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TECHNICAL PAPER

Hybrid-electric airplane design optimization considering climb and cruise phases

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Abstract
In the last years, the development of new non-conventional aircraft has attracted the attention of the scientific community, especially for electric and hybrid aircraft. This is due to the need to reduce fuel consumption, which implies a higher profitability for aeronautical companies and, mainly, a reduction of greenhouse gas emissions. This work recalls some of the concepts and architectures that involve a propulsive system of a hybrid-electric aircraft. Also, this work seeks to understand the impact of electrification, i.e., how the definition of the degrees-of-hybridization can impact in the sizing of a hybrid-electric aircraft at conceptual design stage. To do so, it presents a multi-objective optimization of only two phases of flight: climb and cruise. The optimization seeks to minimize the fuel consumption and to maximize the payload that the aircraft can carry on both flight phases. The results indicated that the genetic algorithm used was able to obtain an optimal solution, enabling the strategy of reducing fuel and maximizing the extra payload. Moreover, since the climb phase is a short-time period, the optimal solution tends to use the maximum degree-of-hybridization, while for the cruise there is a balance between the benefits of the electrification and the penalties due to the extra weight of batteries.

Keywords Hybrid-electric aircraft · Performance · Aircraft design · Multi-objective optimization

1 Introduction

The study of fully or partially electric aircraft has been the subject of discussion between researchers and engineers at universities and the aeronautics industry over the last years. The need to develop ever more efficient and greener aircraft leads to the motivation to expand technologies and move toward previously unfeasible concepts.

Currently, most General Aviation aircraft typically use internal combustion engines (ICE) as a power source. These engines burn fossil fuels with high energy densities, making this type of raw material very advantageous for aviation. However, they are highly polluting, since their burning generates the production of carbon dioxide (CO_2), which is the main responsible gas for global warming [1]. The Air Transport Action Group (ATAG) points out that 2% of anthropogenic carbon dioxide emissions come from aviation, and this number only tends to increase along with the number of aircraft in operation [2, 3]. Under those circumstances, several targets have been defined in Vision 2020 and AGAPE 2020 for the next few years [4].

Besides the problem of emissions and pollution, the amount of fossil fuels available in the world is limited. Even not knowing about its availability and scarcity in future, the fossil fuel prices themselves tend to increase in the coming decades due to the fast growing worldwide energy demands and the uncertain political situation in the Middle East [5].

Thereby, all the situations mentioned above lead to consider and rethink in alternative ways of the power supply. Thus, the introduction of electric propulsion systems has been a great option. First of all, batteries can be used as a power source instead of conventional fuels. However, the battery use itself brings challenges such as the weight on

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board and its specific energy. Regarding the first one, aircraft are very sensitive when it comes to weight because as it increases on board, the available payload diminishes. Regarding the second one, the batteries currently have low specific energy when compared to high specific energy of conventional fuels. However, studies have shown great results for batteries in future. Lithium-air batteries may show an impressive theoretical specific energy of 11,680 Wh/kg [6]. But in more realistic numbers, Zn-O_2 batteries with specific energy of 400 Wh/kg in 2025 are expected [7]. It is also worth remembering the challenge related to the international aviation regulations, which require that the minimum level of safety compared to the batteries be guaranteed. Moreover, engines have a lower efficiency and power-to-weight ratio when compared to electric motors [8]. Hence, hybrid-electric systems are proposed to balance the advantages of both engine and motor systems, improving the performance. Such systems have potential advantages including low fuel costs, lower vibrations, lower pollution, and reduced noise.

After all, it is not an easy task to balance all these interests and to develop a fully or partially electric propulsion system, but it is of great importance and necessity to carry on the study and improvement of physical limitations, fulfilling the requirements and guidelines for the future.

