A Powertrain Sizing Method for Hydrogen-Driven Aircraft

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A new methodology for the sizing of fuel cell-based hybrid-electric powertrain for aircraft 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, provides an estimation of performance and the sizing of the powertrain. This can be used in the design of hybrid-electric fuel-cell conversions of existing aircraft, as well as in the preliminary sizing of new air vehicles of arbitrary weight category. The results of the powertrain sizing of four aircraft across a passengers range between four and seventy-two are presented, together with a parametric analysis showing the sensitivity of the design point to crucial design parameters.

Nomenclature

BP = Battery Pack
COPV = Composite Overwrapped Pressure Vessel
CR = Commuter Regional
EM = Electric Motor
HE = Hybrid Electric
ICE = Internal Combustion Engine
FCM = Fuel Cell Module
GA = General Aviation
LR = Large Regional
MF = Micro Feeder
MTOW = Maximum Take-Off Weight
PEM = Proton Exchange Membrane
TAS = True Air Speed

I. Introduction

THIS work concerns a contribution to the MAHEPA project (Modular Approach to Hybrid-Electric Propulsion Architecture), a Horizon 2020 EU-funded activity developing new more sustainable powertrain architectures for aviation (Ref. 1). Two hybrid-electric (HE) aircraft are currently under development: the Pipistrel Panthera Hybrid and the Pipistrel/DLR HY4 (Ref. 2). 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 made of Fuel Cells (FC) and a BP empowering a EM that drives the single propeller placed in the inner wing (Figure 1).


Figure 1. Pipistrel/DLR HY4 aircraft.

EM have been identified as the best solution for the improvement in the reduction of pollutants and noise during a typical flight mission. This justifies today's ever-increasing interest in pure-electric and HE air vehicles. A powertrain based on a hydrogen tank and a FC Module (FCM) represents an alternative to batteries for energy storage and power supply to the EM, granting zero chemical emissions in all phases of flight – an amazing feature that may drastically change the environmental impact of future commercial aviation.

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The aim of this work is the development of a methodology for the modelling and performance evaluation of a FC-based aeronautical powertrain, to be used in the conceptual and preliminary design of hydrogen-driven aircraft of arbitrary weight category. This methodology, based on the physical model of the FCM, was eventually implemented in a calculation tool called *Flycell*, to be used both as a standalone procedure or integrated within an aircraft preliminary sizing loop. The present contribution shows the results of a validation exercise and of some applications to HE FC powertrain sizing. A broad range of aircraft categories has been considered, starting with the lighter segments of General Aviation (GA) and reaching up to large regional liners, to assess the feasibility analysis and the possible application of hydrogen technology to aviation. This study is completed with a perturbation analysis in which the main design parameters have been varied in the neighborhood of their reference value in order to highlight the sensitivity of the design solution.

II. Fuel cell powertrain modelling

The HE FC-based powertrain configuration considered is shown in Figure 2 (Ref. 3). Typically, a filled hydrogen tank, although relatively bulky and heavy, has an higher energy density with respect to current Li-ion batteries (Refs. 4 and 5). Therefore, a FC-based solution may grant higher performance, in terms of range and endurance, with respect to pure-electric aircraft based on batteries only (here, we term HE any propulsive architecture that does not rely on BP only – even if the additional power source is not a thermal engine). The presence of the BP is justified by the fact that it helps during high-power flight phases and during fast transient phases, because of its faster reaction to changing power loading.

FC functioning is based on an oxidation-reduction (redox) reaction, that takes place in two separate, but electrically connected, zones, so that electrons can move from anode to cathode. In the first zone, oxidation of the fuel (hydrogen) takes place, producing electrons that move to the oxidizing zone (where oxygen is present). Ions pass through the electrolyte, closing the circuit. Therefore, the physical principle at the basis of the FC is the production of electric energy from the recombination of hydrogen, stored in tanks, and oxygen present in ambient air, producing just water as emission. 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. This is different from batteries, where the system behaves as energy storage system and energy conversion system at the same time.

