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An optimal approach to the preliminary design of small hybrid-electric aircraft

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ABSTRACT

Hybrid-electric propulsion is an interesting alternative for the light aviation market, carrying the advantages of electric propulsion in terms of lower noise and pollutive emissions in terminal maneuvers, while not renouncing to the flight performance – especially range – typical to conventional propulsion, based on hydrocarbon fuel. Some difficulty in the spreading of this new technology in light aviation may be ascribed to the lack of consolidated techniques to preliminary design hybrid-electric aircraft, complicating the negotiation of specifications and making design choices difficult. This is also the effect of a notable increase in the number of design variables needed to describe the hybrid-electric power-train, which include characteristics of both its thermal and electric parts, with respect to conventionally powered aircraft. The present paper presents a methodology to efficiently cope with this design problem. The procedure is based on an optimal approach where take-off weight is minimized, and constraints are included to assure meeting the mission performance requirements while not exceeding any technological limit. The paper recalls at first some simple mathematical models, allowing to translate flight performance requirements into constraints on the power-train. Then the proposed optimal design approach is thoroughly presented at a theoretical level. Finally, an example design of a hybrid-electric motor-glider is shown, where the optimal design tool is used both to find a baseline solution and to investigate the sensitivity of that design point with respect to constraints due to performance requirements and technological specifications.

1. Introduction

In recent times, electric propulsion for aircraft has been in the focus of designers and manufacturers of ultra-light (UL) and light general aviation (GA) aircraft, who see in this kind of power-train a possible way to decrease noise and chemical pollution. Considering the specific case of internal combustion engines (ICE), by far the most popular propulsion system in this category, the engine is often identified as the primary source of the overall noise footprint on ground, as well as a major responsible for limited cabin comfort [1–3]. Furthermore, being bound to combustion as an energy conversion method, ICEs are intrinsically less energy-efficient than electric motors (EM), and they invariably release chemicals in the atmosphere as side products of the conversion process, whereas electric motors perform an emission-free conversion. These advantages make the use of EMs really attractive when public acceptance is at a premium [4], as for the case of small private and sport aircraft, typically operating from smaller airports located in crowded areas, and often raising noise and chemical pollution issues [5].

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The chance of electric motors to be adopted as the main power-plant for innovative light aircraft designs is currently limited, due to both a lack of confidence of the potential customers in this radically new technological application, and more substantially to the technological limit of nowadays batteries [6–10]. The latter feature low and penalizing specific energy and power figures, which in turn translate into a very high weight and volume toll on the aircraft, often impacting on the range and endurance of purely electric designs. A study in the field of the design of all-electric light aviation aircraft has been carried out [11], showing a systematic methodology for the preliminary sizing of these aircraft at the current level of technology. Among other results, it was highlighted that the typical mission profiles of electric aircraft can be based only on short cruises and loiter times, typically necessary to increase time in flight allowing for multiple landing circuits, thus in practice relegating these models to training missions typically performed not far from the field. It is shown that, while some examples of purely electric aircraft indeed exist, the substantial limits of this technology are currently hampering its wide adoption in aeronautics, as testified also by the limited literature on the matter. Other studies often concentrate on specific missions,