Along those lines, to achieve such targets of reducing environmental impact, new concepts and systems have also been presented in the last decade, seeking for best aerodynamic efficiency, good stability control, lower associated weight, better aeroelastic behavior, and ease of manufacturing. The Boundary Layer Ingestion (BLI) and Distributed Propulsion (DP), have recently been studied in order to improve aircraft aerodynamics, which benefits the entire project [9]. DP, for example, comprises a set of electric propulsors usually installed along the wing, which generates air-propulsive interactions that result in gains in propulsion and total-lift of the aircraft [10]. Electric vertical takeoff and landing (e-VTOL) concepts have been launched by numerous start-up and mature firms worldwide, including VoloCopter, Ehang, Zee Aero, Joby Aviation, and Airbus. Brelje and Martins [11] presented an article surveying the scholarly and business literature on fixed-wing aircraft propelled in whole or in part by electricity, including all-electric, hybrid electric, and turboelectric architectures.

Furthermore, over the last years, many studies have been developed in order to better understand the design process of hybrid-electric aircraft. Sziroczak et al. [12] evaluated the problems and barriers emerging and required future technologies of effective hybrid-electric propulsion systems and adaptation of the aircraft conceptual design process for the development of hybrid-electric aircraft, applying the conceptual design of a small aircraft with hybrid-electric propulsion system. Hoelzen et al. [13] introduced a new simulation approach for HEA, where the findings underline the importance of choosing the right power-to-energy-ratio of a battery according to the flight mission. Finger et al. [14] described the methodology and the benefits of an initial sizing algorithm that is able to consider aircraft with hybrid-electric propulsion systems by using point and mission performance analysis. Voskuijl et al. [15] presented a validated design and analysis framework with sizing and analysis modules for hybrid electric propulsion system components.

Nonetheless, very often the development of an aircraft requires the integration of an optimization into the design process. Sgueglia et al. [16] proposed a procedure for the conceptual design of hybrid aircraft through the definition of a multidisciplinary design optimization (MDO) framework aimed at handling design problems for such kinds of aircraft, testing for the case of a single-aisle aircraft featuring hybrid propulsion with distributed electric ducted fans. Zhao et al. [17] presented a physics-based simulation and optimization platform for hybrid electric aircraft conceptual design, modeling each subsystem and the aircraft structure. Rotramel [18] worked on the optimization of hybrid-electric propulsion systems for small remotely-piloted aircraft used by warfighters for intelligence, surveillance, and reconnaissance (ISR) missions.

This work seeks to understand the impact of electrification, i.e., how the definition of the degrees-of-hybridization can impact in the sizing of a hybrid-electric aircraft at conceptual design stage. Thus, Sec. 2 recalls some fundamental concepts regarding hybrid-electric aircraft and its propulsive architectures, which are also present in [19]. Sec. 4 presents the mathematical formulation of aircraft performance, but modified to hybrid-electric configurations. Most works of the literature, as mentioned previously, usually choose a specific value for the degree-of-hybridization in a certain flight phase, but this works expands the possibilities, i.e., it looks for what degree-of-hybridization would result in better fuel consumption and payload, directly affecting the sizing of the aircraft. Then, Secs. 5 and 6 presents a multi-objective optimization, where the objectives are to minimize the fuel consumption and to maximize the extra payload the aircraft can carry on. In this study, only the climb and cruise phases are evaluated. The optimization variables involve the number of electric motors arranged on the wings, the degree of hybridization, the speed of operation, the takeoff weight and also the angle of climb. Then, NSGA II is used to solve the multi-objective optimization problem, and the results are presented and discussed in Sec. 7.

2 Hybrid-electric aircraft

Triggered by the need for developing new sustainable technologies, the aerospace industry has recently spent a lot of effort on the designing of greener aircraft. Such alternative among the new concepts and linked to this perspective is the hybrid aircraft.

A hybrid aircraft is an aircraft which has a combination of two or more sources capable of generating power into a single power system. The commonly used term "hybrid-electric" describes a system that utilizes one or more heat engines together with one or more electric-motors in a specific configuration [8].

Since fully electric aircraft do not use fossil fuels as energy source, the operational costs related to fuels and maintenance are reduced considerably [20]. Moreover, the aircraft maneuverability and performance improve, considering the lack of attitude and altitude effects. Furthermore, the aircraft can reach a lower level of vibration and present a reliable start-up [21].

