SIZING AND PERFORMANCE OF HYDROGEN-DRIVEN AIRPLANES

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ABSTRACT

A new, general methodology for the sizing of fuel cell-based hybrid-electric aircraft powertrain is illustrated. The method is based on an accurate physical model of the fuel cell module, integrated within a procedure that, given aircraft and mission parameters, estimates the corresponding sizing and performance. The method is validated vs. a real flying prototype, the Hy4. This can be used in the design of conversions of existing aircraft to battery and fuel-cell powertrains, as well as in the preliminary sizing of new propeller-driven air vehicles of arbitrary weight category. The results of the powertrain sizing for the conversion of two existing aircraft in the General Aviation category are presented, in connection to realistic values of the performance of electric motor, fuel cell, battery, and storage technologies involved.

Keywords: fuel cell aircraft, zero-emission flight, electric airplane

1 INTRODUCTION

In the current quest for viable technologies with the potential of reducing the local and global environmental impact of aviation, the electrification of the powertrain plays a major role. A special type of electric aircraft is that employing hydrogen Fuel Cells (FC), with the possible addition of batteries, as a source of motive power for sustaining flight. Such an aircraft grants zero chemical emissions in all phases of flight, an exceptional feature that may significantly contribute to environmental sustainability, if application to segments of the future commercial aviation proves feasible.

In order to consider such an application, it is mandatory to analyse the potential of this technology in the framework of aircraft conceptual design, to identify strengths and weaknesses, estimate advantages and anticipate possible drawbacks and limitations. This clearly needs adequately modelling of the novel powertrain and, concurrently, the ability to integrate it within a general aircraft design process, starting with the preliminary sizing loop and the performance evaluation

A natural, preparatory step towards the goal of designing an aircraft from scratch, according to given mission requirements and other applicable specifications, is represented by designing the retrofit of an existing aircraft with the new powertrain. This basically involves keeping the airframe structure unchanged and coping with the need of restraining the maximum take-off mass (MTOM) at the original design value.

Previous works related to the few prototypal examples that have already flown lack an approach in general terms to the topic, as they typically focus on the design and integration of a single product. The first FC manned aircraft, first flown in 2008, was a HK36 Superdimona motor-glider from Diamond, retrofitted with a “hybrid” gaseous H_2 fuel cell system, *i.e.* a system where batteries are also present to boost high-power phases such as take-off and climb [1]. Other significant examples are the Antares DLR-H2 project [2], another heavily retrofitted motorglider that flew on fuel cells alone, starting in 2009, and the Rapid 200-FC [3], an ultralight 2-seater aircraft empowered by gaseous H_2 and batteries, first flown in 2010. In the previously cited works, which are limited to very light and high lift-to-drag-ratio aircraft with no significant payload, several details are disclosed, but no general method for the sizing of the powertrain is provided.

Therefore, the present work aims at contributing to the development of sizing and performance analysis procedures applicable to aircraft of arbitrary category, departing the motor-glider and ultralight segments, in order to allow the study of higher weight vehicles that may enable air transportation in the future.

In particular, this work concerns activities framed in the MAHEPA project (Modular Approach to Hybrid-Electric Propulsion Architecture), a Horizon 2020 EU-funded activity developing new more sustainable powertrain architectures for aviation [4]. Two hybrid-electric (HE) aircraft are currently under development within this project: the Pipistrel Panthera Hybrid and the Pipistrel/DLR Hy4. The former is a HE version of the Panthera 4-seater, with a serial powertrain composed by an Internal Combustion Engine (ICE) coupled with an electric generator, an Electric Motor (EM) driving the propeller, and a Battery Pack (BP). The latter is the evolution of the NASA Green Flight Challenge winner, the dual-fuselage Pipistrel Taurus G4, featuring a propulsion architecture combining a BP and FC running on gaseous H_2 empowering a EM that drives the single propeller placed in the inner wing. The Hy4 made its maiden flight in 2016 and is currently being upgraded to fly on the new MAHEPA powertrain in 2020 [5].

