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PRELIMINARY SIZING AND ENERGY MANAGEMENT OF SERIAL HYBRID-ELECTRIC AIRPLANES

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ABSTRACT

A novel methodology for the preliminary sizing of pure-electric and serial hybrid-electric airplanes is presented, which is general and capable of dealing with propeller-driven airplanes of arbitrary configuration and size. The method takes into account the wider design space available to hybrid-electric aircraft compared to conventional ones, allowing to consider varying degrees of "hybridization", i.e. *the share in power and energy between the components of the powertrain. Furthermore, the energy management strategy adopted for the sizing flight mission is considered, by iteratively performing a thorough time simulation after an initial estimation of the sizing. This allows to adjust the energy-storage-related masses in order to optimize the results. Applications to 8- and 70-passenger aircraft and realistic missions are shown, highlighting the impact of three possible energy management strategies, including an optimized one.*

Keywords: electric aircraft, serial hybrid-electric propulsion, environmentally-friendly aviation, micro-feeder

1 INTRODUCTION

This paper describes a general methodology for the preliminary sizing of pure-electric (PE) and hybrid-electric (HE) manned aircraft, a topic that is currently attracting much attention in view of near-future applications in the quest of improved sustainability in aviation. A significant body of scientific literature dedicated to the analysis of PE and HE has been produced in recent years and a growing number of concepts and applications is undergoing advanced development (see [1] for a recent review). Indeed, several prototypes and demonstrators have already flown (examples cited in [2,3]), while a few reached the series production stage, starting with motor-gliders and currently peaking with the 2-seater Pipistrel Alpha Electro, an ultralight undergoing a certification process in the EU and USA.

Notwithstanding this impressive development, general methodologies for initial PE and HE aircraft design are still far from the maturity achieved in tackling conventional machines. In particular, this applies to preliminary sizing, conceived as the determination of the gross design mass and its breakdown into its main components, the determination of the total installed power and the performance of each powertrain component, and the determination of the reference dimension (typically, the wing surface, or wing planform area).

The present 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]. Among the MAHEPA goals, scenario studies for a future environmentally-friendly air transportation system are pursued, considering the application of HE powertrain technologies to short-haul passenger aircraft. To this end, the present methodology has been developed by extending the approach presented in [2,3], aiming to the setup of a preliminary sizing framework applicable to the initial design of propeller-driven airplanes of arbitrary configuration and size. This is at variance with respect to many recent contributions in the literature, where typically a *retrofitting* approach is considered, by designing a pure-electric or hybrid-electric propulsion system in substitution of the native thermal one for an existing aircraft. The presented method takes into account the energy management strategy adopted for the sizing flight mission. Indeed, the various possibilities to exploit the two energy sources on board (battery and fuel) in each flight phase may play an important role, leading to more or less optimized solutions.

2 SIZING METHODOLOGY

The proposed approach applies to the preliminary sizing of PE and serial HE propeller-driven aircraft. The serial propulsive architecture implies the presence of an electric motor (EM) driving each propeller, powered by a battery pack (BP) and an electric power generation system (PGS) [1]. The latter is typically represented by a hydrocarbon-burning internal combustion engine (ICE), being either a reciprocating engine or a turboshaft, coupled with an electric generator. Other possibilities for the PGS include the case of a fuel cell system, as discussed in [5]. In the present context, a PE aircraft is obtained as the case of a serial HE one without a PGS.

The sizing procedure consists in a modification of an approach commonly employed in the conceptual design of conventional aircraft, making use of suitably adapted formulations and tools. The first element which is at variance with conventional aircraft is given by the design maximum take-off mass (MTOM) M_{mto} breakdown:

$$M_{mto} = M_p + M_a + M_m + M_b + M_g + M_f, \tag{1}$$

where M_p represents payload mass, M_a non-propulsive airframe mass, M_m electric motor mass, M_b BP mass, M_g PGS mass, and M_f fuel mass. We remark that, here, non-propulsive airframe mass takes into account of all airframe masses (structure, on-board systems, landing gear, etc.) except those related to the powertrain. Therefore, the sum $\left(M_a + M_m + M_b + M_g\right)$ corresponds to the "empty mass" commonly referred to in a conventional aircraft. This is typically estimated as a single term in the mass breakdown through historical statistical regressions based on similar existing aircraft, a process that is not applicable for PE and HE aircraft, due to the lack of consolidated data for these new airplane types.

