Recent Developments in Electric Aircraft Conceptual Design

Lorenzo Trainelli (1), Carlo E. D. Riboldi (2), Alberto Rolando (3)
Department of Aerospace Science and Technology, Politecnico di Milano, Via G. la Masa 34, 20156 Milano, Italy
1 : lorenzo.trainelli@polimi.it 2 : carlo.riboldi@polimi.it 3 : alberto.rolando@polimi.it

Abstract

We discuss recent aircraft design activities carried out at the Dept. Of Aerospace Science and Engineering of the Politecnico di Milano in the field of electrically-powered aircraft. These concern the development of methodologies as well as of complete conceptual and preliminary designs of highly innovative airplanes. Dedicated methodologies and tools for the preliminary sizing aircraft with pure-electric and hybrid-electric powertrains have been established, first dealing with light aviation and subsequently extending the framework towards commuters and regional aircraft. In its most advanced implementation, this approach provides an optimal determination of the design point for a serial hybrid-electric airplane. The design of four unique machines, three of which have been awarded top rankings in renowned international competitions, is presented. These aircraft are a pure-electric metropolitan air taxi, a pure-electric micro-feeder, a parallel hybrid-electric regional liner, and a serial hybrid-electric General Aviation light airplane endowed with a structural battery airframe. All of them relate to a disruptive technology and/or an operational scenario currently investigated worldwide for near- or mid-term implementation.

Introduction

A thriving field in aeronautics concerns the progressive electrification of aircraft, including the integration of electric propulsive elements. This amounts to pure-electric (PE) vehicles, where an electric powertrain is adopted in substitution of the typical ICE (Internal Combustion Engine), as well as to various forms of hybrid-electric (HE) vehicles, which feature some kind of collaboration of an electric powertrain and another source of energy for flight.

Some recent realizations, in the field of airplanes and even rotorcraft, are giving a convincing sign that electrically-powered, passenger-carrying aircraft may represent a key element in the capability of the future aviation sector to pursue performance and enhance quality of life, while lowering its overall environmental impact. Such realizations, although often purely experimental, typically do not rely on a general design methodology, applicable to different aircraft models and categories. Therefore, there is a significant space for research efforts towards the definition of general, accurate, and flexible models to be used in design, analysis, and verification.

The present contribution concerns recent aircraft design activities carried out at the Dept. Of Aerospace Science and Engineering of the Politecnico di Milano in the field of PE and HE aircraft. These include the development of dedicated methodologies and tools for aircraft preliminary sizing, as well as of complete conceptual and preliminary design exercises for specific case studies. The following presentation briefly reports on both topics, underlying the core elements and the original contributions involved.

Methodologies

The major effort in the recent development of methodologies for PE and HE design focus on preliminary sizing. Indeed, while long-lasting, consolidated approaches are available to the designer of conventionally-powered aircraft [1,2], when it comes to PE or HE propulsion, a lack was observed in general methodologies capable to yield reliable estimations of the design point, *i.e.* the set of parameters that, together with a chosen configuration, represent the start of a preliminary design process for an aircraft with given design specifications.

Therefore, a first contribution made in [3] was devoted to the preliminary weight sizing of small PE fixed-wing aircraft. In most cases, existing models and design studies in this field refer to modification of existing machines, originally designed as gliders or ICE-propelled airplanes, either motor-gliders of ultralight/very light airplanes. A general framework to determine the design point was established, by substantial modifications to the traditional sizing methods. These include, on one hand, bringing into play new statistical regressions and, on the other hand, coupling the weight estimation with the performance matching matrix, represented by the Sizing Matrix Plot (SMP).

Statistical regressions are proposed for both the specific airplane category, based on the existing examples, and the electric motor (EM), which does not appear among conventional aircraft subsystems and therefore cannot be easily integrated in traditional methods. Here, the empty weight is defined as the design all-up weight deprived not only of payload weight and fuel weight, as in the case of conventional aircraft, but of the combination of weights pertaining to the EM, the battery pack, and the payload.