2 FUEL CELL SYSTEM MODELLING

Among the possible solutions to the need to extend the limited range and endurance of a pure-electric aircraft empowered by batteries only, the option of integrating an on-board power generation through a H_2-processing FC power module (FCPM) is extremely appealing for its zero-chemical-emission ability in flight. Indeed, a filled H_2 tank, although relatively bulky and heavy, has a higher energy density with respect to current Li-ion batteries [6,7]. Nevertheless, the presence of a BP is justified by several reasons, including the fact that it is more convenient during high-power flight phases and during fast transient phases, because of its faster reaction to changing power loading. Therefore, we consider a “hybrid” BP+FC-based powertrain configuration as shown in Figure 1. It should be noted that a FC is not an energy storage system, but it is an energy conversion system. Energy is stored in an external tank, which contains the fuel, i.e. hydrogen. This is different from batteries, where the system behaves as energy storage system and energy conversion system at the same time.

The considered FC type is the Proton Exchange Membrane (PEM), which is the most suited for transport application. Hydrogen is assumed to be stored in gaseous form in high pressure tanks, while the air flow necessary to the redox reaction may be compressed using a compressor, which acts as an auxiliary system, or not.

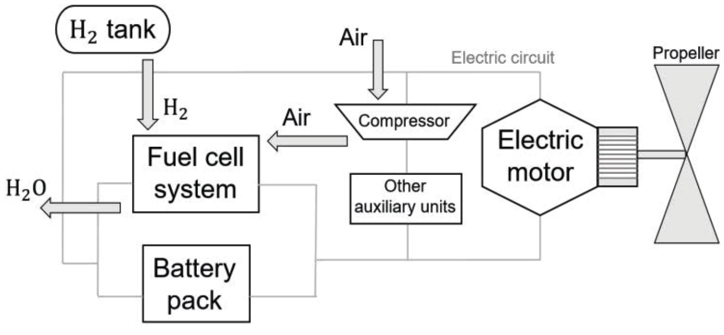

Figure 1. Powertrain scheme.

The proposed modelling of the FC system is based on its inner physics and specifically on the polarization curve that relates current density input to the voltage output [8]. The FCPM is composed by several elementary cells connected in order to achieve the required power, through the product of output current and voltage. These two parameters can be varied by connecting the total number of cells in different ways. Specifically, by connecting cells in series, the total voltage is the sum of the voltage of each cell, and a new sub-system, called stack, is obtained. Connecting multiple stacks in parallel, the total current is the sum of the current flowing in each stack.

3 POWERTRAIN SIZING AND PERFORMANCE

The model the BP+FC-based powertrain introduced above can be integrated within a general aircraft performance analysis framework, in order to derive flight performance estimations related to a given powertrain sizing, as well as powertrain sizing data when performance are set. Indeed, the inherent modular character of the FCPM model discussed above is perfectly suited to a general approach to powertrain sizing based on mission and other aircraft requirements. In this way, the development of a preliminary sizing methodology fit for the conceptual design of hydrogen-based aircraft can be achieved. Modularity means that each procedure and component considered are scalable, so that, in principle, aircraft belonging to any weight category may be considered.

This methodology has been implemented in a software tool called Flycell, within a Matlab® environment. Flycell allows considering an arbitrary fixed-wing aircraft, described through its main design parameters and a specified mission. The design parameters include payload, wing surface and aspect ratio, aerodynamic polar, airframe mass. The reference mission is composed of various phases such as take-off, climb to cruising altitude, cruise, descent, loiter, approach, and landing, each described through adequate prescriptions for airspeed, rate of climb or descent, altitude. In addition, a BP+FC-based powertrain model is included, described by battery properties (type, mass, specific power, specific energy), FCPM properties (type, mass, FC area, operating conditions – pressure, temperature, density –, specific power output), and H2 tank properties (mass, operating pressure).