In contrast, the amount of battery to provide a reasonable endurance and the minimum required power of the aircraft would be enormous, since the energy capacity of the batteries is currently very small, which would result in a large weight of batteries on board [22, 23]. In addition, the associated costs, availability, and project maturity are the major constraints.

Therefore, a synergy between the qualities of both conventional and full electric aircraft result in what is called hybridization, which means the integration of the propulsion system with energy stored source (batteries) and fuel source (conventional engine). The Degree-of-Hybridization (DoH) express the percentage of total power required by the aircraft that comes from the electric system [2]. Most commonly used in literature are the degree of hybridization for energy (HE) and power (HP) [24], defined as:

$$H_P = \frac{P_{electric}}{P_{total}} = \psi \tag{1}$$

$$H_E = \frac{E_{electric}}{E_{total}} = \phi \tag{2}$$

When designing a hybrid electric propulsion system, there are many distinct possible architectures [24]. The series hybrid architecture and the parallel hybrid architecture are the most commonly used. But, to choose which one of them is the best for a certain project, it depends on the applications and limitations of the project that they are being designed for. In road vehicles, for example, the series hybrid architecture has the lowest fuel consumption, as presented by Bayindir et al. [25]. However, Hung points out that it has a larger weight than a parallel architecture, which is crucial and determinant in aerospace applications [26]. In a design study of light aircraft, Friedrich and Robinson assert that the parallel configuration provides the highest efficiency for aerospace applications [8]. The series and parallel configurations are further discussed in the following sections.

2.1 Series architecture

Series architecture involves an internal combustion engine (ICE), a generator, a battery pack, an inverter, a controller and electric motors, as shown in the simplified diagram in Fig. 1. The ICE is used to drive a generator, which in the sequence provides power to the controller. This controller also receives power from an inverter, which drains power from a battery pack. Thus, the controller combines both powers from the ICE and the battery pack, and finally provides power to the electric motors.

The main benefit of a series architecture is that the ICE driving the generator can be designed to operate at a consistent and optimum engine speed [27], because the ICE is not directly mechanically linked to the propellant of the aircraft. Also, the arrangement can be installed in different positions on the aircraft layout system. A drawback to a series architecture is that the electric motor must be sized based on the capability to provide the maximum power output the aircraft requires. If so designed, the aircraft can operate fully electric using the battery pack, turning the ICE off, operating at its maximum efficiency point, leading to improved fuel efficiency and lower carbon emissions compared to other configurations.

2.2 Parallel architecture

The parallel architecture comprises a turboshaft engine, a battery pack, an inverter, and an electric motor, as shown in the simplified diagram in Fig. 2. Fuel is used to power a turboshaft engine, and batteries are used to power an electric motor. Both turboshaft engine and electric motor power the drive train coupled to the propellers.

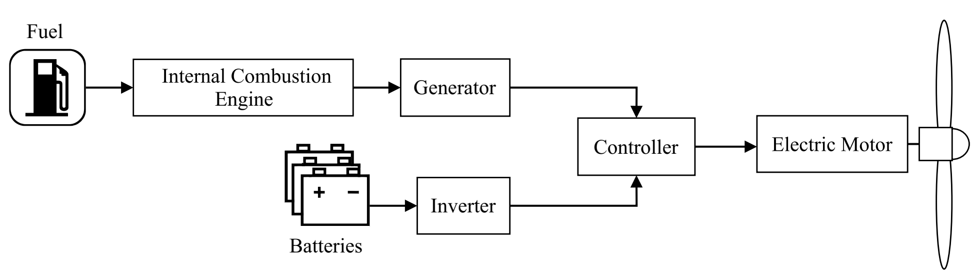


Fig. 1 Illustrative diagram of series architecture

Good performance is possible, in this case, because the power is generated with both engines [25]. Different control strategies are used in a preferred approach. If the power required by the transmission is higher than the output power of the turboshaft engine, the electric motor is turned on so that both engines can supply power to the transmission. If the power required by the transmission is less than the output power of the ICE, the remaining power is used to charge the battery pack [27]. Moreover, mechanical and electric power could be decoupled, and the system has a high operating flexibility enabling three modes of operation: purely combustion; purely electric and hybrid.

