reference model has AR=12.

Table 1: Wing data for ATR72-like

Area	61 [m^2]
AR	12 [-]
Kink 1	0.176 [-]
Taper tip	0.59 [-]

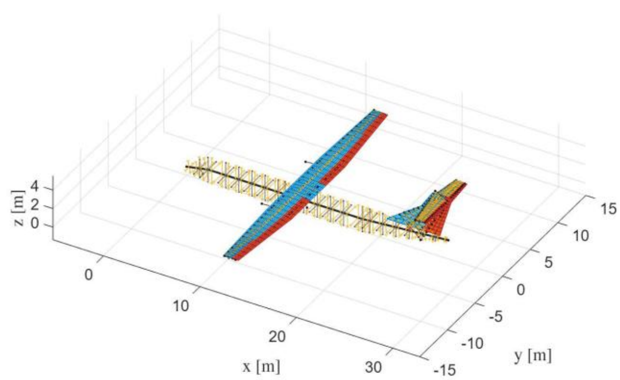

Figure 1: ATR72-like model

Sizing has been computed considering EASA CS25 maneuvers, for 4 mass configurations: Maximum Take-Off Weight (MTOW), Maximum Landing Weight (MLW), Maximum Zero Fuel Weight (MZFW) and Operative Empty Weight (OEW). The sizing results in terms of total masses are reported in Table 2, while Fig. 1 shows the aeroelastic model.

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Table 2: Sized total masses for ATR72-like

MTOW	23000 [kg]
MLW	22350 [kg]
MZFW	21000 [kg]
OEW	13600 [kg]

UERA-like. As anticipated, ATR72-like model has been modified into UERA-like to account for the presence of the hybrid propulsive system of HERA aircraft, including two concentrated masses (the batteries) inside rear and forward portions of the fuselage, while fuel mass has been reduced of 70%. ATR72-like geometry has been kept unchanged.

Total masses obtained for UERA-like model are reported in Table 3. The last column represents the increase obtained with respect to the values of Table 2.

Table 3: Sized total masses of UERA-like, compared to ATR72-like

MTOW	27420 [kg]	+16%
MLW	27220 [kg]	+18%
MZFW	25920 [kg]	+19%
OEW	18520 [kg]	+26%

UERA with increased AR (UERAAR). To improve aerodynamic efficiency, a possible option is to increase wing AR. Indeed, the induced drag coefficient is inversely proportional to wing AR, as reported in Eq. 1.

$$c_{D_i} = \frac{c_L^2}{\pi e AR} \quad (1)$$

Nevertheless, this has an impact on wing loads and consequently on wing weight. To alleviate the excess of loading, LA systems can be implemented. They consist of dedicated control surfaces, generally placed close to the wing tip to increase their effectiveness in load redistribution. In principle, if the sizing is recomputed including the presence of such devices, wing weight can be kept limited. A quantification of these concepts is given in the current work, for different wing ARs.

Starting from UERA-like model, only wing planform has been adjusted to reach the desired values of ARs, as reported in Fig. 2 left. Also wing aileron and LC tab are displayed, with the former kept fixed for all the models. Sizing procedure is the same adopted for ATR72-like and UERA-like models. The results can be found in Fig. 2 right, where the induced drag coefficient has been estimated following Eq. 1 and, concerning the total masses, just MTOW has been reported for simplicity. As expected, as AR increases, MTOW increase, while c_{D_i} decrease. The data have been a-dimensionalized for the values correspondent to AR=12 model (i.e. UERA-like). Maxima deviations are reached for UERA16.

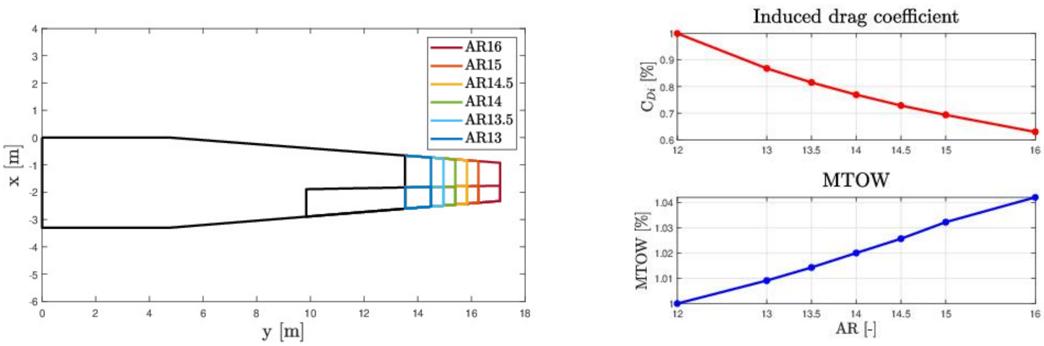

Figure 2: UERAAR, effects of wing AR on wing planform (left) and on induced drag coefficient and MTOW (right)

Analyses

To show the static effect of LA system, a pull-up maneuver at cruise design point has been computed for UERA-like model (black). Then, the same analysis has been applied to UERA16 in three different conditions: without any deflection of the LC tab (red); with $\delta_{LC_{tab}}$=10 [deg] (orange); with $\delta_{LC_{tab}}$=10 [deg] coupled with δ_{ail}=5 [deg] (yellow). These results, normalized for the wing root loads of UERA-like configuration, are shown in Fig. 3. As one can notice, for both bending and torsion, the increase in wing AR leads to a higher root load (red curve is higher than black one). A deflection of LC tab produces the expected load alleviations, bringing root torsional moment to even lower values than the reference one. The situation is even better if a deflection of the LC tab is combined to a deflection of ailerons.

