Design of near-zero emission aircraft based on refined aerodynamic model and structural analysis

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Abstract. During recent years, aircraft manufacturers focused their attention on environmentally friendly and aerodynamically efficient aircraft concepts that could allow a radical reduction of emissions. The use of hybrid-electric powertrain is one of the most effective ways to design near-zero emission aircraft. These aircraft are highly performing and sophisticated. Hence, the design process must be extremely accurate and should make use of multidisciplinary design optimization. It is indeed crucial to establish both aerodynamic and structural models to simulate the aircraft performance and design required according to top level aircraft requirements. Despite the largely discussed literature about preliminary design of such an unconventional aircraft, there is still a lack of reliable weight estimation approaches, simulation-based mission analysis and optimization tools. In order to step towards higher technological readiness levels, the purpose of this paper is to describe and apply a design platform for conventional, turboelectric, hybrid-electric and full-electric aircraft, integrating aero-propulsive interactions, accurate power system modelling and medium-fidelity structural weight estimation. In particular, the comprehensive structural analysis of the aircraft wing opportunely designed according to certification specification and equipped with different powertrain architectures shows that it is worth looking into structural dynamics from preliminary design to estimate aircraft weight properly. Meanwhile, the mission analysis reveals performance benefits by implementing distributed engines all over the wingspan.

1. Introduction

Distributed propulsion is barely a new concept and has captured the attention of major players in the aviation landscape to increase propulsion system efficiency along with better aerodynamic flow [1]. However, one of the major concerns is to establish updated and enhanced preliminary design approaches, useful to estimate the potential outcomes after the implementation of such an innovative concept on a selected aircraft configuration. Indeed, it is worth noting that new and better preliminary design approach can strongly improve the impact of such a non-conventional architecture on the aircraft weight. That is also useful to address the potential outcomes after the implementation of such innovative concept on the selected aircraft configuration. For preliminary design concepts, it is necessary to understand the performance limits, and the overall physical reconfiguration that an airframe experiences when switching to distributed propeller propulsion. One of the main goals is to define the effect of implementing distributed propulsive technologies in commuter aircraft. Furthermore, when referring to the preliminary aircraft design model, it is
essential to have a better understanding of how to include these subsystems and a proper analysis in the preliminary design phase of the aircraft model is crucial. In general, the framework of the pre-conceptual design concepts is very much dependent on several key parameters such as the principal dimensions, aerodynamic parameters, weight, propulsion system characteristics, and flight performance. The following main aspects will require refinements: geometric-modeling capabilities, propulsion module, aerodynamics, performance analysis, weights and mission definition.

In particular, the mass breakdown analysis requires estimation models on weight of each aircraft component in order to compute the Operating Weight Empty and Maximum Take-off Weight. The use of distributed engines over the wing span to improve aerodynamic performances poses new challenges from a structural perspective. Despite the static relief, generally introduced thanks to the load alleviation induced by the outboard mass of the engines, the dynamic response of the wing gives rise to concern. It is indeed expected that outboard mass, and especially tip-mounted propeller, may require a complicated design due to reduced flutter performance. This results in higher stiffness requirements and consequently increased mass. Hence, a dedicated design model is needed to establish the mass and stiffness of the wing.

Generally, different methods are available in the literature to estimate the mass of the airframe as well as the overall aircraft weight. It is possible to broadly divide those methods according the approach adopted in: (i) empirical and semi-empirical methods [2, 3], (ii) analytical and quasi-analytical based methods [4, 5], and (iii) finite element-based methods [6]. Empirical methods consist mostly of statistical evaluation based on existing aircraft. Although great and valuable results have been obtained, the implementation and accuracy level of statistical-based methods in predicting aircraft mass depends primarily on the amount and quality of the data available for existing aircraft and, as such, of limited practical use for DEP equipped aircraft. A similar discussion can be done for semi-empirical methods, used when a simplified geometrical layout of the aircraft configuration becomes available. However, it is still difficult to capture the layout peculiarities of a specific configuration. Analytical and semi-analytical approaches require the use of a simplified structure model to estimate the mass and performance of the structure. As such, they are well suited to perform parametric studies. However, they still require holistic approaches able to account for aerodynamic effects and aeroelasticity. To overcome these limits, specific effects of static and dynamic aeroelasticity can be accounted resorting to high fidelity models, such as those relying on Finite Element Methods (FEM) [7]. Then, the findings can be adopted to estimate the weight necessary to compensate such an aeroelastic penalty in an inverse approach. The combination of these approach allows to define 4 classes of methods (I, II, III&1/2, III) according to the inherent fidelity and versatility.