On the other hand, Miller [28] comes up with other similar definitions, but in a different perspectives. He splits the parallel hybrid-electric systems into three major types: mild, power-assist, and dual-mode. The types are nominally classified based on the sizing and participation of the electric motor. In the mild system, for example, the electric motor is relatively small and it is used to aid in acceleration and utilizes excess power to recharge the batteries. The power-assist parallel system uses a larger electric-motor and a more substantial battery pack, what warrants a modest downsizing of the engine. Likewise, the dual-mode parallel system utilizes a yet even larger electric motor and larger energy storage bank (battery). In other words, the higher the participation of the electric-motor and the battery pack, the lower the turboshaft engine sizing.

3 Typical mission profile on an aircraft

In the design of any aircraft, it is extremely important to know the requirements and specifications of the project, since they are responsible for determining the direction and details of the project [29]. Therefore, it is important to define:

(I) *Purpose of the aircraft*: typical use of the aircraft;

(II) *Typical missions*: description of the typical mission of the aircraft, i.e., time and altitude of operation during a typical flight;

(III) *Target of performance*: maximum speed, maximum range, stall speed, and so on;

(IV) *Desired features*: materials used, ease of construction, affordable maintenance;

(V) *Requirements*: basis of certification adopted, aeronautical legislation requirements that must be fulfilled.

Thus, for this work, it is necessary to define a typical mission to study the design and performance analysis of the aircraft. To do so, consider the typical mission profile shown in Fig. 3.

The typical mission profile considered defines each flight phase as:

- *Takeoff*: this phase comprises the moment which the aircraft leaves the gate and accelerates until it reaches sufficient speed to leave the ground;
- *Climb*: the aircraft climbs from the altitude of the airport to the pre-established cruising altitude;
- *Cruise*: at this stage, the aircraft flies at a constant altitude and speed until it reaches the expected range;
- *Descent*: phase in which the aircraft ends the cruise regime and begins to descend to a certain altitude to prepare for landing;

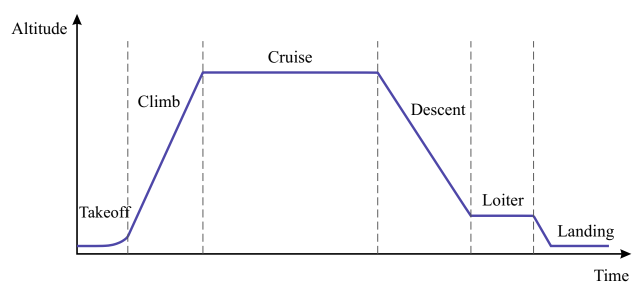
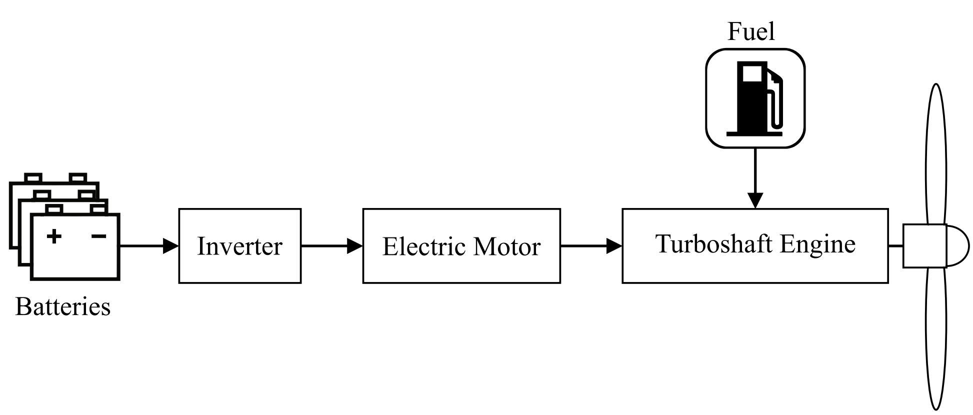


Fig. 3 Typical mission profile

Fig. 2 Illustrative diagram of parallel architecture



- *Loiter*: the aircraft keep flying over for a certain amount of time at a certain altitude until it gets permission to land;
- *Landing*: moment when aircraft touches the ground and decelerates until reaching minimum speed, and finally, park at the airport.