The mass estimation procedure is therefore crucial for a reliable sizing, and is inherently coupled with power and wing surface estimation in a much more elaborate way than in conventional aircraft. Indeed, one possibility to tackle conventional aircraft preliminary sizing consists in finding the MTOM by coupling a historical statistical regression for the empty mass and a fuel-fraction procedure for the fuel mass, based on mission energy requirements. Then, power and wing surface are determined by choosing the design point in the feasible design space drawn according to the sizing matrix plot (SMP), which takes into account all point and terminal performance requirements [2,3].

In the case of a PE or HE aircraft, power considerations apply directly to mass estimation, as EM, BP, and PGS masses inherently depend on their power output. Therefore, starting with the choice of a design point on the SMP, which amounts to the determination of the design power loading W_{mto}/P_b and wing loading W_{mto}/S, being P_b the shaft brake-power and S the wing surface, the method derives the component masses of Eq. 1 starting with an initial MTOM guess and loops until convergence. In this process, all mission requirements and performance specifications deriving from the applicable certification basis or other design considerations are involved, as well as numerous parameters yielded by the market analysis and technology survey that are normally performed as an initial phase in conceptual design.

Among these specifications, on-board energy management is of paramount importance for HE aircraft. As an essential advantage of serial HE powertrains is the possibility of operating in PE mode, this is often considered as an element to be included in the mission profile, by requiring PE operations below a given altitude. This grants zero-emission and a considerable noise abatement in the vicinity of airports, greatly contributing to eco-friendliness of future air transportation. Other energy management specifications, concerning the amount of power from BP and/or PGS during the various phases of the flight profile and the amount of residual energy stored on board at mission completion cannot be taken into account accurately at this level and is one of the main reasons for the subsequent refinement of the preliminary sizing.

In fact, once the above discussed sizing is accomplished, a second process is deployed, which involves the time-marching simulation of the sizing mission. In this process, the flight profile is covered from take-off to landing by applying performance equations and considering different modes of energy supply to the EM. These are the PE mode, in which only the BP provides motive power, and the HE mode, in which the PGS is switched on, providing power to either the EM, the BP or both. Also, energy recuperation in gliding flight by deriving battery recharging power from the windmilling propeller can be considered. This process corrects the sizing previously achieved, through the adjustment of the components M_b and M_f of the mass breakdown, according to the actual needs observed in the simulation.

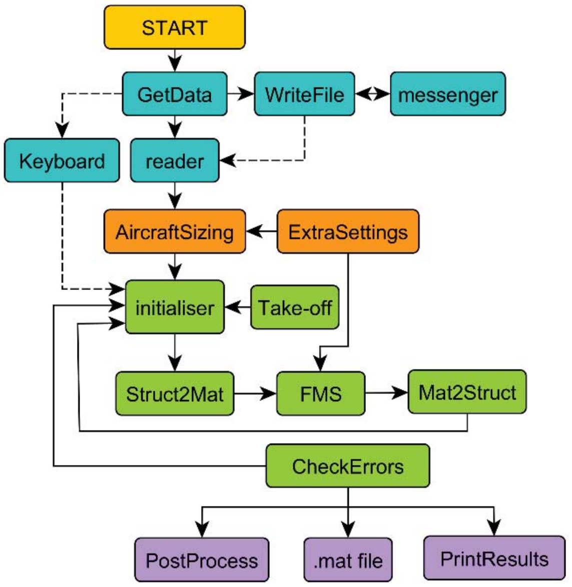

Figure 1: Block diagram of the Hyperion tool for electric aircraft preliminary sizing.