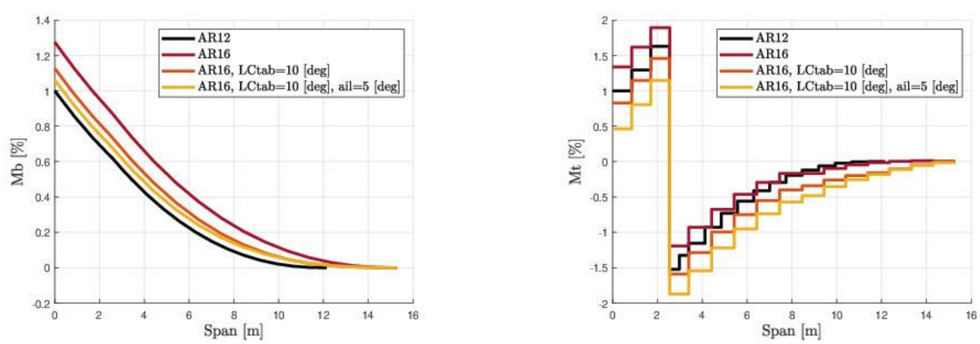

Figure 3: Effect of LC tab deflection on UERA16's bending moment (left) and torque (right)

Table 4 summarizes the root load alleviations obtained for different LC tab and aileron deflections, for UERA16, expressed as percentage of UERA-like root loads. Looking at the trend, it is possible to reach and reduce further the wing root loads with higher deflections.

LA systems are particularly suited when a gust is encountered during flight. This situation must be addressed carefully especially for future aircrafts, since, due to climate change, atmospheric turbulence is changing [9], and the probability to encounter a hard gust will increase. As anticipated, NeoCASS allows to compute also gust responses. In general, this kind of analyses are conducted simultaneously with the design of a control law - as it was done e.g. in [10] - whose output is the evolution of the LC tab deflection that matches the desired load alleviation level. These analyses are currently under investigation.

A preliminary estimation of the effectiveness of control surfaces deflection on Wing Root Bending Moment (WRBM) and Wing Root Torsion Moment (WRTM) is provided in Fig. 4, where the Transfer Functions (TF) between the wing root load and a unitary gust, a unitary aileron deflection and a unitary LC tab deflection, for UERA16, are presented. Figure 4 left shows that aileron deflection is more effective on bending than LC tab. The opposite is valid for torsion: the blue peak at torsional frequency in Fig. 4 right is much larger than the black one.

Table 4: Root load alleviation, UERA16

$\delta_{LC_{tab}}$ [deg]	δ_{ail} [deg]	M_b [%]	M_t [%]
0	0	+27.3	+17.3
5	0	+19.9	+8.3
10	0	+12.6	-0.6
10	5	+6.1	-46

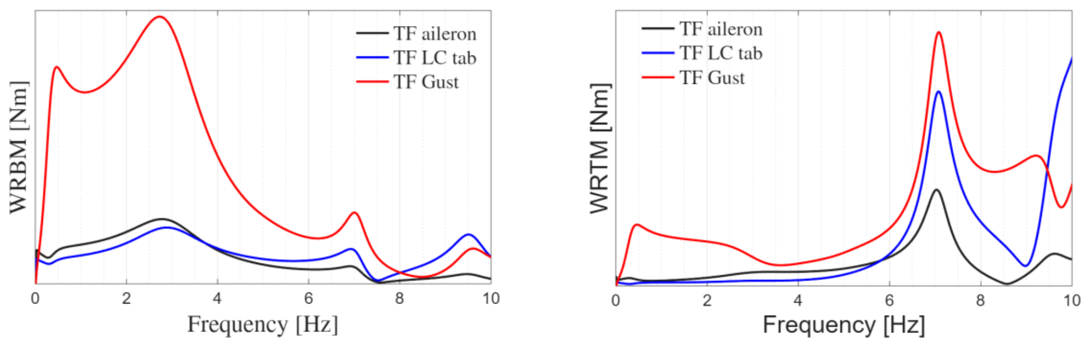

Figure 4: Transfer functions for UERA16, WRBM (left) and WRTM (right)

Conclusions and Future Work

Different models have been created and analyzed, with varying wing AR. The highest aerodynamic efficiency has been reached for UERA16, along with the highest wing root internal actions. An additional control surface has been introduced to alleviate such loads. Static analyses showed promising load reductions, within reasonable LC tab and aileron deflections. A control law for Gust Load Alleviation (GLA) is under investigation, along with the creation of the wing aero-servo-elastic experimental model, to be gust tested inside POLIMI Wind Tunnel.

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