In this context, the present paper shows a design chain for electric platforms including a comprehensive structural analysis of the aircraft wing opportunely designed according to certification specification and equipped with different powertrain architectures. These are derived by implementing a mission analysis revealing main performance of the aircraft. Instead, the structural design is performed via combined semi-analytical and statistical assets converging to a comprehensive Class II&1/2 approach.

2. Materials and Methods
This section introduces the statement of the problem along with the semi-analytical model set up to look into the aircraft performance and design the aircraft properly.

2.1. Statement of the problem
The idea behind DEP is to get advantage of local propeller blowing to get to more efficient wing. With many propellers blowing air over it at high speed, the wing behaves as though it is traveling faster than it actually is, providing greater lift. During takeoff and landing,
air can be blown over the wing at higher speeds, providing additional lift without sacrificing cruise performance. However, sizing and weight estimation becomes complicated because of the non standard load ratio, $W_{\text{fs}}$. A typical configuration under investigation for different platforms ranging from general aviation to regional aircraft is reported in Figure 1. It displays how the the engines are typically distributed over the wingspan. Namely a gas turbine can be either tip- or inner-mounted and connected to the electrical motor (EM) cluster through an electric generator (EG) mounted just behind. The number of electrical engines depends upon many aspects which are faced within [11] and briefly described in Section 2.2. This may strongly affect the design of the wingbox, requiring refined methodologies for comprehensive analysis. In this context, a class II&$\frac{1}{2}$ design framework is established using Analytical/Semi-analytical methods with statistical/Semi-empirical methods and high-fidelity models in such a combination to look into different aspects which affect airframe design (see Section 2.3).

2.2. Aerodynamic and powertrain design

This section shows the modelling set up to design the aircraft equipped with distributed propulsion. According to a specific mission profile and Top Level Aircraft Requirement, both aerodynamic and powertrain performance are analyzed and a preliminary configuration is conceived. When modelling hybrid-electric, full-electric or conventional aircraft, the first and most important difference from which the design process starts is the propulsive system. Regardless to the configuration, innovative or not, the propulsive system is what characterize the electrification of the aircraft. For the present application, the architecture reported in Fig. 2 describes the power grid of a single semi-span on which four different distributed propellers are installed.

The power requirements are estimated according to mathematical models proposed in literature [11, 12]. The linear system of ten equations, addressed in the present work as powertrain equations, is written according to the energy conservation principle. In this context it is worth noting that hybrid-electric powertrain consists of two different power sources which makes more complicate the relationship between engine deck and shaft power. In the present work, the approach studied in [11] is used to define the sizing power of each component.

From aerodynamic point of view, the load acting on the wing is estimated via a vortex lattice method in order to include the effect of the engine placement. Indeed, each propeller blows the air inducing an alteration of pressure field compared to isolated wing. Then, a mission simulation and performance analysis loop is carried out to estimate the flight performance and emission.

2.3. Structural design

According to the airframe geometry, the structure is sized to withstand the aerodynamic and inertial loads. Here is where the certification standard comes into play, driving the structural
design to accomplish the safety during flight. Among all components, the wing sizing is the focus of this paper and it is estimated through a wing mass prediction model described hereinafter theoretically. For this purpose, the formulation widely follows an analytical asset based on some physical assumptions, along with a novel semi-analytical approach to include engine aeroelastic correction. The wing is modelled as the combination of primary and secondary structure. The mass of the primary structure is computed using simple structural analysis based on stress and deformation sizing. The amount of mass is merely that required to withstand critical loads and/or deformation. Otherwise, the mass of the secondary structure is estimated statistically according to [2].

The primary structure generally is composed of upper and lower stiffened skin panels, spars, ribs and the so-called "Non-Optimum Weight" where the weight penalties (joints, attachments, cut-outs) are considered. The primary structure sustains the main efforts applying on the wing. The former contribution weight is computed analytically, as far as possible, according to an optimum structure sizing. The latter contribution weight is estimated empirically. The secondary structure is made up of fixed leading and trailing edges, control surfaces and high-lift devices, whose weight is estimated with statistical methods depending on the geometry of the different components. Thus, as described above, the problem of the wing mass can be expressed as the sum of primary and secondary structure masses. An outline of the structural classification of several components is reported in Figure 3.