The complete procedure was implemented in the Hyperion (Hybrid Performance Simulation) tool according to the scheme seen in Figure 1 (FMS stands for flight mission simulation). A fully detailed account of the proposed methodology and its implementation is presented in [6].

3 IN-FLIGHT ENERGY MANAGEMENT

Given the possibility to draw power for flight from two independent power sources, *i.e.* the BP and PGS, in-flight energy management needs to be defined according to some criteria. Here, a number of possibilities arises, which may have an impact on the overall energy efficiency of the sizing mission and, therefore, on the optimal sizing of the aircraft as well as on its operational efficiency.

Several parameters play a role in this regard, including BP power/energy and PGS power performance specifications, requirements on the alternative or concurrent usage of the two power sources, upper and lower threshold values of BP state of charge (SOC), BP charge/discharge rates, and PGS throttle rating.

Hereinafter, we shall consider the following requirements for HE aircraft:

a. PE mode below a specified transition altitude;

b. EM sized to fulfil maximum mission power (take-off & climb) at its highest (non-continuous) rating;
c. BP sized either to fulfil maximum mission power first, and then increased if needed to provide energy for the flight phases below the transition altitude;
d. PGS sized to fulfil the cruising power requirement, plus some extra power in order to be able to recharge the BP;
e. Fuel tank sized to provide the required mission energy, except for the part provided by the BP at full charge;
f. Minimum values for BP SOC and fuel remaining at mission completion.

The flight profile considered for the sizing mission is the typical transfer for a civil passenger of freight airplane, composed by take-off, climb, cruise, descent, loiter (according to applicable regulations), and landing. Apart from terminal ones, all phases are flown at constant equivalent airspeed (EAS).

In the following, three relatively simple energy management strategies are considered, in order to illustrate their impact on aircraft sizing.

A first strategy shall be indicated as strategy #1 and is represented by a “cyclic” operation for the BP. Indeed, in this case, the battery is discharged in the beginning of the mission, up to the lower threshold and then recharged. As soon as the upper threshold is reached, the BP is again discharged, and so on. The activation of the PGS follows accordingly to the current power requirement, so that it is kept off if the BP power is enough, and then turned on when the BP cannot sustain the power required for flight.

A second strategy shall be indicated as strategy #2 and corresponds to operating the BP in a quasi “steady” SOC for most of the time. In this case, after the completion of the initial portion of the flight performed in PE mode, the BP is recharged and kept as close to full charge as possible during the remaining part of the mission. Consequently, the PGS is kept running until the transition altitude is reached during descent.

It can be demonstrated that neither of the previous strategies is energy-optimal, under the considered conditions [6]. Indeed, both of them cannot guarantee to complete the sizing mission with the minimum amount of energy stored on board, nor to fly each segment at the best possible efficiency, given that the aircraft mass changes in different ways. A study in optimization reveals that the optimal strategy is very similar to the “steady” strategy (#2). This has the advantage of burning fuel, so reducing aircraft mass, as soon as possible, except for the fact that towards the end of the mission, the PGS is switched off before reaching the transition altitude and PE mode is established so that the residual energy on board at landing exactly matches the requirements. This strategy shall be indicated as strategy #3.

4 NUMERICAL STUDIES

4.1 Preliminary considerations

The proposed methodology was applied to a number of example cases across several aircraft categories, ranging from 4 to 70+ occupants. Here, results concerning a light, 8-passenger commuter airplane (named H8) and a 70-passenger regional liner (named H70) are illustrated.

The interest in the light commuter is spurred by the fact that 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 [7], 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. This is envisaged in the Flightpath 2050 document [8], which calls for a continental 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 environmentally-friendly, short-haul airliners is crucial to connect smaller cities and open country territories to major airports.

The case of the large regional airliner is also of high interest, as regional air transportation may benefit of substantial environmental advantages and thus contribute to sustainability of civil aviation at large.

In the numerical studies that follow, we assume that the battery specific power is 1.50 kW/kg; the battery specific energy is 0.50 kWh/kg; the EM overrating is such that 25% extra power can be exploited in take-off and climb; the target final values for BP SOC and fuel remaining are 25% and 10%, respectively; the transition altitude is set at 1,000 m above ground level (AGL).