Integrating the mission profile analysis, with its performance specifications, and the applicable design constraints allows obtaining a procedure that determines the necessary battery weight, closing the problem. Figure 1 shows the SMP relative to a design example, with the feasible design space (dashed magenta borders) completed by the design points representing existing PE aircraft models (red circles).

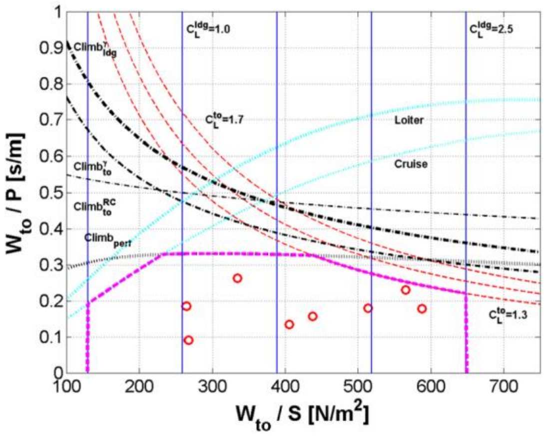

Fig. 1: Sizing matrix plot for a pure-electric airplane

This approach has been extended to the case of small HE airplanes in [4]. By building upon the previous PE sizing methodology, a serial HE configuration has been considered, including addition of an ICE, an electric generator, and a fuel tank. The generalization is carried out assuming that the PE procedure basically holds true when the battery weight necessary for the cruise phase is substituted by the combination of battery, ICE system, and fuel. Again, a new statistical regression is introduced, to take into account the ICE system power density (*i.e.* power to weight ratio). Within the sizing process, a used-defined parameter is represented by the “cruise power ratio”, defined as the ratio of ICE power on power required in cruise. Figure 2 shows the constant-range curves obtained as functions of the fuel carried on board and the cruise power ratio (indicated by K_h).

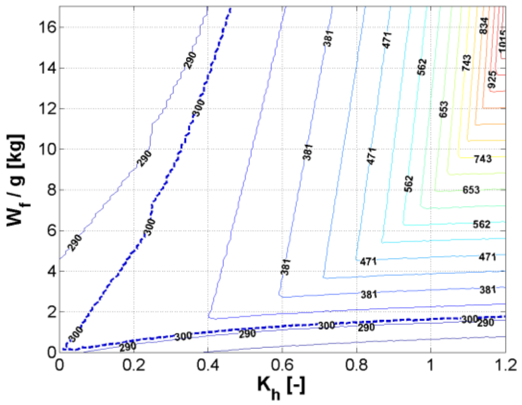

Fig. 2: Contour plot of range as a function of fuel weight and cruise power ratio

The methodology developed in [3] and [4] served as the base for a more comprehensive design tool implemented in the HYPERION code [5]. This is conceived to be employed in the preliminary sizing of aircraft in a larger weight range, including commuters (CS23) and regional liners (CS25). This tool has been validated by sizing a number of existing conventional aircraft, as well as some electrically-powered ones.

In an effort to generalize further the approach to preliminary sizing for HE machines, removing some hypotheses present in [4], a new framework has been established in [6]. This consists in an optimization method aimed to the direct solution of the preliminary sizing problem, i.e. the determination of the design point in terms of empty weight, design all-up weight, power loading, and wing loading, by minimizing the design all-up weight, subject to a set of constraints. Such constraints are the mathematical representation of mission profile requirements and certification barriers, as well as power and weight characteristics and limits of the HE powertrain.

The proposed function of merit is composed of the sum of the squares of each of the all-up weight components. The parameters left free in the optimization are the ICE weight, fuel weight, EM weight, battery weight, structural empty weight, and the throttle settings of both ICE and EM. It is remarked that the latter two quantities are properly functions of time, evolving along the mission profile. The resulting procedure, albeit complex, has the merit of determining an optimal solution in a rigorous, deterministic way. Table 3 illustrates the results of the optimal sizing of a HE airplane in comparison to a PE design satisfying similar requirements, while Figure 3 describes the optimal time evolution of throttle settings for the mission considered.