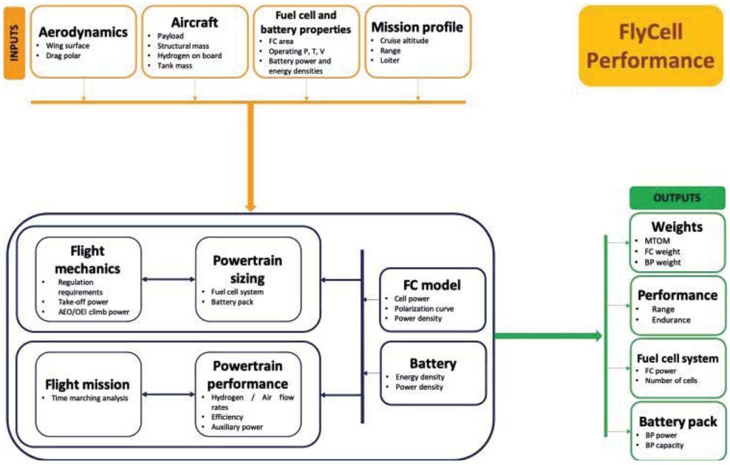

Figure 2. Flycell/Performance block diagram.

The code has been developed in two versions according to two different approaches:

- Flycell/Performance is a performance evaluation code. Here, the stored hydrogen and the battery capacity are inputs. In output, the complete powertrain sizing (output power, number of FC and stacks, battery size, powertrain masses) and the range and endurance performance are provided for a given aircraft and a given mission.
- Flycell/Sizing is a pure sizing code. Here, the target range is an input. In output, the complete powertrain sizing (output power, number of fuel cells and stacks, battery size, powertrain masses), as well as the energy storage system sizing (hydrogen to be stored, tank mass, and battery capacity) are provided for a given aircraft and a given mission.

Both the performance code and the sizing code are based on six main functions, inter-related using both direct and iterative computations, concerning the flight mission and the sizing and usage of the powertrain. Figure 2 shows the functional diagram of the Performance version.

4 NUMERICAL STUDIES

4.1 Validation

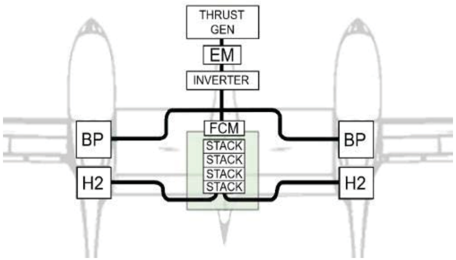

Figure 3. Hy4 powertrain layout.

In order to validate the proposed methodology, a study devoted to the already-flying hydrogen-driven aircraft involved in the MAHEPA project, the Pipistrel/DLR Hy4, was carried out. The general arrangement of the Hy4 powertrain is shown in Figure 3, with H_2 tanks and batteries positioned in the fuselages, while the FCPM is placed right behind the EM in the central nacelle.

The considered flight mission profile is a simplified one, composed by five phases: take-off, climb at constant Equivalent Air Speed (TAS), cruise at constant EAS, descent at constant EAS, and landing. The energy management during the mission calls for the exploitation of the BP at maximum power output in take-off and climb, up to full discharge. The FC system is sized for cruising power requirement plus a 15% safety margin. The H_2 tank is sized in order to provide the energy required for the total mission, save for the energy delivered by the BP up to full discharge. The value used for the H_2 storage efficiency, which refers to the ratio between the mass of hydrogen stored and the tank mass, is 5.7%. This is relative to the current state of the art of Composite Overwrapped Pressure Vessel (COPV). The most used H_2 storage method for transport application is compression, and the improvement of that ratio is crucial in aviation, in which the subsystems masses are relevant design parameters.

Electric motors mass	−3.0%
FC system mass	−0.2%
Hydrogen mass	+12.6%
Tank mass	+6.2%
BP mass	+1.1%
Aircraft MTOM	+1.4%

Table 1. Hy4 mass breakdown validation.

The validation of the code in both versions returns very good results with respect to the real aircraft data, as seen in Table 1, which details the errors in the mass breakdown for the case of sizing for 1,000 km range. The achievement of such a high performance is clearly related to the quasi-glider aerodynamics of this special vehicle. The values considered for battery specific power and energy are 800 W/kg and 200 W·h/kg, while FC specific power is 370 W/kg, which represent fairly conservative values with respect to cutting-edge technology. Structural and payload masses are known input data. Most of the mass components appear very well captured, with higher approximation in the value of hydrogen-related quantities. It is remarked that the total H_2 mass stored on board amounts to less than 1% of the MTOM.

