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A new approach to calculating endurance in electric flight and comparing fuel cells and batteries

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HIGHLIGHTS

- Gross endurance of an UAV calculated with literature correlations.
- Net endurance calculated with an innovative mission-based approach.
- Three state-of-the-art battery technologies compared to a PEM fuel cell.
- Analysis with different values of energy stored on board.
- Effect of powertrain mass and volume of aircraft empty mass and wing area.

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ABSTRACT

Electric flight is of increasing interest in order to reduce emissions of pollution and greenhouse gases in the aviation field in particular when the takeoff mass is low, as in the case of lightweight cargo transport or remotely controlled drones.

The present investigation addresses two key issues in electric flight, namely the correct calculation of the endurance and the comparison between batteries and fuel cells, with a mission-based approach. As a test case, a light Unmanned Aerial Vehicle (UAV) powered exclusively by a Polymer Electrolyte Membrane fuel cell with a gaseous hydrogen tank was compared with the same aircraft powered by different kinds of Lithium batteries sized to match the energy stored in the hydrogen tank. The mass and the volume of each powertrain were calculated with literature data about existing technologies for propellers, motors, batteries and fuel cells. The empty mass and the wing area of the UAV were amended with the mass of the proposed powertrain to explore the range of application of the proposed technologies.

To evaluate the efficiency of the whole powertrain a simulation software was used instead of considering only level flight. This software allowed an in-depth analysis on the efficiency of all sub-systems along the flight. The secondary demand of power for auxiliaries was taken into account along with the propulsive power.

The main parameter for the comparison was the endurance but the takeoff performance, the volume of the powertrain and the environmental impact were also taken into account. The battery-based powertrain was found to be the most suitable for low-energy applications while the fuel cell performed better when increasing the amount of energy stored on board. The investigation allowed the estimation of the threshold above which the fuel cell based powertrain becomes the best solution for the UAV.

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1. Introduction

The reduction of pollutants and greenhouse gases emissions from aircraft is a topic of increasing interest. Even if air travel accounts for 2% of global CO_2 emissions, this proportion is set to grow in the future [1]. The industry is reliant on a selection of measures to contribute to reduce emissions [2,3] amongst which is the increased use of electricity.

Battery based and fuel-cell powertrains are used either as auxiliary power units for aircraft or as an electric propulsion system, for small Unmanned Aerial Vehicles (UAVs) [4,5]. Unmanned aircraft are used in a variety of military, homeland security, and

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civilian applications. Electric propulsion is preferred for its advantages: quiet operation, higher safety, precise power management and control.

Recently, a certain number of fuel-cell powered small unmanned UAVs and transport airplanes have been tested [6–9]. Hydrogen is a clean-burning fuel that produces heat and electricity if combined with oxygen with only water vapor as a by-product (from a tank-to-wing point of view). However, hydrogen is not an energy source but an energy carrier obtained by other sources of energy, such as reforming natural gas or by water electrolysis. Indirect pollution and greenhouse gas emissions should be carefully evaluated [10] to assess the well-to-wing environmental impact of hydrogen aircraft. Fuel cell systems are able to guarantee high specific energy as well as high efficiency and so they prove to be convenient in some aeronautical applications [11].

Several types of fuel cells with different electrolytes can be used to power aircraft and they can require compressed or liquefied hydrogen. Polymer Electrolyte Membrane (PEM) fuel cells are the most commonly used and are appropriate for the application to UAV owing to their small size and their light weight [12–18,8,19,20]. For this reason they were chosen the test case considered in the present investigation to explain the proposed procedure.

Most studies on fuel cells applied to aircraft are exclusively conceptual. Only few works considers the usage of fuel cells on light or ultra-light aircraft [15–18,8,19,20] where battery-based powertrains are usually preferred. However, batteries have many drawbacks, the main being the limited values of power and energy density, that is the power and energy per unit mass and volume. These aspects discourage the use of batteries in heavier aircraft. In addition, the capacity and the life time of batteries are affected by many factors like discharge and recharge currents and operating temperature [19]. New battery technologies are under development but the present investigation focuses on Lithium batteries because they are the most commonly used for electric powered aircraft, are mass produced and readily available [21]. Battery-based powertrains also allow zero emissions from tank-to-wing point of view and, in addition, avoid the emission of water vapor in the atmosphere.