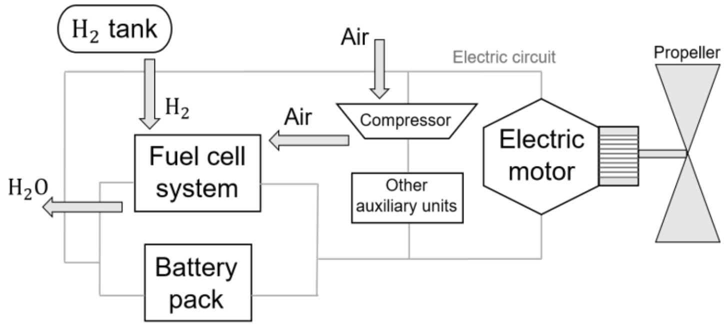

Figure 2. Powertrain scheme.

The considered FC type is the Proton Exchange Membrane (PEM), which is the most suited for transport application. Hydrogen is stored 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.

The modelling of the FC is based on the inner physics and specifically on the polarization curve that relates current density input to the voltage output (Ref. 6). The FCM is composed by several elementary cells connected in a proper way, in order to achieve the required power, i.e. the product of current I and voltage V. 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 (Figure 3).

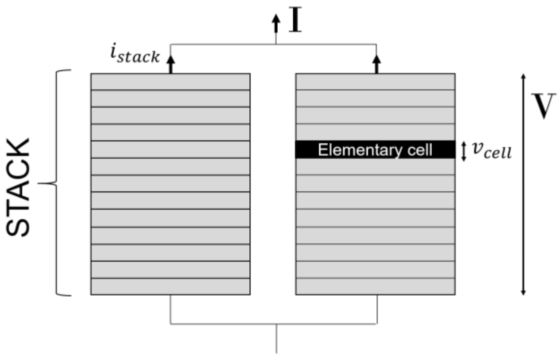

Figure 3. Fuel cell system scheme.

III. Powertrain preliminary sizing

The inherent modular character of the FCM 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 to be used in the conceptual design of hydrogen-based aircraft is achieved. Modularity means that each procedure and component considered are scalable, so that aircraft belonging to any weight category may be considered in principle.

The desired results are relative to an initial design approach, in which the new powertrain technology is analysed an tested in a simulated environment, which allows to understand the design trend. Therefore, the goal is to obtain quantitative results, that can eventually be used as a starting point for the preliminary aircraft design process. In fact, the new powertrain characteristics have an impact upon several aircraft parameters, such as the structural mass and the wing surface, that require an in-depth re-design process.

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

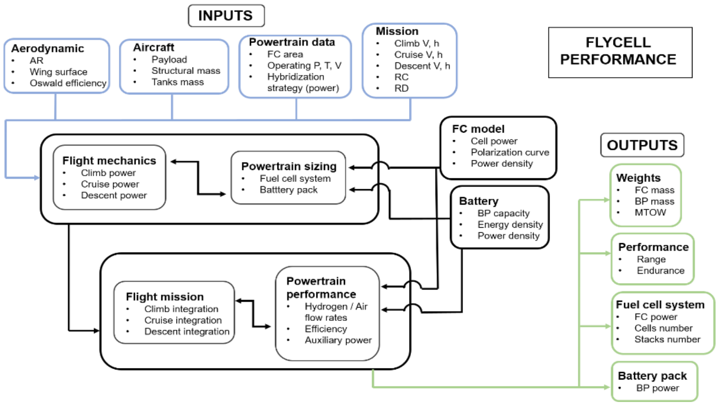

Figure 4. Flycell/Performance block diagram.