As to the primary structure, it consists of several elements. If the wing is stressed, all the components withstand the loads, but some of them will have a specific task. A simplified solution for this problem is represented by the following assumption: the wing box is a statically determined equivalent system where each component bears a certain type of solicitation:

(i) The web of the front and back spars sustains the vertical shear forces;
(ii) The caps of the spars are sized to withstand the bending moment;
(iii) The covering skin of the wing bears the torsion moment;
(iv) the ribs support the wing panels against buckling and serve for maintaining the shape of the wing. They are also present at each introduction of local forces;

Figure 2. The most general propulsive system possible.
Figure 3. Wing structural decomposition and calculation method proposed in this framework.

(v) The other elements resume their own efforts.

With the aim of developing an efficient and minimum time consumption wing mass estimation model for the primary structure, two main hypotheses were adopted. First, the aerodynamic load distribution is estimated from the aerodynamic model and the lift is only due to the wing, in favor of safety. Second, concerning the propulsion, the torque moment and the torsion contribution coming from the thrust are not considered since the effect is negligible. To achieve a rational determination of what the components bear, distribution of internal solicitation over the wingspan is determined. Firstly, the Shear stress distribution is calculated considering the effect of lift, wing and engine weight. After the shear diagram is obtained, the moment distribution over the wingspan is obtained as per integration of the shear distribution. Finally, the Twist Moment is obtained considering the lift applied at the airfoil focal point and the relative focal twist coefficient is introduced to reconstruct the twist wingspan distribution. After the definition of these three specific load distributions, the several components constituting the primary structure are sized accordingly.

The secondary structure is made up of fixed leading and trailing edges, control surfaces and high-lift devices, whose weight is estimated with statistical methods depending on the geometry of the different components. The mass estimation of the secondary structure is essential to complete the computation of the wing mass as it generally contributes roughly 30% of the total wing mass and it has an important effect on inertial relief. Due to the complexity of the different components, a statistical approach appears useful to estimate the secondary mass contribution. That is the reason why the Torenbeek’s semi-empirical equations seem to be well suited for the estimation of the secondary mass contribution when the necessary details are available. Furthermore, numerical findings from high-fidelity model to study the aeroelastic effect of DEP are moved back to Statistical/Semi-empirical formulation to account for the specificity of DEP configuration from preliminary design (i.e.: including improved aeroelastic correction).

3. Results
This section reports the results obtained by implemented the model conceived to estimate the weight of the wing. A first preliminary analysis is carried out validate the model on the conventional configuration. Afterwards, three different innovative configurations are studied.
The main characteristics of the several aircraft configurations studied are reported in Figure 4. It is worth noting how the distributed electric propulsion returns higher load ratio $W_{S}$ due to the better aerodynamic performances. In addition, the hybrid configurations have an additional mass due to battery packs, which affects MTOW according to the degree of hybridization. The motorization adopted after implementing powertrain and aerodynamic models is reported in Figure 5. It is worth noting how the electric motorization strongly depends on the type of configuration (turboelectric or hybrid) and the degree of hybridization.

Based on the available data, the structural model returns the internal load distribution according to CS-25 guidelines. Shear distribution is depicted in Figure 6 as the combination of wing weight (initial guess), aerodynamic loads, and engine weight. Bending and twist are derived according to shear distribution and aerodynamic load and reported in Figure 7.

| Configuration  | $b$ [m] | $S$ [m$^2$] | $c_w$ [m] | $c_l/c_w$ | $\Lambda$ [°] | $W_{W,\text{kgdual}}$ [Kg] | MTOW [Kg] |
|----------------|--------|-------------|----------|------------|---------------|------------------|----------|
| Conventional   | 24.57  | 54.40       | 2.56     | 0.635      | 0             | 449              | 17521    |
| Turboelectric  | 24.57  | 44.74       | 2.14     | 0.635      | 0             | 455              | 21444    |
| Hybrid I       | 24.57  | 44.74       | 2.14     | 0.635      | 0             | 307              | 23021    |
| Hybrid II      | 24.57  | 44.74       | 2.14     | 0.635      | 0             | 305              | 20226    |