For the next sections, this work will evaluate only two phases of flight: climb and cruise.

4 Mathematical model of performance for hybrid-electric aircraft

Unlike conventional aircraft, hybrid-electric aircraft have the peculiarity of allowing a range of operations, since their propulsion systems are combinations between conventional internal combustion engines and a battery bank. In this work, two flight phases of a hybrid aircraft are specifically evaluated: climb and cruise. The architecture of the propulsive system under analysis is a series architecture, with electric multi-motors of the same nominal power attached to the wings (n motors on each wing), as shown in Fig. 4.

An aircraft, in any flight phase, presents a certain required power required to fly at a certain speed (V), which is directly related to the drag force (D) acting on the aircraft, as described in Eq. 3.

$$P_{Req} = D \cdot V = \left(\frac{1}{2}\rho V^2 S C_D\right) \cdot V \tag{3}$$

where ρ is the air density at a specific flight altitude in kg/m^3, S is the reference area in m^2, and C_D is the aerodynamic drag coefficient defined as:

$$C_D = C_{D_0} + C_{D_L} \tag{4}$$

with C_{D_0} being the drag coefficient of the profile (pressure + friction) and C_{D_L} the induced drag coefficient, which is considered as a function of lift:

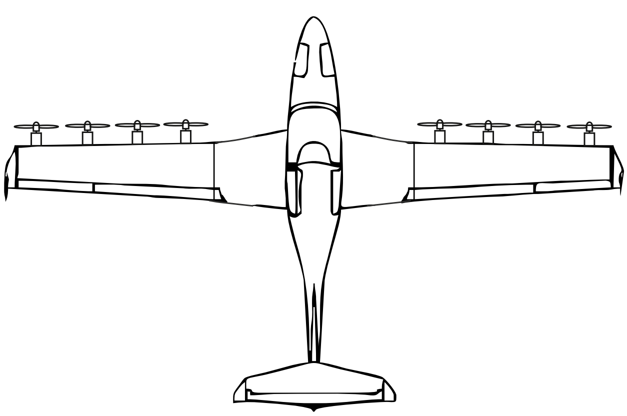


Fig. 4 Illustration of the aircraft under analysis, adapted from [22]

$$C_{D_L} = k(C_L^2) \tag{5}$$

where k is a constant defined by:

$$k = \frac{1}{\pi e \mathit{AR}} \tag{6}$$

with e being the Oswald efficiency factor and AR the wing aspect ratio.

For a straight level flight, the lift force (L) is equal to the weight of the aircraft (W). Thus, combining Eqs. 3, 4, 5 and 6, the following expression is obtained for the total Required Power of the aircraft:

$$P_{Req} = \frac{1}{2}\rho V^3 S C_{D_0} + \frac{2kW^2}{\rho S V} \tag{7}$$

This power for a hybrid-electric aircraft can be split into two contribution installments: the one from batteries (P_{bat}) and the one provided by the internal combustion engine (P_{ICE}). They can be related to the degree of hybridization in terms of power:

$$P_{Req} = \eta_H P_{em} = P_{bat} + P_{ICE} = \psi P_{Req} + (1-\psi)P_{Req} \tag{8}$$

where η_H is the propeller efficiency and P_{em} the total power provided by all electric motors.

On the other hand, the total takeoff weight of a hybrid-electric aircraft can be divided into the following parts:

$$W_{TO} = W_{empty} + W_{payload} + W_{em} + W_{bat} + W_{ICE} + W_{fuel} \tag{9}$$

with W_{empty} being the empty weight of the aircraft, $W_{payload}$ the weight of the payload, W_{em} the weight of the electric motors on the wings, W_{bat} the weight of the batteries, W_{ICE} the weight of the internal combustion engine, and W_{fuel} the weight of fuel.