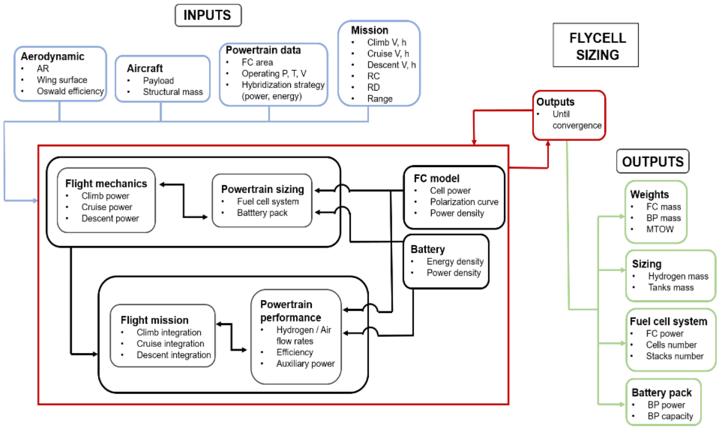

Figure 5. Flycell/Sizing block diagram.

The code has been developed in two versions: *Flycell/Performance* and *Flycell/Sizing*. These allow to size the powertrain 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 HE powertrain sizing (output power, number of fuel cells and stacks, battery size, powertrain weights) 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 range to be reached is an input. In output, the complete HE powertrain sizing (output power, number of fuel cells and stacks, battery size, powertrain weights) 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, concerning the flight mission and the sizing and usage of the powertrain. Such functions are inter-related using both direct and iterative computations. The code block diagrams of the two versions are presented in Figures 4 and 5. In the sizing version, due to the fact that an important sizing parameter, the stored hydrogen (which is proportionally related to the tank structural weight), is given in output, a global iterative computation is required.

IV. Validation

The validation of the *Flycell* code has been done using the hydrogen-driven aircraft involved in the MAHEPA project, the Pipistrel/DLR HY4. In this aircraft, FCM and BP supply the maximum power to the EM according to a

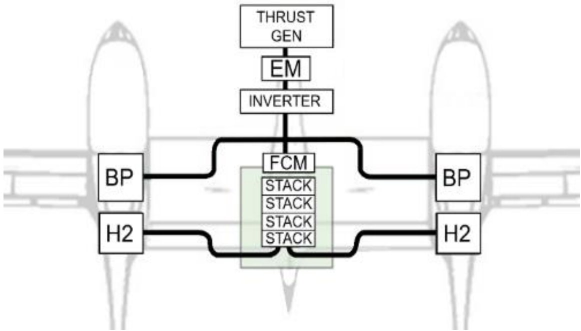

Figure 6. HY4 powertrain layout.

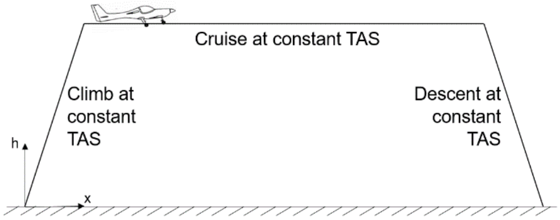

Figure 7. Mission profile.

Table 1. Flycell/Performance validation.

Parameter	Unit	Flycell	Real case	Δ [%]
Total cells number	-	436	440	-0.9
Cells in series	-	109	110	-0.9
Stacks in parallel	-	4	4	0
FC system mass	kg	101	100	+1.0
Battery pack mass	kg	133	130	+2.3
Total aircraft mass	kg	1 526	1 500	+1.7
Range	km	1 019	800-1 500	-
Endurance	min	384	-	-

Table 2. Flycell/Sizing validation.

