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# An integrated approach to the preliminary weight sizing of small electric aircraft

C.E.D. Riboldi *, F. Gualdoni

*Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa 34, Milano 20156, Italy*

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ABSTRACT

Electric propulsion has received attention in aviation as witnessed by studies in hybrid designs and by the production of aircraft with support electric motors to be used in limited parts of the mission with ancillary roles. Until the recent past, the main limit to a wider adoption of electric propulsion, which besides having a lower environmental impact with respect to internal combustion engines (ICE) in terms of noise and emissions, can also improve reliability and on-board comfort, was the need for mass and volume-inefficient battery packs as devices for energy storage. However, thanks to the level of technology now reached by batteries, it is becoming possible to design and build electrically propelled aircraft at least in the category of light or general aviation. Due to the relative novelty of this technology, only few examples of similar aircraft exist today, mainly modifications of more traditional concepts, and thinking of a completely new electric aircraft is made difficult by the lack of a consolidated design framework, differently from the case of traditional ICE-powered models. This paper tries to cope with some basic aspects typical to electrically propelled aircraft, to the aim of setting up a stable and reliable preliminary sizing procedure allowing designers and aircraft companies to quickly size up and compare all-electric designs. To this aim, a statistical analysis of the basic characteristics of existing aircraft is presented first, showing a good correlation level between some of them. Next a method for the preliminary sizing of weights is shown, obtained starting from a more usual step-by-step procedure typically adopted for ICE-propelled aircraft. Due to the peculiar characteristics of electrically powered aircraft, the new procedure involves an integrated use of the case-specific mission profile and sizing matrix. The validity of the proposed procedure is testified by example analyses on two realistic designs of lightweight aircraft.

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## 1. Introduction

Electric and hybrid propulsion systems have received a great deal of attention in recent years in various branches of transportation including aviation. This is due not only to the unpredictability of oil price in this era, making a less oil-dependent source of power more attractive for owners and operators in terms of cost and budget planning, but also to the better level of reliability and economy attained by electric motors [1,2], as well as to the improved comfort generated by less noisy electric motors with respect to internal combustion engines (ICE) [3].

Nowadays, electric motors are generally more reliable than internal combustion engines (ICE), and their efficiency in converting stored energy into mechanical energy is much higher by constitution. The main limit to the usability of the electric alternative for propulsion has been bound to the limits of energy storage systems, i.e. batteries, which especially for aircraft did not offer until recently sufficient energy-to-mass and energy-to-volume densities [4] to be accommodated on board an aircraft without a relevant negative impact on payload or aircraft size. Today, as a result of many research efforts towards the improvement of such performance indices, it is possible to design and fly an electrically propelled aircraft, as testified by some existing examples, both prototypical and production models, in the categories of ultra-light and general aviation [5].

Among the factors limiting the diffusion of the existing models of electric aircraft is their relatively high production cost, which will be only recursively lowered by the spreading of this technology, through know-how consolidation and scale economy effects. Also the cold perception by the potential customers plays a role in the lingering diffusion of such systems. Especially private pilots and flight training organization tend to be very cautious with re-

* Corresponding author. Fax: +39 02 2399 8334.
*E-mail addresses:* carlo.riboldi@polimi.it (C.E.D. Riboldi), federico.gualdoni@polimi.it (F. Gualdoni).

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**Nomenclature**

| | | | |
|---|---|---|---|
| $AR$ | Aspect ratio | $T$ | Time of flight |
| $C_{AC}$ | Purchase cost of aircraft | $TTC$ | Time to climb |
| $C_{\text{bat}}$ | Cost of batteries | $USD$ | United States Dollars |
| $C_D$ | Drag coefficient | $W_{\text{bat}}$ | Battery weight |
| $C_L$ | Lift coefficient | $W_e$ | Empty weight |
| $E_{\text{bat}}$ | Energy of batteries | $W_m$ | Motor weight |
| $E_{\text{r}}$ | Energy required (propulsive) | $W_{pl}$ | Payload weight |
| $FAR$ | Federal Aviation Regulations | $W_{to}$ | Take-off weight |
| $ICE$ | Internal combustion engine | $e$ | Battery-specific energy, Oswald coefficient |
| $J^{\text{acro}}$ | Merit function for acrobatic class | $g$ | Gravitational acceleration |
| $J^{\text{tour}}$ | Merit function for touristic class | $h$ | Altitude |
| $K$ | Drag-due-to-lift polar coefficient | $p$ | Battery-specific power |
| $P_{\text{bat}}$ | Battery power | $q_C, q_R, q_{RC}$ | Optimization weights |
| $P_{\text{m}}$ | Power of electric motor | $\gamma$ | Climb angle |
| $P_r$ | Power required (propulsive) | $\eta_P$ | Propeller efficiency |
| $P_{SL}$ | Power required at sea level | $\lambda$ | Energy-specific cost of batteries |
| $R$ | Range of flight | $\xi$ | Power loss coefficient |
| $RC$ | Rate of climb | $\rho$ | Density of air |
| $S$ | Wing reference surface | $\tau$ | Power ratio |
| $SMP$ | Sizing matrix plot | | |