4.2 Light commuter airplane

We consider a sizing mission with a range of 1,330 km, plus a final loiter of 45 minutes below the transition altitude (here at 300 m). The total take-off distance requirement is 654 m and the cruising speed 150 kn at 1,800 m.

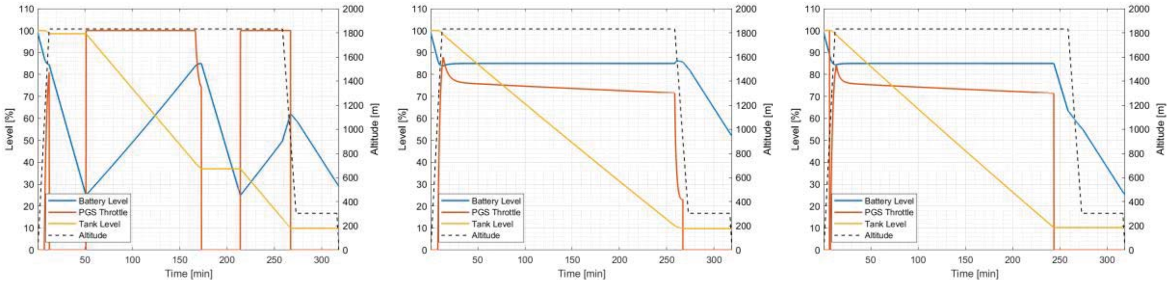

Figure 2: Time histories of battery state of charge (blue), PGS throttle (red), fuel quantity (yellow), and altitude for the H8 using the three energy management strategies (left: #1; center: #2; right: #3).

Figure 2 shows the time evolution of the energy stored on board obtained by applying the three energy management strategies. The BP SOC and fuel quantity are shown, together with the PGS throttle level and altitude profile. The difference between strategies #1 and #2 is apparent in the SOC and PGS throttle time histories.

In case #1, the battery is partially discharged in PE mode up to transition altitude, then the PGS is turned on, providing some extra power to climb up to cruising altitude. At the top of climb, the PGS is turned off and the battery provides power for flight up to discharge at the lower SOC threshold. This is a consequence of the BP being sized for power, which implies extra energy at the end of climb. From then on, the PGS is turned on again at maximum rating, providing both cruising power and BP recharging power. Battery SOC increases until hitting the upper threshold. There, the PGS is switched off and a segment of the cruise is flown on battery only, up to discharge, which triggers again the PGS on. Descent ensues and the PGS is turned off when crossing the transition altitude and the final loiter is flown in PE mode.

In case #2, the battery is discharged only during the PE phases, while it is charged throughout the rest of the flight. The PGS is kept running during the BP charging phases (without the need to operate at maximum rating) to provide the recharge, with a marked reduction during descent, when at fully charged BP, the PGS provides the power required for flight in descent down to transition altitude.

The only difference between cases #2 and #3 lies in the full switching-off of the PGS about 15 minutes before the start of descent for the optimal case, when the required residual fuel is achieved. The following BP usage insures the required residual SOC at mission completion.

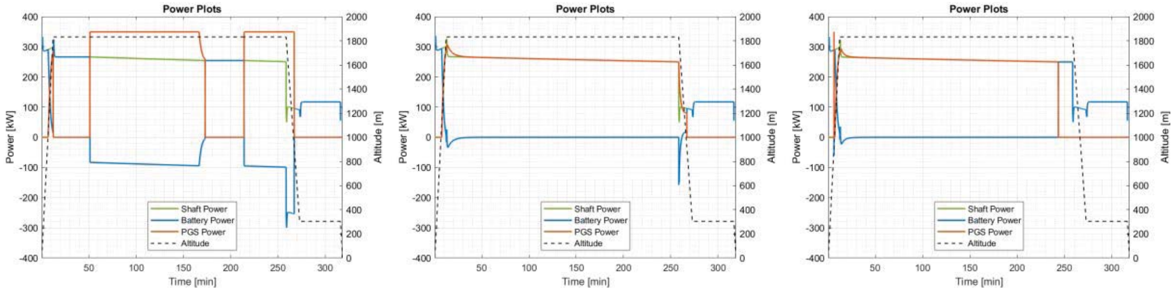

Figure 3: Time histories of shaft power (green), BP power (blue), PGS power (red), and altitude for the H8 using the three energy management strategies (left: #1; center: #2; right: #3).