Parameter	Unit	Flycell	Real case	Δ [%]
Total cells number	-	432	440	-1.8
Cells in series	-	108	110	-1.8
Stacks in parallel	-	4	4	0
FC system mass	kg	100	100	0
Battery mass	kg	136	130	+4.6
Total aircraft mass	kg	1 543	1 500	+2.8
Tank weight	kg	171	170	+0.6
Stored H_2	kg	9.04	9	+0.4
Battery capacity	Ah	73	75	-2.6

50-50 hybridization configuration, *i.e.* half of the power is provided by the FCM and half by the BP. Hydrogen tanks and batteries are positioned in the fuselages behind the occupant seats, while the FCM is placed right behind the EM (Figure 6). Being part of the MAHEPA consortium has allowed a direct contact with the DLR and H2Fly, the main developers of the HY4 powertrain, in order to obtain the correct aircraft data to be used as input, and to get a reliable feedback about the obtained results.

The considered flight mission profile is shown in Figure 7. Given the preliminary character of the present analysis, it is a simplified profile, composed by three phases: a climb at constant True Air Speed (TAS), a cruise at constant TAS, and a descent at constant TAS.

The validation of the code returns very good results with respect to real aircraft data (Tables 1 and 2). The higher errors, always below 5%, occur on the mass sizing of the subsystems of the powertrain (the FCM and the BP). This values are highly dependent on the specific power (or power density) and on the specific energy (or energy density) given as inputs. Concerning the BP, the considered specific power and energy values are, respectively, 350 W/kg and 200 Wh/kg. Regarding the FCM, the specific power used is 500 W/kg. As seen in the tables, the characteristics of the powertrain are captured fairly accurately in terms of FC number and stacks, BP capacity, and hydrogen mass.

V. Application studies

The described powertrain sizing approach has been applied to the conversion of existing aircraft to the new hydrogen-based powertrain. The range-based *Flycell/Sizing* version has been used, in order to compare the results at equal performance between the existing (conventionally-powered) aircraft and its HE FC conversion. In this way, the complete powertrain sizing and the new MTOW necessary to accomplish the mission are estimated. The considered range is applied at the maximum payload.

A. General approach

Four aircraft have been considered, across multiple weight categories spanning a passenger number between four and seventy-two. The aircraft classes considered are: General Aviation, with a 4-seater; Microfeeder (MF), i.e. a small liner in the ten-seat range (Ref. 7); Commuter Regional (CR), i.e. a mid-sized regional aircraft with 19 seats, certified according to CS-23, as the previous ones; and Large Regional (LR), in the 70-seat range, certified according to CS-25.

The motivation for including higher seat-range categoris lies in the increasingly important role of such aircraft within future air transportation scenarios. Indeed, regional aircraft may represent a key element in the future development of a more connected transportation network.

Europe's vision for aviation for the next thirty years, developed in the *Flightpath 2050* document (Ref. 8), calls for a network capable of moving people from any city inside Europe to any other in less than four hours, door to door. To do that, a novel class of regional airliners is crucial to connect smaller cities and open country territories to major airports.

At the same time, a significant reduction in total pollution is required by the *Flightpath 2050* vision, so that hydrogen-based regional may represent a promising solution to both these aspects.

The presented results are relative to an hybridization strategy similar to the one used for the HY4 validation, using the following values:

- *Power hybridization factor:* it is the ratio between the BP power and the total (maximum) power. The set value is 0.5.
- *Energy hybridization factor:* it is the ratio between the energy content of the BP and the total energy necessary to accomplish the flight mission. The set value is 0.15.

The value used for the hydrogen 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 hydrogen 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.

B. General Aviation – Cessna 172 Skyhawk

The Cessna 172 is the most famous trainer aircraft in the world and also the most produced aircraft ever. This is the reason why it has been chosen to represent the GA class in the conceptual conversion to a hydrogen-based powertrain. The imposed range is 780 km. The evaluated new aircraft total mass is 1,510 kg. This is 35.6% higher with respect to the original version with its thermal powertrain, a Lycoming IO-360-L2A reciprocating engine, providing 120 kW.