	Hybrid-electric	All-electric
W_{to}/g [kg]	585	856
W_{ICE}/g [kg]	65.3	0
W_f/g [kg]	42.6	0
W_m/g [kg]	10.7	17.2
W_{bat}/g [kg]	38.2	279
W_e/g [kg]	278.6	409
$P_{ICE,n}$ [kW]	25.0	0
$P_{m,n}$ [kW]	14.8	52.5
S [m^2]	9.6	14.0

Table 1: Comparison of sizing results: optimal hybrid-electric vs. pure-electric

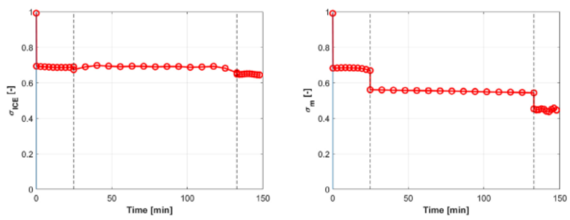

Fig. 3: Optimal time histories of ICE (left) and EM (right) throttle settings

Pure-electric aircraft case studies

Two highly innovative PE airplane concepts are recalled: Flynk [7] and Project A [8]. They share some broad characteristics, being of similar general configuration and payload capability. However, their design is driven by very different mission requirements, in both cases related to future groundbreaking scenarios in air mobility.

Flynk

The Flynk is an innovative all-electric, 9-passenger STOL airplane designed for low-fare very short-haul missions used for mass commuter transportation, in an attempt to contribute to the improvement of the quality of life in large metropolitan areas. It has been designed to provide an answer to the AIAA Graduate Student Design Competition 2014-2015, in which it was awarded the first place.

The competition Request for Proposal called for the design of an air taxi system with either VTOL or STOL (Short Take-off and Landing) capability, entering service in 2020. The air taxi mission had to be operated within a large metropolitan areas such as New York or San Francisco in the U.S.A., and was required to outperform any other commuting means, including automotive and rail transportation, also in terms of end-user cost.

A thorough preliminary study framed in the New York Metropolitan Area (NYMA) was carried out, investigating the peculiarities of the community demand, in order to determine the primary requirements to be met. These contributed to the drafting of design specifications that triggered a complete conceptual and preliminary design study. The result is a rather unusual airplane, characterized by the specifications reported in Table 2.

Engine power	4 x 110 kW
Wing surface	20 m^2
Aspect ratio	9.4
Max payload weight	915 kg_f
Max gross weight	2,870 kg_f
Runway length	150 m
Cruising speed	370 km/h

Table 2: Flynk main specifications

The most original features of the Flynk design stem from the atypical mission profile: a typical range of 25 statute miles, or 40 km; cruise altitude of 500 ft (or 150 m) AGL (Above Ground Level); and exceptionally short take-off and landing runs, below 150 m. This called for distributed propulsion with four wing-mounted propellers, two of which partially tilting; oversized wing, with huge trailing edge double-slotted flaps for maximum lift coefficient values above 4.0.

Project A

In this case, the design challenge targeted the possibility to exploit the existing small local airport European network to provide a micro-feeder service to larger hubs through a small passenger airplane, starting in 2025-2030. The envisioned service should seek to enable the ACARE “Flightpath 2050” policy towards a 4-hour door-to-door total journey time reduction for European citizens.

Also in this case, design requirements stemmed from a broad preliminary study. This allowed determining the peculiar continental market scenario, based on hub traffic data, small airport geographic distribution, potential feeding routes, and ground transportation cost analysis. Furthermore, an online survey with over 1,600 answers provided additional guidance.