The empty weight (W_{empty}) is calculated using a statistical regression proposed by Roskam [30] from the relationship with the total takeoff weight, expressed by:

$$\log_{10} W_{TO} = A + B \log_{10} W_E \tag{10}$$

where the A and B coefficients are obtained from [30]. It is worth mentioning that Eq. 10 is based on historical data, which has not accounted for the impact of hybrid-electric systems. Even though the estimation is not very accurate for case study of this work, the authors consider that these empirical methods could still be valid for hybrid-electric aircraft within the general aviation class.

On the other hand, the payload weight ($W_{payload}$) is directly obtained by the number of people who make up the crew (N_{crew}) and the number of passengers to be transported (N_{pax}). Thus, considering an average weight of 78 kg for each crew member and 102 kg for each passenger, including baggage, the estimation becomes:

$$W_{payload} = \left(N_{crew} \cdot 78 + N_{pax} \cdot 102\right)g \quad (11)$$

where g is the gravitational acceleration in m/s^2.

Regarding the characteristics of electric motors and engine, this work assumes a linear trend behavior for a historical database. Thus, a linear regression is computed through two suitable populations of electric motors and engines, as reported in Tables 1 and 2, respectively.

Next, the power split that comes from each part of the architecture are described, i.e., the amount of power that is supplied by the combustion engine and by the batteries to drive the electric motors in each flight phase. Also, their respective sizing are computed.

4.1 Climb

During a climb at a constant angle θ, as illustrated in Fig. 5, the vertical component of speed is considered, by definition, the Rate of Climb (ROC or $\dot{h}$):

$$ROC = \dot{h} = V \sin\theta \quad (12)$$

Table 1 Electric motors examples

Electric motor	Power [kW]	Mass [kg]
REX30	20	5.2
REX50	28	7.9
REX90	60	17
Siemens SP90G	65	13
REB90	70	22
EMRAX 348	210	42
Siemens SP260D	261	50
Magnix Magni 250	280	71
Magnix Magni5	300	53
Magnix Magni500	560	133

Solving fot the equilibrium of forces for a constant climb, we have that:

$$T - D - W\sin\theta = 0 \quad (13)$$

$$L - W\cos\theta = 0 \quad (14)$$

Since $L = W\cos\theta$, the expression of the Required Power in the climb phase is given by:

$$P_{Req_{climb}} = \frac{1}{2}\rho V^3 S C_{D_0} + \frac{2k(W\cos\theta)^2}{\rho S V} \quad (15)$$

Each weight component of Eq. 9 is then calculated:

– *Weight of electric motors* (W_{em}):
  From Eq. 8, the total power required in the electric motors is obtained and, consequently, the power in each of the n motors in each wing:

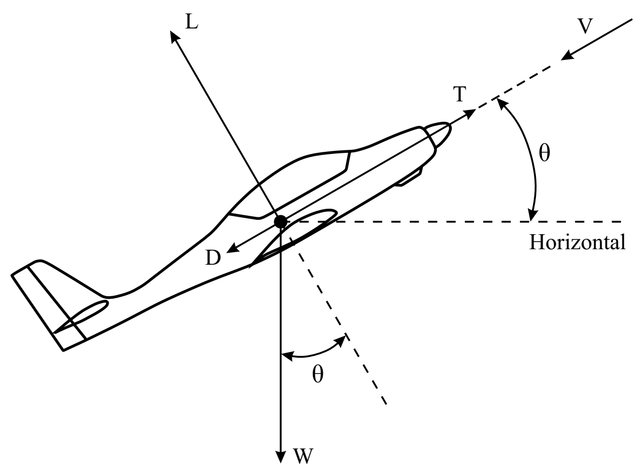


Fig. 5 Illustration of forces acting on the aircraft during climb

Table 2 Engines examples

Engine	Power [kW]	Mass [kg]	Fuel consumption [kg/hr]
Rolls-Royce 250-C20	294	96,2	71,5
Rolls-Royce 250-C20F	309	73,1	101,1
Rolls-Royce Bell 206L LongRanger	331	78,5	101,6
Turbomeca Artouste IIC	353	115.1	178.6
Rolls-Royce 250-C28	368	105.7	112.5
Turbomeca Astazou IIA	385	122.1	147.3
Pratt & Whitney PT6A-6	431	122.5	175.8
Pratt & Whitney PW206D	471	107.5	156.8
Honeywell LTS101-750C-1	503	121.5	178.4
Pratt & Whitney PW207D	522	110.1	172.3

$$P_{em} = \frac{P_{Req}}{\eta_H} \Rightarrow P_{i,em} = \frac{P_{em}}{2n} \quad (16)$$

Using the linear regression obtained through Table 1, the value of the weight of each motor individually is obtained and, consequently, the total weight of the electric motors:

$$W_{em} = 2nW_{i,em} \quad (17)$$

– *Weight of batteries* (W_{bat}):
  The required power in the battery is easily found by the relation $P_{bat} = \psi P_{Req}$. To calculate the battery weight, it is necessary to estimate the amount of energy consumed during the flight phase. During the climb phase, the energy consumption time is equivalent to the time taken for the aircraft to leave the altitude of the airport and reach the cruising altitude (which in this case is 12000 ft) at a certain vertical speed $\dot{h}$. From that time, one can get:

$$W_{bat} = \frac{\psi P_{Req} \Delta t_{climb}}{s_{bat}} g \quad (18)$$

where s_{bat} is the specific energy of the battery in Wh/kg.

– *Weight of the internal combustion engine* (W_{ICE}):
  From Eq. 8, the total required power in the internal combustion engine is obtained:

$$P_{ICE} = (1 - \psi)P_{Req} \quad (19)$$

Having the linear regression obtained through Table 2, the corresponding internal combustion engine weight is obtained.

– *Weight of fuel* (W_{fuel}):
  The fuel consumption is directly related to the type of internal combustion engine and the time this engine will be operating. Therefore, using the linear regression obtained from Table 2, the corresponding internal combustion engine consumption value ($\dot{m}_{ICE}$) is obtained and, using the phase duration time (which in this case it is Δt_{climb}), the total fuel weight is obtained:

$$W_{fuel} = \dot{m}_{ICE} \Delta t_{climb} g \quad (20)$$

It is worth mentioning that the fuel consumption is considered constant during the flight phase. This happens because the propulsive system has a hybrid-electric architecture, i.e., a combination of power supplied by batteries and engine that drive the electric motors. Therefore, as the mission goes on, fuel is burnt, which reduces the aircraft total weight. Since the power required changes along the flight, the energy and power supplied by the battery varies along with it, and the engine keeps its behavior constant.

4.2 Cruise

The procedures for calculating the weight components of electric motors, batteries, internal combustion engine and fuel are similar to those performed for the climb; however, as a straight level flight is considered during cruise, there is no climb angle ($\theta = 0$) and the time, which was previously related to the climb duration (Δt_{climb}), now it is used the estimated time to reach a pre-established range (R) at a certain flight speed (V):

$$\Delta t_{cruise} = \frac{R}{V} \quad (21)$$

5 Multi-objective optimization

Most of the real problems found in the optimization area involve the achievement of several goals that must be achieved simultaneously [31]. They are generally conflicting, that is, there is no single solution that optimizes them all at the same time. For such a class of problems we must seek a set of efficient solutions.

Problems of this nature are called multi-objective optimization problems because they involve simultaneous minimization (or maximization) of a set of objectives satisfying a set of restrictions. In this case, the decision-making is responsibility of the analyst, who must weigh the overall objectives of the problem and choose one of the solutions from the set of efficient solutions [32].