C. Microfeeder – Tecnam P2012 Traveller

The Tecnam P2012 is a 11-passengers (crew included), high wing, double engine aircraft that made its maiden flight in 2016. It is a modern and performing aircraft that well represent the MF class. The imposed range is 1,450 km. The evaluated new aircraft total mass is 4,847 kg. This is 34.6% higher with respect to the original version with its thermal powertrain composed of two Lycoming TEO-540-C1A reciprocating engines, each providing 280 kW.

D. Commuter – Beechcraft 1900D

The Beechcraft 1900 is a 19-passengers, low wing, double engine aircraft. The production ended in 2002, but its characteristics have been used as starting point for the hydrogen conversion for the CR class. The imposed range is 1,650 km. The evaluated new aircraft total mass is 9,869 kg. This is 27.1% higher with respect to the original version with its thermal powertrain composed of two Pratt & Whitney Canada PT6A-67D turboprop engines, each rated at 954 kW.

E. Large Regional – ATR 72-600

The ATR 72-600 is a 72-passengers, high wing, double engine aircraft. It is the updated version of the ATR 72 and it made its maiden flight in 2009. It is exploited both for cargo and short haul passengers service. It well represent the LR class. The imposed range is 1,250 km. The evaluated new aircraft total mass is 30,420 kg. This is 32.2% higher with respect to the original version with its thermal powertrain composed of two Pratt & Whitney Canada PW127M turboprop engines, each rated at 1,846 kW.

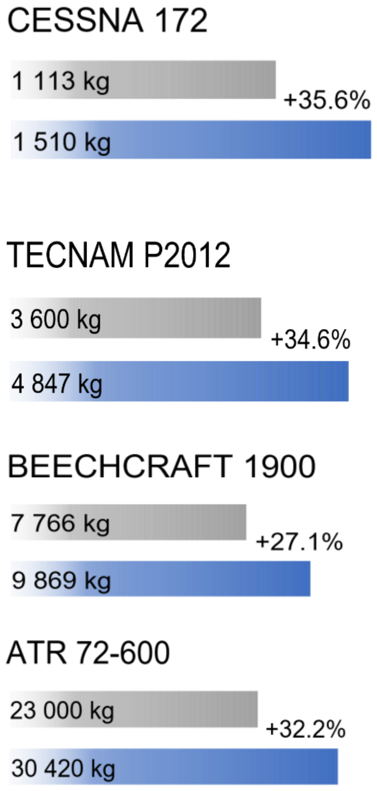

Figure 8. MTOW results for the four aircraft considered (grey bar: original aircraft; blue bar: HE FC conversion).

F. Remarks

In the cases presented, the hydrogen conversion always implies a significant increase in total aircraft weight (Figure 8). This is an occurrence for virtually any HE conversion and its reason can be traced to the overwhelming superiority of conventional hydrocarbon fuel when compared to other power generation means in terms of specific energy, *i.e.* the ratio of stored energy to mass. Clearly, with a variation in MTOW between 27.1% and 35.6 %, a re-design should be considered, in order to harmonize the new powertrain weight and balance within a suitably modified airframe. This being the case, the present study shuld be looked at as a preliminary step towards the new design or re-design of hydrogen-powered aircraft. The potential of the proposed model can be exploited when included within an aircraft preliminary sizing procedure, to be used in conceptual aircraft design. In such a configuration, the inherent coupling between airframe, aerodynamics, and powertrain characteristics would lead to more reliable results. The implementation of such an approach is currently ongoing.

A second approach to powertrain sizing has been performed in order to complement the analysis, based on the near-preservation of total aircraft weight. In this case, the sizing led to configurations that do not achieve the same range performance as the original versions. For the ATR 72-600, it can be shown that a new sizing of the HE FC powertrain inducing a variation in MTOW of 27% instead of 32.2% as in the previous study, translates into a reduction in range by 15%.