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Nomenclature

$\boldsymbol{H}$	Set of constraints
A, B	Take-off vs. empty weight regression coefficients
AR	Aspect ratio
C, D	Weight vs. power of electric motor regression coefficients
$C_{D,0}$	Parasite drag coefficient in parabolic polar
C_L	Lift coefficient
E_{bat}	Energy level of battery
E_f	Energy level of fuel
E_0	Total energy level
EM	Electric motor
GA	General aviation
H	Constraint identifier in set $\boldsymbol{H}$
ICE	Internal combustion engine
J	Merit function for optimization
K	Induced drag coefficient in parabolic polar
L	Length of take-off run
P_a	Available power
P_f	Required power due to wheel friction
$P_{\text{ICE},n}$	Nominal power of ICE
$P_{\text{ICE}_{\min,DB}}$	Minimum power of ICE in the database of real data
$P_{m,n}$	Nominal power of EM
P_r	Required power due to aerodynamics
P_{rec}	Battery charging power
S	Area of reference surface
T	Time duration
UL	Ultra-light
V	Airspeed
V_v	Rate of climb
W_{bat}	Battery weight
W_e	Empty weight
W_f	Fuel weight (initial)
W_{ICE}	Weight of ICE group
$W_{\text{ICE}_{\min,DB}}$	Minimum weight of ICE group in the database of real data
W_m	Weight of EM group
W_{pl}	Payload weight
$\boldsymbol{q}$	Set of optimization parameters
$\bar{\boldsymbol{q}}$	Set of optimization parameters accounting for discretization in time
$\boldsymbol{s}$	Set of time-discretized values of the throttle parameter function σ^*
e_{bat}	Specific energy of battery
e_f	Specific energy of hydrocarbon fuel
f	Shape function
g	Gravity
h	Altitude
k	Time index
p_{bat}	Specific power of battery
t	Time
β	Percentage limit on regression coefficients
η_C	Efficiency of the battery charging process
η_{ICE}	Conversion efficiency of ICE
$\eta_{\text{ICE},n}$	Nominal conversion efficiency of ICE
η_m	Conversion efficiency of EM
η_P	Propulsive efficiency of the propeller
μ	Friction coefficient
ν	Percentage limit defining minimum battery residual energy
ξ	Percentage limit defining residual energy
ρ	Density of air
σ	Generic throttle setting
σ_{ICE}	Throttle setting of ICE
σ_m	Throttle setting of EM
$(\cdot)_{\text{final}}$	Related to the end of a phase of the flight
$(\cdot)_{\text{initial}}$	Related to the beginning of a phase of the flight
$(\cdot)_{\text{lower}}$	Lower limit
$(\cdot)_{\text{ref}}$	Reference value
$(\cdot)_{\text{upper}}$	Upper limit
$(\cdot)^{\text{climb}}$	Related to climb phase
$(\cdot)^{\text{cruise}}$	Related to cruise phase
$(\cdot)^{\text{loiter}}$	Related to loiter phase
$(\cdot)^{\text{to}}$	Related to take-off phase
$\dot{(\cdot)}$	Time derivative
$(\cdot)^*$	Function of time
$\bar{(\cdot)}$	Discretized in time

where purely-electric propulsion is thought to become viable and advantageous with respect to existing ICE-propelled systems in the near future [12].

In this scenario, the hybrid-electric alternative seems to put together the advantages of ICEs and EMs, allowing to increase efficiency and reduce emissions without renouncing to a good flight performance. The idea of hybrid-electric propulsion has been developed well into the production stage in the automotive sector [13,14]. Concerning the adoption of hybrid-electric propulsion in aeronautics, a substantial analysis of the performance and an identification of the design indices allowing to characterize and compare hybrid-electric aircraft over different weight categories has been carried out to a good extent in some recent works [15–18], encompassing some diverse hybrid concepts and configurations not limited to ICE for the fuel-burning component, and extending to distributed propulsion. Some example designs based on hybrid-electric propulsion systems have been described for instance in [19], dealing with a re-engined version of an existing UL. Notwithstanding the appreciable knowledge-base, hybrid-electric aircraft have been developed only rarely beyond the conceptual design phase [20,21].

The reasons for that can be found on one side in the high risk perceived by the stakeholders when experimenting with the application of a new technology in the aviation field, similarly to the case of electric aircraft [11]. Furthermore, a comprehensive practical approach to the sizing of a hybrid-electric aircraft from an assigned set of requirements has not been envisaged yet. A limited effort in this sense has been documented for instance in [22], yet in that work the sizing of the hybrid-electric power-train has been constrained by stringent hypotheses.

The present paper moves farther in this research area, and outlines a possible new general methodology to face the preliminary sizing of a hybrid-electric aircraft, considering the UL or lighter GA category as a field for testing. The proposed design procedure is based on an optimal approach which had not been investigated in previous works, aimed to the direct solution of the sizing problem, where a suitable optimization method is deployed to target the components of take-off weight through a suitable measure of merit. Multiple constraints, coming from the mission analysis and certification barriers as well, are put in mathematical terms. Similarly, the power and weight characteristics and limits of the hybrid power-plant, composed of a single ICE and a single EM in this study, will be formulated as constraints in the optimization process. In order to make this study more readily usable, a stress is put on using most of the existing methodologies developed for conventional propulsion [23,24] and more recently emended to

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