4.2 Applications to powertrain conversions

The described powertrain sizing approach has been applied to a preliminary study of the powertrain conversion of existing aircraft. This means that the original conventional ICE-based is assumed to be substituted by a novel BP+FC-based powertrain, while the airframe is unchanged. This approach was extended to several existing propeller-driven airplanes across a wide range of categories. Hereafter, we shall present some results obtained for two specific models in the General Aviation (GA) segment: a 4-seater and an 8-seater.

The interest in the former is motivated by the general perception that the transition to more environmentally-friendly aircraft shall start from the low-end of the weight (and complexity) product range. Smaller airplanes shall achieve future certification requirements and reach the market more easily and quickly than larger ones. Also, the design of a hydrogen-driven 4-seater may be contrasted with those using other propulsive architectures, such as the Panthera Hybrid also under advanced development within the MAHEPA project.

The case of the 8-seater is of interest as well, as this type of aircraft may fulfil the role of a "microfeeder", *i.e.* a small liner intended to operate from a diffuse network of small airports and even airstrips in order to feed passengers to and fro regularly scheduled flights at major airports. This concept, recently explored in [9], is of primary concern in the research carried out in the MAHEPA project, as a possible key component in the future development of a more connected transportation network. Europe's vision for future aviation, as presented in the Flightpath 2050 document [10], calls for an air transportation system capable of moving people from any European location to any other in less than four hours, door to door. To do that, a novel class of short-haul airliners is crucial to connect smaller cities and open country territories to major airports, capable to provide a significant reduction in total pollution at the same time.

The Flycell/Performance tool was applied to the study of the possible retrofit with a BP+FC-based powertrain with battery specific power and energy values of 1,550 W/kg and 186 W·h/kg, and FC specific power of 650 W/kg. A flight profile similar to that adopted for the Hy4 was adopted, using airspeed, rate of climb, and altitude values consistent with the existing aircraft published data, plus the provision of a 45 min loiter phase before final approach and landing. This is required by currently enforced GA regulations and is considered here in order to derive realistic information about the actual market capabilities of converted airplanes.

The criterion for the sizing of the FCPM and BP is based on the following considerations: (a) the FC system is first sized to provide cruise power; (b) the BP is sized to provide the power boost, defined here as the extra contribution needed to fulfil maximum power conditions, *i.e.* take-off and climb; (c) the BP mass is increased to provide the boost energy needed to complete take-off and climb, in case the sizing-to-power does not allow that; (d) after climb is completed, the positive residual BP energy in the sizing-to-power case is used up to full discharge at a given rating, here chosen as the ratio between the BP power value and the sum of FC and BP power values. In-flight battery recharge is not considered.

The analysis was carried out by exploring a wide design space for the masses of BP and FCPM which, added to the airframe mass, led to a significant variation in MTOM. As power required for flight strongly depends on the gross mass of the vehicle, this clearly has a strong impact on performance. Given the significant increase in powertrain mass when switching from an ICE-based to a BP+FC-based one at equal power output (*i.e.* shaft-power transferred to the propeller), a significant drop in performance is to be expected.

In order to appreciate the global performance capability of the retrofitted aircraft, results are shown in terms of payload-range diagrams parameterized by MTOM. Clearly, as the original airframe mass is kept constant during computations, only the payload-range pairs corresponding to MTOM values close to the original value for the existing aircraft represent feasible design points for a possible retrofit. Points characterized by higher MTOM values are unfeasible, since the higher all-up mass would necessarily impose a resizing of the airframe in order to withstand the corresponding airloads.

4.3 Cessna 172 Skyhawk

The 4-seat Cessna 172 is the most famous trainer airplane in the world and the most produced aircraft ever as well [11]. For this reason, it was chosen to represent the light GA class in the present study. Published specifications considered here include a MTOM slightly over 1,100 kg, a structural mass of 632 kg, a cruising speed of 125 KEAS, and a range of 959 km with a payload of 258 kg (pilot included). Installed power amounts to 120 kW, provided by a Lycoming IO-360-L2A reciprocating engine.

