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Performance of a hybrid, fuel-cell-based power system during simulated small unmanned aircraft missions

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ABSTRACT

Hybrid electric, fuel-cell-based power systems can significantly increase the endurance of small unmanned aerial systems (UAS) in comparison with that available from batteries. However, their detailed performance in realistic aircraft missions is relatively unknown, a situation that hinders optimal system selection and integration. This article presents the results of tests with a compact, hybrid fuel-cell/battery power system intended for aerospace applications. Flight simulations representative of surveillance and remote-sensing missions conducted with small UAS were created using the aerodynamic and system characteristics of a notional UAS with a 3.1 m wingspan; and the hybrid-power-system hardware was subjected to power-demand profiles for missions with different cruise speeds and climb rates. The results demonstrate that the performance of the fuel cell can deviate significantly from its steady-state polarisation curve for short periods of time and that careful selection of the mission profile (or inversely, selection of a specific fuel-cell/battery combination for a given mission) can increase overall performance and reduce fuel consumption by up to 3% by exploiting the high efficiency of the fuel cell at part-load.

Introduction

Small, electrically-powered unmanned aerial systems (UAS) are increasingly platforms of choice for remote-sensing and reconnaissance missions [1]. Electric propulsion offers the advantages of low cost, high efficiency and reliability, as well as low noise and infrared signatures compared with piston engines [1,2]. However, conventional electrically powered systems are impaired by the comparatively low energy density of current batteries, which limits the mission endurance and hence potential utility of the UAS [3,4].

In contrast, fuel cell systems typically have a considerably higher energy density than do batteries and thus offer the

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Nomenclature

PEMFC	Proton-exchange-membrane fuel cell
UAS	Unmanned aerial system(s)

prospect of greatly improved UAS mission endurance [4]. Yet, fuel cells can suffer from a low power density and slow dynamic response [5]. Furthermore, rapid load changes can result in reactant starvation and membrane dehydration, especially for a fuel cell system without a humidifier [6]. The design of non-humidified fuel cell systems is complicated by the need to balance the fuel cell's temperature, humidity and stoichiometry by controlling the air flow through the system [7]. To overcome these drawbacks and increase the flexibility of the power-system design, a hybrid system may be created by coupling a fuel cell with a secondary, fast-acting boost-power source such as a battery or super-capacitor [5]. Hybrid systems exploit the advantages of both power sources, thereby creating a highly responsive system having a high power density, while maintaining a significant energy-density advantage over batteries alone [8]. However, the complex, dynamic interaction of subsystems and the power management of the hybrid system present integration challenges.

The potential advantages of fuel cells have led to abundant research on their design for aircraft propulsion and integration into aircraft [2–5,9–20], although the literature on fuel-cell-powered hybrid-electric aircraft typically presents only limited flight-test results with minimal evaluation of the performance of the propulsion system. All reported fuel-cell-powered flight tests consist of a high-powered climb, followed by a cruising or loitering flight phase at medium to low power, and descent at minimal power [2,4,11,14–16]. In-depth investigations of fuel-cell-based, hybrid propulsion systems are scarce [19,21]; and no detailed experimental characterisation of the mission performance of a fuel-cell hybrid propulsive system has been undertaken, though this is crucial to fully understand the operation of the system and ensure optimal integration.

This paper aims to address this gap and presents, for the first time, the mission performance of a hybrid power system designed for use in small UAS and built around a proton-exchange-membrane fuel cell (PEMFC). Subjecting the physical hardware of the hybrid power system to power-demand profiles simulating actual missions with small, fixed-wing UAS permits the in-depth characterisation of the subsystems without integration into an aircraft and can thus reveal characteristics that are difficult to accurately model [17,22]. Mission simulation also allows a controlled test environment and the use of data-acquisition hardware that is not flight-worthy [17]. Here the commercial-off-the-shelf AeroStack fuel-cell-based, hybrid power system is subjected to a power-demand profile that includes climb, cruise, loiter, descent, taxi, and idle phases sequenced to be representative of intelligence, surveillance, and reconnaissance applications [17,23]. Its performance for different climbing and cruising profiles is evaluated under the flight conditions of a notional UAS. For all presented results, an existing experimental setup is used [12,18]; and data is sampled at 10 Hz, which is sufficient to capture the relevant transients [17]. A block diagram showing the mission-simulation procedure is provided in Fig. 1.

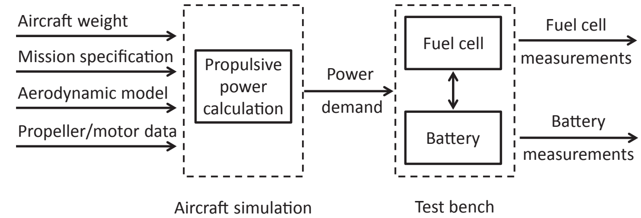

Fig. 1 – Mission-simulation block diagram.

Notional UAS and baseline mission

For the tests presented here, the propulsive requirements are derived for a notional UAS design that was sized to fit the AeroStack fuel-cell system. This vehicle is shown in Fig. 2. The fuselage was sized so that its volume was sufficient to fit the fuel-cell/battery unit together with its fuel cartridge. A tank was incorporated into the design to collect waste from the fuel cartridge. Additionally, room was provided for the avionics, payload, and the electric motor used to drive the propeller. The airframe and avionics have a mass of 2.84 kg, while the fuel-cell/battery system has a mass of 2.23 kg. A 0.25 kg payload is assumed to be integrated into the aircraft, which has an overall mass of 5.32 kg.

A medium aspect ratio wing was selected to minimise the lift-induced drag and provide good flight performance. The wing span is 3.1 m with an aspect ratio of 14.4, providing a wing loading of approximately 78 N/m^2. The aircraft design incorporates an all moving horizontal tail to provide pitch control. This is attached to a fixed vertical fin connected to the main fuselage by an elliptical tail boom. Roll and yaw control is achieved through the deflection of flaperons located on the trailing edge of the main wing. The length of the tail boom was chosen to ensure the aircraft was static stable in pitch with the horizontal tail providing effective control. The overall length of the aircraft is 1.25 m.

The aerodynamic properties of the aircraft were computed using the USAF's Digital Datcom program [24]. The aircraft's lift to drag ratio in cruise is approximately 20.5, which is comparable to high-performance RC gliders of a similar size [25,26]. A twin-blade CAMCarbon 12 × 8 (inch) propeller, driven by a Hacker B50-25XL brushless DC motor, was chosen for the propulsion system due to the availability of experimental data detailing the combination's propulsive performance [27].

The power required from the fuel cell for the different missions analysed in this paper has been calculated using the aerodynamic and propulsive characteristics of this notional aircraft. Trimmed cruise and climbing flight power demands were calculated at different airspeeds and throttle conditions (using a simulation). A polynomial fit was applied to the data allowing alternate flight conditions to be analysed, as well as simplify the test set-up. An example of the calculated cruise