VI. Parametric analysis

In order to better appreciate the capability of the proposed model and to grasp the sensitivity of obtained results with respect to several design and performance parameters, a thorough parametric analysis has been carried out. In particular, we considered the variations in range, maximum take-off mass, BP mass, hydrogen tank mass, and FCM mass for the four aircraft considered above. Here, the case of the ATR 72-600 is shown for the sake of brevity. Each analysis was repeated for different values of the power hybridization factor Φ, ranging from 0 (no BP invoved) to 1 (pure-electric aircraft , without a FCM).

Figure 9 shows the mass variations as functions of the hybridization factor for a given mission range. As clearly seen, as the aircraft becomes more and more dependent on its BP, the MTOW increases up to 72%. The considered BP is a Li-ion one, which is characterized by specific power and specific energy values that are lower with respect to those related to hydrogen FC technology. Therefore, by increasing the BP percentage on board, a consequent increase in MTOW is found.

Figure 10 shows the range variation as a function of the hydrogen storage technology at different hybridization factors. The storage technology is represented by the value of the ratio of the mass of stored hydrogen to the mass of the tank. The dependance of range upon this ratio is almost linear, a higher storage mass ratio being clearly beneficial, with an effect of the

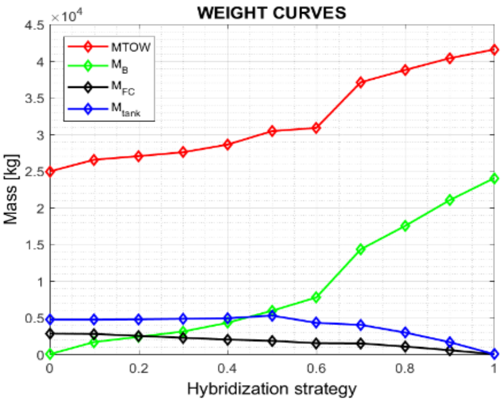

Figure 9. Mass sensitivity to hybridization factor for a given range.

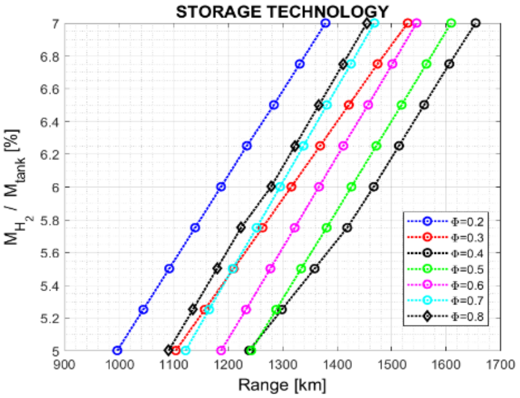

Figure 10. Range sensitivity to hydrogen storage mass ratio at various hybridization factors.

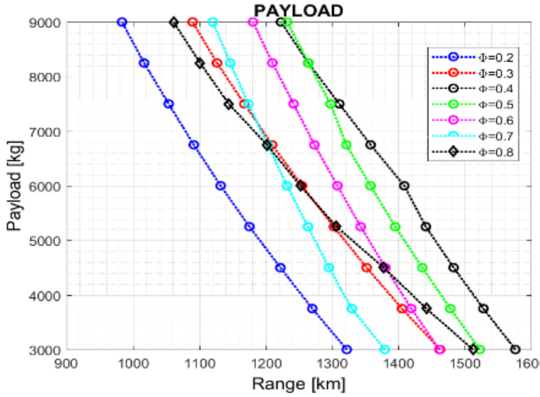

Figure 11. Range sensitivity to payload at various hybridization factors.