Recently, some efforts have been dedicated to the comparison between the two available technologies (batteries and fuel cells) for electric flight [22–24]. The comparison requires a correct estimation of electric endurance and must take into account the amount of energy stored on board. Note that the battery system stores energy in form of electricity while in the case of PEM fuel cells, energy is stored in form of compressed gaseous fuel.

For conventional powertrains, thermal engines burning liquid fossil fuels, the amount of energy on board is not a key issue because of the very high gravimetric and volumetric density of liquid fuel [21]. For these systems the endurance is usually evaluated in conditions of level flight using the well-known Breguet formulas [25].

Breguet formulas can be used for fuel cell-based powertrain but not for the battery-based one, because the dependence of battery capacity on the discharge current makes it difficult to establish the actual energy available during the flight. Moreover, the concept of overall efficiency is meaningless because of the complexity of the charge/discharge processes.

Traub [26] proposed a formula to evaluate the endurance of battery-based powertrains in level flight that was corrected and validated experimentally in [27]. Another correction was proposed by Avanzini and Giulietti [28] that underlined the increasing of the battery during level flight to compensate the reduction of voltage.

In the present investigation, a new approach is proposed to evaluate the efficiency of an electric aircraft. This approach is derived from the automotive field where it is a common practice to compare different drive trains on the same driving cycle [29], i.e. a series of data points representing the speed of a vehicle versus time. To apply the method to the aircraft field, a "mission" is defined as a series of data points representing the speed and the altitude of the aircraft versus time. At any point, the efficiency is evaluated by using detailed models for each powertrain subsystem. In particular, an efficiency map is used for the propeller while the fuel cell and the batteries are simulated with electrical equivalent circuit network models, that are characterized by simplicity, speed and acceptable accuracy [30,31].

The endurance calculated at level flight will be henceforward referred to as Gross Endurance (GE) while the terms Net Endurance (NE) will be used for the endurance evaluated with the proposed method.

The investigation consists of three parts. The first describes the proposed mission-based approach. In the second part the Gross and Net Endurances of a battery-based and a fuel-cell based UAV are analyzed over two different missions with an initial content of energy on-board of about 2 MJ. The takeoff performance and the environmental impact of the proposed powertrains was also taken into account.

In the third part of the investigation, the energy on board is increased up to five times the initial value and the gross endurance is used to define a threshold above which the fuel cell based powertrain becomes the best solution for the electric UAV.

2. Specification of the UAV and modeling approach

In the present investigation the authors considered, as test case, a small and light UAV whose specifications were derived from literature [20] and reported in Table 1.

Two virtual powertrain were considered (see Fig. 1). The propeller and the electric motor were assumed to be the same for both cases.

The propeller considered in the present investigation is a 22×10 APC E. The mass of the propeller is 169 g [32] and its speed was set equal to 3000 rpm in the simulations. The efficiency was calculated with a performance map as explained later.

For the aim of selecting an electric motor for the aircraft, the authors made use of *Drive Calculator 3.4*, an on-line tool to match motors and propellers [33]. Among the several electric motors compatible with the propeller, the Hacker C50-10 L Acro Competition brushless motor was chosen because of its low weight, small size and long life [34]. The selected electric motor has a mass of only 423 g, including the gearbox. It was equipped with a Spin Master 125-opto controller whose mass is 160 g. The Spin Master 125-opto controller needs an operating voltage from 12 V to 50 V and it is directly connected to the motor in order to provide the required current and voltage.

This gear is incorporated into the Hacker motor C50-10 L Acro Competition and it assures a 6.7:1 reduction between the motor axis and the propeller axis [34].

Table 1
Specification of the aircraft [20].

Aircraft specifications	Value
Wing area (dm^2)	188
Aspect ratio	23
Wing span (m)	6.58
Tail area (dm^2)	45.5
Length from nose to tail (m)	2.38
Static thrust/weight	0.165
Wing airfoil	SD-7032
Airframe mass (kg)	7.4

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