The BP is sized to provide 616 kW and 290.5 kWh, while the PGS is sized to 350 kW. Figure 3 shows the time evolution of the power delivered by the two power sources on board, contrasted with the shaft power required for flight and the altitude profile. BP and PGS activities clearly follow trends corresponding to those seen in Figure 2. Negative values of the BP power output corresponds to battery charging.

The mass breakdown obtained in the three cases is shown in Table 1. It is readily seen that for the cyclic and optimized strategies we get almost identical results, due to the fact that the final BP SOC and fuel remaining values happen to be extremely close to the target values in case #1, as seen in Figure 2. With respect to the cyclic strategy, the optimized strategy yields a reduction in MTOM 1.0%, and fuel consumption by 1.3%. This corresponds to a saving of 6 kg of fuel for the same mission. If compared to the steady strategy, the MTOM reduction is 1.0% and fuel consumption reduction is 6.1% or 37 kg.

	#1		#2		#3	
	[kg]	%	[kg]	%	[kg]	%
Maximum Take-off Mass	3,254	100.0	3,285	100.0	3,248	100.0
Empty mass	1,374	42.2	1,374	41.8	1,374	42.3
Occupant mass	819	25.2	819	24.9	819	25.2
Battery mass	581	17.9	581	17.7	581	17.9
Fuel mass	479	14.7	510	15.5	473	14.6

Table 1: Mass breakdown for the H8 according to the three energy management strategies.

4.3 Large regional airplane

We consider a sizing mission with a range of 800 km, plus a final loiter of 45 minutes above the transition altitude (here at 3,000 m). The total take-off distance requirement is 1,370 m and the cruising speed 175 kn at 7,000 m..

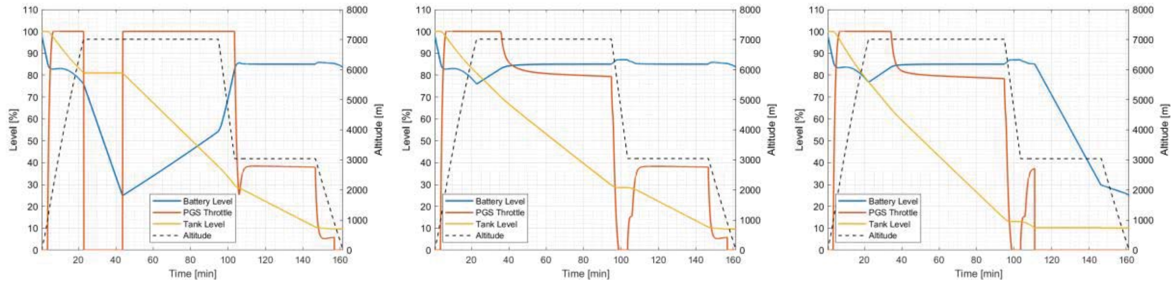

Figure 4: Time histories of battery state of charge (blue), PGS throttle (red), fuel quantity (yellow), and altitude for the H70 using the three energy management strategies (left: #1; center: #2; right: #3).

Figure 4 shows the time evolution of the energy stored on board obtained by applying the three energy management strategies. Again, the difference between strategies #1 and #2 is apparent in the SOC and PGS throttle time histories. The difference between cases #2 and #3 is seen in the final part of the mission, with the PGS on during loiter and final descent for case #2 and mostly off in case #3. Indeed, with the optimized strategy, the BP sizing allows to fly most of the loiter and the subsequent final descent in PE mode, even if above the transition altitude.