spect to radically new technologies and prototype aircraft, when it comes to risking a relevant capital.

Also on the side of researchers and designers, the tendency to treat electric aircraft as prototypes is testified by the lack of literature illustrating a common framework for preliminarily designing such aircraft, which in most cases are obtained through a modification of existing machines, originally gliders or ICE-propelled designs. This is also due to some peculiar features of electric aircraft, requiring an analysis of the design point which will not be limited to those variables – basically empty and take-off weights, wing loading and power loading – usually considered for sizing a traditionally propelled aircraft. Some works exist in the literature about the similar issue of the sizing of hybrid propulsion aircraft [6,7], but the futuristic assumptions concerning the performance of batteries and motors typically made in such analyses does not allow to consider these works for an immediate practical outcome. Some more realistic past research efforts are focused on parametric studies for all-electric designs, starting from a design point which is already well characterized, and from well proven data concerning the power-plant and the general sizing of the aircraft obtained from an existing testbed [8,9]. Being based on precise measurements from an assigned aircraft example, these works do not present methods sufficiently general to allow application to a generic aircraft with given desired specifications. Another part of the literature on all-electric aircraft is devoted to the design and optimization of sub-systems on an assigned testbed, hence it is more centered on a later stage of the design, where the design point for the aircraft has been already determined [10]. Very little exists about the preliminary design of electric aircraft with respect to assigned mission requirements, trying to bend the procedures typically adopted for ICE-propelled aircraft to this new field of aeronautics. The lack of standard best practices among designers and aircraft builders in turn fuels the lack of confidence by customers, leaving the sector of electrically propelled aircraft in a condition of stagnation.

Trying to fill this lack in the existing literature, this script concentrates on the existing technology and introduces a possible simple way to preliminarily size electric aircraft, borrowing much from the preliminary design technique typically studied and implemented for ICE aircraft, but with some substantial modifications. A first fact that was noted is that the few electric aircraft already existing – both prototype and production aircraft – clearly show a statistical correlation on some key design parameters. This fact, that will be suitably documented in the present paper, suggests a design approach starting from the statistical analysis of what has been done up to the present time. Subsequently, in the proposed sizing procedure, differently from the well-known procedures for non-electric aircraft where the analysis of the sizing matrix and the sizing of the aircraft weights are basically independent processes, these two areas of the design are intimately linked for the case of electric aircraft, due to the peculiar construction of the mission-specific correlation between weights for such design case. This yields and integrated procedure for sizing the new aircraft, where weights, wing loading and power loading influence each other, hence they need to be sized together.

In a first stage, the paper presents a statistical database of existing electric aircraft types and illustrates the sizing procedure at a theoretical level. In a subsequent section two examples of quantitative analyses are presented, showing the ability of the procedure to produce designs matching acceptable requirements typical to existing aircraft in the same weight class, thus proving its significance. In a final stage, it will be shown again through practical examples how the design method bends itself to an optimal analysis, thus making the potentially complex scenario of integrated design easier to deal with by means of a computationally-intensive approach. Finally, the approach and the results are recalled and critically discussed in the paragraph devoted to the conclusions.

## 2. Preliminary sizing of electric aircraft

### 2.1. Database of existing aircraft

Similarly to what is usually done for the preliminary sizing of ICE aircraft [11,12], also for electric aircraft it is possible to set up a statistical analysis of the values assumed by some key parameters for some designs already existing. To this aim, in a first stage of the research the characteristics of some such aircraft have been collected and analyzed. The fact that an aircraft has been flown and the completeness of the available data on the electric plant have been considered as criteria for the inclusion of a model in the database.

Table 1 presents the values of some key construction parameters for the aircraft included in the database. For the sake of clarity,

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