As a result, Project A, an all-electric, twin propeller, 8-passenger airplane, was conceived and designed. The aircraft is capable of up-to-1-hour missions for a maximum range slightly over 250 km, operating from any smaller General Aviation airport including grassy airstrips. The main specifications of Project A are given in Table 2.

Engine power	2 x 260 kW
Wing surface	20.2 m^2
Aspect ratio	12
Max payload weight	760 kg_f
Max gross weight	3,060 kg_f
Runway length	500 m
Cruising speed	405 km/h

Table 3: Project A main specifications

Project A provides a coverage over 80% for the intra-European short and medium network considered, including over 900 candidate routes. Furthermore, a 80% reduction in travel time compared to both automobiles and trains may be achieved.

Hybrid-Electric aircraft case studies

Two highly innovative HE airplane concepts are recalled: Flybrid [9] and Hybris [10]. The former is a regional liner, while the latter is a General Aviation model for training and leisure flight.

Flybrid

A market study for a regional liner in the 2030s scenario led to size a 90-passenger aircraft for a 700 km design mission. Seeking economic and environmental sustainability, a parallel HE solution was considered for the Flybrid airplane, coupling two turboshafts with two EMs in the wing nacelles, and providing for a sizable, modular battery pack to be accommodated in the cargo bay using standardized container units. A very effective provision for flexibility, insuring effectiveness in missions with a block range between 250 and 1,000 km, is represented by the possibility to trim the number of battery containers. Also, careful sizing of the propulsive system yielded further operational and safety advantages, such as those implied in One Engine Inoperative (OEI) situations. Table 4 lists the main Flybrid specifications.

Maximum take-off weight	32,500 kg_f
Maximum payload weight	9,600 kg_f
Maximum fuel weight	5,000 kg_f
Maximum battery weight	3,600 kg_f
Cruising speed	560 km/h
Maximum range (90 pax)	750 km
Ceiling	7,000 m

Table 4: Flybrid main specifications

This concept was presented in the 2013 edition of the "Fly Your Ideas" international student competition sponsored by Airbus and supported by the United Nations Educational, Scientific and Cultural Organization (UNESCO), emerging among the five finalists.

Hybris

The Hybris is the response to the RFP issued in the Royal Aeronautical Society (RAeS) First Annual General Aviation Design Competition launched in 2015. The context, dubbed "E-conditions Fixed-Wing Aircraft Design Challenge", called for fresh, innovative designs, to spur the regeneration of the stagnant U.K. General Aviation milieu. The project was awarded the first place in the competition, due to its remarkably innovative character: a serial HE aircraft employing a Structural Battery (SB) airframe.

This out-of-the-box concept, which does not appear to have been previously considered, provides a way to contain the aircraft gross weight without impacting on performance, and thus yielding lower environmental impact and operating costs. SBs are multi-functional materials, capable of withstanding structural loads and storing electrical energy at the same time. Sizing the aircraft with this groundbreaking airframe arrangement required the definition of a dedicated procedure, in which structural weight and propulsion are inherently coupled. A discussion of this novel methodology is presented in [11,12].

EM max power (continuous/transient)	60/150 kW
Wingspan	10.5 m
Length	11.5 m
Max gross weight	1,275 kg_f
Range	>2,200 km
Cruising speed	280 km/h
Cruise altitude	2,400 m

Table 5: Hybris main specifications

The Hybris, featuring the specifications disclosed in Table 5, is a conventional-looking, single-propeller, low wing monoplane adopting SBs for as much as 45% of the total structural weight. These amount to 73% of the total battery mass, the remaining 27% being made of conventional batteries. The optimized Hybris design provides for pure-electric mode operations up to 3,000 ft (or 900 m) AGL, wiping out chemical emissions and drastically reducing noise in terminal maneuvers, those that affect overflown communities the most. While offering performance comparable to conventionally-powered 4-seaters, predicted costs appear in the order of 20% lower than the most modern competitors.

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