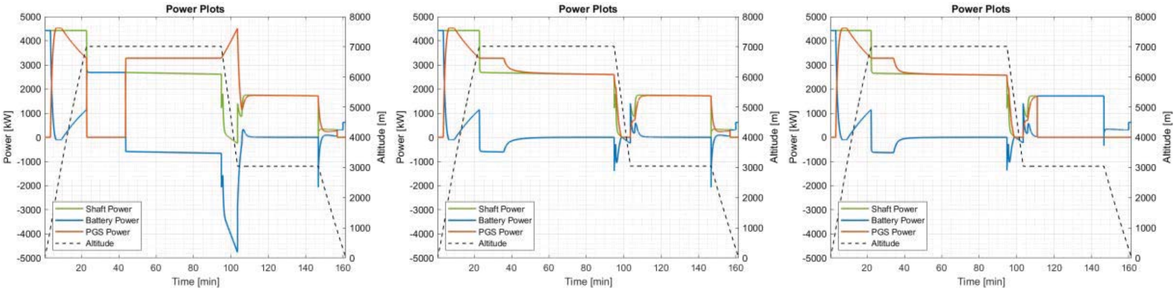

Figure 5: Time histories of shaft power (green), BP power (blue), PGS power (red), and altitude for the H70 using the three energy management strategies (left: #1; center: #2; right: #3).

The BP is sized to provide 5,252 kW and 1,829 kWh, while the PGS is sized to 4,524 kW. Figure 5 shows the time evolution of the power delivered by the two power sources on board, contrasted with the shaft power required for flight and the altitude profile. It is seen that for this specific aircraft, the power required for cruise is significantly lower than the power for take-off and climb. BP and PGS activities clearly follow trends corresponding to those seen in Figure 4. It is apparent the similarity of the loiter and final descent phases in cases #1 and #2, and the similarity of the rest of the mission in cases #2 and #3.

The mass breakdown obtained by applying the three energy management strategies is shown in Table 2. Also in this case, we get identical results for the cyclic and steady strategies, since the final BP SOC and fuel remaining values happen again to be almost identical, as seen in Figure 4. However, for the optimized strategy, the MTOM is reduced by 1.2% and fuel consumption by 19%. This corresponds to a saving of 401 to 410 kg of fuel for the same mission, compared with #1 and #2, respectively. This appears a significant result, justifying an investment in the consideration of optimized energy management early in conceptual design.

	#1		#2		#3	
	[kg]	%	[kg]	%	[kg]	%
Maximum Take-off Mass	31,706	100.0	31,697	100.0	31,297	100.0
Empty mass	18,969	59.8	18,969	59.8	18,969	60.6
Occupant mass	6,955	21.9	6,955	21.9	6,955	22.2
Battery mass	3,658	11.5	3,658	11.5	3,658	11.7
Fuel mass	2,125	6.7	2,116	6.7	1,715	5.5

Table 2: Mass breakdown for the H70 according to the three energy management strategies.

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 general methodology for the preliminary sizing of pure-electric and serial-ICE hybrid-electric aircraft has been developed, which can be applied to vehicles of arbitrary weight category. The methodology allows to consider the effect of all mission requirements, certification specifications, and other design constraints, as in conventional aircraft initial design, and to include the peculiar aspects of electric propulsion. Among them, an important role is played by the degree of "hybridization" in power and energy, *i.e.* the share between the output capabilities of the electric and thermal components of the powertrain. In addition, the energy management strategy during the mission implies variations in the overall energy efficiency and, therefore, on the needed masses of battery and hydrocarbon fuel. As such, this can have an impact on the optimal sizing of the aircraft. The application to the preliminary sizing of two passenger aircraft designs is presented for realistic sizing missions, considering three different energy management strategies. It is shown that significant advantages in fuel efficiency may be achieved with an optimal energy management, in contrast to simpler strategies, leading to significant fuel savings. This motivates the interest in considering energy management strategies from the very initial phases in conceptual design, in order to identify the most promising design configuration. A detailed discussion of the method, together with its validation and further applications are found in [6].

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