The payload-range diagram depicted in Figure 4 clearly shows the expected drop in performance when the curve corresponding to the original MTOM is considered (red line). This curve joins a point with 77% of the original payload at a range up to the sum of the distance

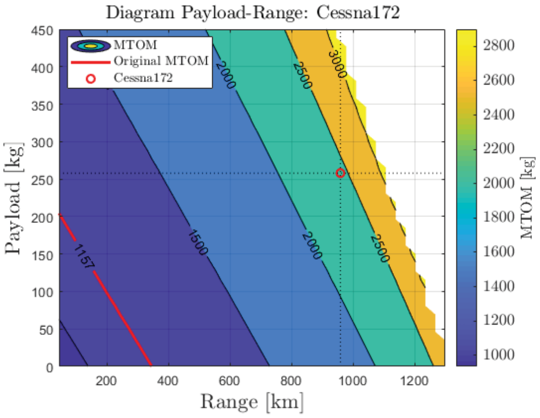

Figure 4. C172 payload-range diagram.

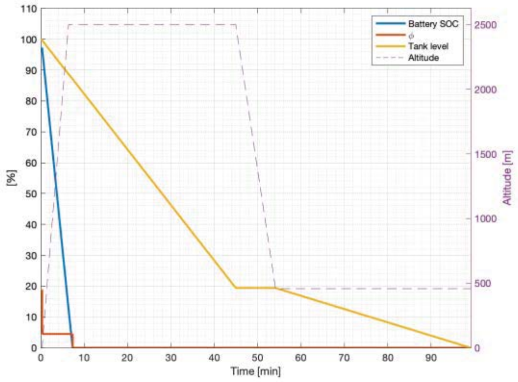

Figure 5. C172 mission energy and power.

covered in climb and descent to a point for which the 37% of the original range is reached at null payload. The original performance combination (red circle) lies far away from what is achievable with a pure retrofit, *i.e.* without redesigning the airframe.

Figure 5 shows the time histories of the battery state of charge (SOC, blue line), percentage of power required delivered by the BP (red line), and H_2 tank level (yellow line) for the sizing mission corresponding to an intermediate point in the red line of Figure 4, the one corresponding to a payload of 99 kg and a range of 201 km. The altitude profile is shown as well. For this case, the powertrain is sized as seen in Table 2, and the resulting mass breakdown is seen in Table 3.

FC system	
Output power	154 kW
No. of cells in series per stack	224
No. of stacks in parallel	4
Total no. of cells	896
BP	
Output power	7.1 kW
Capacity	4.3 Ah

Table 2. C172 powertrain sizing.

Structural mass	632.3 kg
Electric motors mass	21.8 kg
FC system mass	236.2 kg
H_2 mass	8.2 kg
H_2 tank mass	155.0 kg
BP mass	4.6 kg
Payload mass	99.0 kg
Aircraft MTOM	1,157.2 kg

Table 3. C172 mass breakdown.

4.4 Tecnam P2012 Traveller

The Tecnam P2012 is an 11-passengers (crew included), high wing, double engine aircraft that made its maiden flight in 2016. This is a modern and performing aircraft that well represent the class fulfilling the role of a microfeeder [12]. Published specifications include a MTOM of 3,600 kg, a structural mass of 1,748 kg, a cruising speed of 148 KEAS, and a range of 1,333 km with a payload of 774 kg (pilot included). Installed power amounts to 560 kW, provided by two Lycoming TEO-540-C1A reciprocating engines.

The payload-range diagram depicted in Figure 6 clearly shows the expected drop in performance when the curve corresponding to the original MTOM is considered (red line). This curve joins a point with 80% of the original payload at a range up to the sum of the distance covered in climb and descent to a point for which the 44% of the original range is reached at null payload. In this case, the original performance combination (red circle) lies even farther away from what is achievable with a BP+FC conversion.

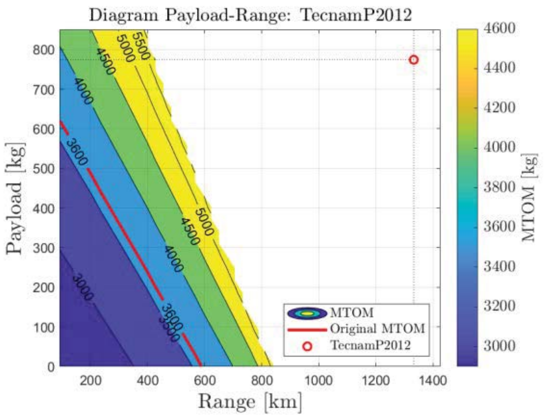

Figure 6. P2012 payload-range diagram.