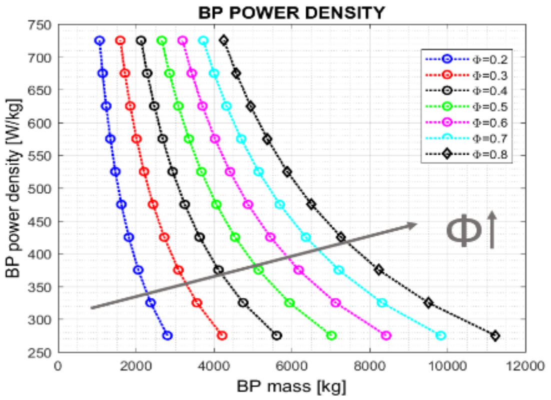

Figure 12. Battery mass sensitivity to battery specific power at various hybridization factors.

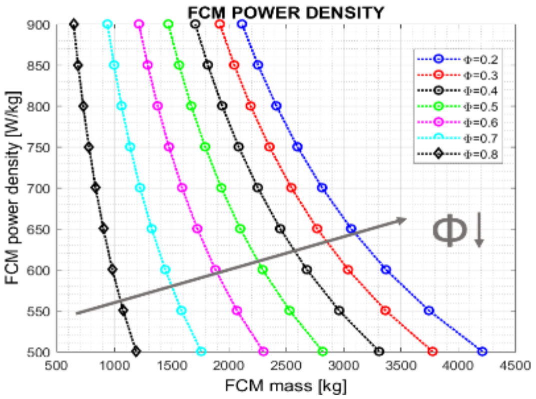

Figure 13. Fuel cell module mass sensitivity to fuel cell module specific power at various hybridization factors.

hybridization factor that often comes as an offset. This offset is positive in the range $\Phi \in (0.0,0.4)$ and then negative in the range $\Phi \in (0.4,1.0)$.

Figure 11 shows the range variation as a function of the paylod at different hybridization factors. Here, the marked reduction in range at increasing payload mass values appears nonlinear. The effect played by the hybridization factor is again variable, being beneficial up to about 0.4 and then penalizing.

Figure 12 shows the BP mass variation as a function of the BP specific power at different hybridization factors. This stands for the effects of future improvements in battery technology. Here, the role played by increasing the hybridization factor is clearly displayed by a monotonic increase in BP mass for a given specific BP power.

Figure 13 shows the FCM mass variation as a function of the FCM specific power at different hybridization factors. Again, this aims to predict the effects of future possible technology improvements. The results shows a trend opposite to that of BP mass sensitivity, with a monotonic decrease in FCM mass when the hybridization factor increases for a given specific FCM power. This is due to the increasingly lower importance of the FCM size as Φ grows towards 1, i.e. a pure-electric aircraft.

In both cases, it is clear that ameliorations in the basic BP and FCM output power performance could make the no-emissions powertrain configurations more and more convenient in aviation, given the lower mass values involved.

VII. Conclusions

This work contributes to the EU-funded H2020 MAHEPA project, in which a Politecnico di Milano research unit is responsible for scalability studies in aircraft design and for the analysis of future scenarios for GA and regional air transportation by exploiting hybrid-electric aircraft, based on both serial thermal-hybrid and fuel-cell hybrid powertrains.

A physics-based methodology for sizing a hydrogen-based powertrain for aircraft has been presented and preliminarily validated against an existing HE FC aircraft, the Pipistrel/DLR HY4. 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 appear accurate, even more so within a conceptual design framework, the developed formulation appears applicable to future design exercises, both for refurbishing existing aircraft by substituting their native propulsion system with a zero-emission one, as granted by a HE FC architecture, and for the design of new air vehicles for a more sustainable aviation. A preliminary study regarding the powertrain sizing for four existing, widely different aircraft types demonstrates the ability of this approach in coping with variable application scales. The study was completed with parametric analysis that offer a first answer to the problem of the sensitivity of a HE FC aircraft design solution with respect to several design specifications, technology parameters, and mission performance requirements. This may be useful to anticipate the effect of technology progress expected in the next years, helping the introduction of a new generation of aircraft that may achieve adequate performance, strongly improving on pure-electric (i.e. battery-only) aircraft, while maintaining the same ability to operate without chemical emissions in all phases of flight.

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