Figure 4. Main characteristics of different aircraft configurations

| Configuration  | $\eta_{GT}$ | $\eta_{EG}$ | $\eta_{EM1}$ | $\eta_{EM2}$ | $\eta_{EM3}$ | $\eta_{EMA}$ | $W_{GT}$[Kg] | $W_{EG}$[Kg] | $W_{EM}$[Kg] |
|----------------|--------------|--------------|---------------|---------------|---------------|---------------|--------------|--------------|--------------|
| Turboelectric  | 0.99         | 0.98         | 0.21          | 0.39          | 0.57          | 0.75          | 455          | 280          | 100          |
| Hybrid I       | 0.99         | 0.98         | 0.21          | 0.39          | 0.57          | 0.75          | 307          | 198          | 100          |
| Hybrid II      | 0.99         | 0.98         | 0.21          | 0.39          | 0.57          | 0.75          | 305          | 149          | 75           |

Figure 5. Motorization adopted for different aircraft configurations

Figure 6. Shear distribution over the turboelectric wing configuration in design condition at ultimate load due to: wing weight (a), aerodynamic load (b), engine weight (c) and combination of loads (d)

and the mass breakdown is compared to point out the effect of the distributed propulsion which cannot be assessed with simplified statistical or semi-empirical models due to lack of information.
Figure 7. Bending (a) and Twist (b) distribution over the turboelectric wing configuration in design condition at ultimate load

| Wing Structure Weight [Kgf] | Primary Structure [Kgf] | Secondary Structure [Kgf] | Statistical Estimation [Kgf] | Conventional Aircraft [Kgf] |
|-----------------------------|-------------------------|---------------------------|----------------------------|-----------------------------|
| 1392.12                     | 1032.04                 | 262.08                    | 1382                       | 1392.12                     |
| 1376.48                     | 1084.63                 | 291.85                    | 1461                       | 1392.12                     |
| 1519.07                     | 1134.04                 | 296.28                    | 1676                       | 1392.12                     |
| 1435.57                     | 1058.03                 | 289.25                    | 1539                       | 1392.12                     |

Figure 8. Wing structure weight estimated for conventional and unconventional configurations

The wing estimation is then reported in Figure 8 highlighting the mass of both primary and secondary structure and comparing the findings with the statistical estimation. The estimation for conventional aircraft, where statistics can be considered a reference, reveals the effectiveness of the model adopted achieving a well suited validation.

The extension of the model to different DEP configurations reveals the weight decrease when turboelectric configuration is conceived. Instead, hybridization increases the weight of the primary structure due to the higher MTOW. In addition, it is worth noting how the mismatch between this model and statistical estimation increases. Indeed, statistics cannot account the peculiarities of DEP, including static relief and dynamic effects. Actually, the unconventional higher $\frac{\text{W}}{\text{S}}$ drives the statistical estimation resulting in a lack of realism.

Concluding remarks
This work presents preliminary sizing methodologies of hybrid-electric aircraft based on refined aerodynamic model and structural analysis. The structural model is validated considering conventional aircraft and then extended to DEP accounting for some non-linear effects, which including static relief and dynamics introduced by distributed engines. When moving to non conventional wing configuration, statistical approaches fails to estimate the structural weight due to the non-conventional architecture. This is mostly due to the different load factor $\frac{\text{W}}{\text{S}}$ returned by electric-like configurations. It is worth noting that the preliminary sizing can be converted into high fidelity modeling for further optimization of the structure. In addition, it
can be integrated into design loop to estimate properly the aircraft performance extending the structural design to other components. Finally, the deformation analysis will be implemented to account elastic effect and better assess the aircraft performance considering elastic airframe.

Acknowledgments
The authors gratefully acknowledge the support received in the context of project ELICA. The ELICA project has received funding from the Clean Sky 2 Joint Undertaking under the European Union’s Horizon 2020 research and innovation program under Grant Agreement nº 864551. The authors are grateful to all other partners for the support on this research topic. The content of this paper reflects only the author’s view and both the European Commission and the Clean Sky 2 Joint Undertaking are not responsible for any use that may be made of the information it contains.

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