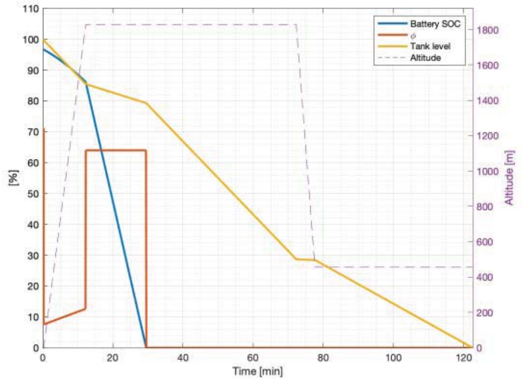

Figure 7. P2012 mission energy and power.

Figure 7 shows the time histories of the battery SOC (blue line), percentage of power required delivered by the BP (red line), and H_2 tank level (yellow line) for the sizing mission corresponding to an intermediate point in the red line of Figure 6, the one corresponding to a payload of 350 kg and a range of 300 km, together with the altitude profile. For this case, the powertrain is sized as seen in Table 4, and the resulting mass breakdown is shown in Table 5.

FC system	
Output power	328 kW
No. of cells in series per stack	266
No. of stacks in parallel	6
Total no. of cells	1,596
BP	
Output power	583 kW
Capacity	280 Ah

Table 4. P2012 powertrain sizing.

Structural mass	1,748.0 kg
Electric motors mass	85.0 kg
FC system mass	503.8 kg
H_2 mass	26.6 kg
H_2 tank mass	501.8 kg
BP mass	376.0 kg
Payload mass	350.0 kg
Aircraft MTOM	3,591.2 kg

Table 5. P2012 mass breakdown.

4.5 Discussion

In the cases presented, the conversion to a BP+FC-based powertrain always implies a significant loss in mission performance, leading to the need to reduce both payload and range. This occurs for virtually any HE conversion of existing aircraft, even in the case of ICE hybrid-electric powertrains [13,14], due to the overwhelming superiority of conventional hydrocarbon fuel when compared to other power generation means in terms of specific energy.

In the case of the Cessna 172, based on the obtained results, the converted aircraft may continue to fulfil the trainer role, as a crew of two and a limited range are adequate for the typical mission. The resulting BP is optimally sized according to energy, so that at take-off it provides 20% of the required power, which reduces to 5% in climb, as the climb and cruising power for this airplane are very close. Full discharge is reached at the top of climb.

For the Tecnam P2012, the degradation in mission performance is comparatively more severe, as a single-pilot microfeeder mission is achievable with a fairly limited payload of three passengers only. The optimal BP sizing point is widely different, being related to power instead of energy, due to the large reduction from climbing to cruising power. In fact, the BP provides first over 70% of the take-off power, than a much lower value – around 10% – during climb. Once at cruising altitude, the BP is called to contribute to power required for flight for a share over 60%, using the residual energy, up to full discharge after less than a third of the cruise leg.

5 CONCLUSION

This work contributes to the EU-funded H2020 MAHEPA project, encompassing scalability studies in aircraft design and analysis of future scenarios for GA and regional air transportation by exploiting hybrid-electric aircraft, based on both thermal and fuel-cell systems. A physics-based methodology for sizing a hydrogen-based powertrain has been presented and preliminarily validated. To the best of the authors' knowledge, this seems the first attempt ever made to derive a general, scalable formulation applicable to aircraft of arbitrary category. As the validation results are accurate, in the frame of a conceptual design framework, the developed formulation appears applicable to future design exercises, both for refurbishing legacy aircraft by substituting their native propulsion system with a zero-emission one and for the design of new air vehicles for a more sustainable aviation. A preliminary study regarding the powertrain sizing for two existing General Aviation types shows that, at the current level of technology, performance degradation due to the high weight toll imposed by the BP+FC-based powertrain is significant. Expected improvements in fuel cell and battery technologies may prove highly beneficial, leading to mission performance amelioration in terms of range and payload.

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