Multi-objective optimization can be defined as the problem of finding a vector of decision variables whose elements represent objective functions. These functions form a mathematical description of the optimality criterion that are in conflict with each other. In this case, the term “optimize” means finding a set of solutions that cannot be improved simultaneously for the analyst.

Formally, a multi-objective optimization problem can be formulated as:

$$\text{minimize} \quad z = f(x) = (f_1(x), f_2(x), \dots, f_{OB}(x)) \quad (22)$$

$$\text{subject to:} \quad g(x) = (g_1(x), g_2(x), g_3(x), \dots, g_r(x)) \leq 0 \quad (23)$$

$$x = (x_1, x_2, x_3, \dots, x_n) \in X \quad (24)$$

$$z = (z_1, z_2, z_3, \dots, z_r) \in Z \quad (25)$$

where x is the vector of design variables, OB the number of objectives, z is the objective vector, X denotes the decision search space, and $z = f(x)$ is the X image, called the objective space.

While in mono-objective optimization an optimal solution is clearly identified, in multi-objective optimization there is a set of alternatives, generally known as Pareto-optimal solutions, which can also be called efficient solutions, or an acceptable set of the problem.

According to Pareto [33], the concept of Pareto-optimal is the origin of the search for multi-objective optimization. By definition, a vector z is Pareto-optimal if there is no other viable vector z^* that can improve some objective, without causing a worsening in at least one other objective. In other words, a z solution vector belongs to the Pareto-optimal solution set if there is no z^* solution vector that dominates z.

5.1 NSGA II

The NSGA II algorithm (Non-dominated Sorting Genetic Algorithm II) was proposed by Deb et al. [34] as an evolution of the NSGA algorithm [35]. It combines the current population with the previous population to preserve the best individuals. In addition, it is based on an elitist order of dominance (Pareto ranking).

NSGA-II employs a tournament selection process, considering that the aptitude (fitness), rank_S, of each individual S, depends on the N_{i_d} frontier which belongs and on the crowd distance $dist_S$. In this case, an individual S is compared to an individual p to choose which one should be used to generate descendants in the new population.

The selected individual will be the one with the lowest *rank* value. In other words, the individual S will be chosen if S has a *ranking* lower than p ($rank_S < rank_p$). If both individuals have the same *ranking*, the one with the highest crowd distance value will be chosen ($rank_S = rank_p$ and $dist_S > dist_p$).

The selected individual will be the one with the lowest value of rank. In other words, the individual S will be chosen if S has a ranking less than p ($rank_S < rank_p$). If both individuals have the same ranking, the one with the highest crowd distance value ($rank_S = rank_p$ and $dist_S > dist_p$) will be chosen.

6 Methodology

In this work, the NSGA II will be used to perform the multi-objective optimization of the flight phases during the climb and cruise of a hybrid-electric aircraft. The objective functions are to minimize fuel consumption and maximize the extra payload. The design variables include the number of electric motors per wing, the degree of hybridization, speed, takeoff weight and angle of climb (in the case of the climb phase). The constraint involves the fact that the aircraft's speed must be at least 20% of the stall speed. The number of electric motors, n, up to 4 is a personal choice. The degree-of-hybridization, ψ, from 0.1 to 0.99 represents the possible range. The values of the airspeed, V, from 60 m/s to 90 m/s and takeoff weight, W_{TO}, from 1600 kg to 2200 kg comprise the average of the competitors of the aircraft in the market. The range of θ from 9^o to 13^o covers the typical climb angle of most aircraft.

The problems of multi-objective optimization per flight phase are summarized as follows:

$$Climb : \begin{cases} \left(W_{fuel}\right) \quad \text{and} \quad max\left(W_{payload,extra}\right) \\ g : V \geq 1.2V_{stall} \\ x : [n, \psi, V, W_{TO}, \theta] \\ 0 \leq n \leq 4 \\ 0.1 \leq \psi \leq 0,99 \\ 60 \leq V \leq 90 \quad [\text{m/s}] \\ 1600 \leq W_{TO} \leq 2200 \quad [\text{kg}] \\ 9^o \leq \theta \leq 13^o \end{cases}$$

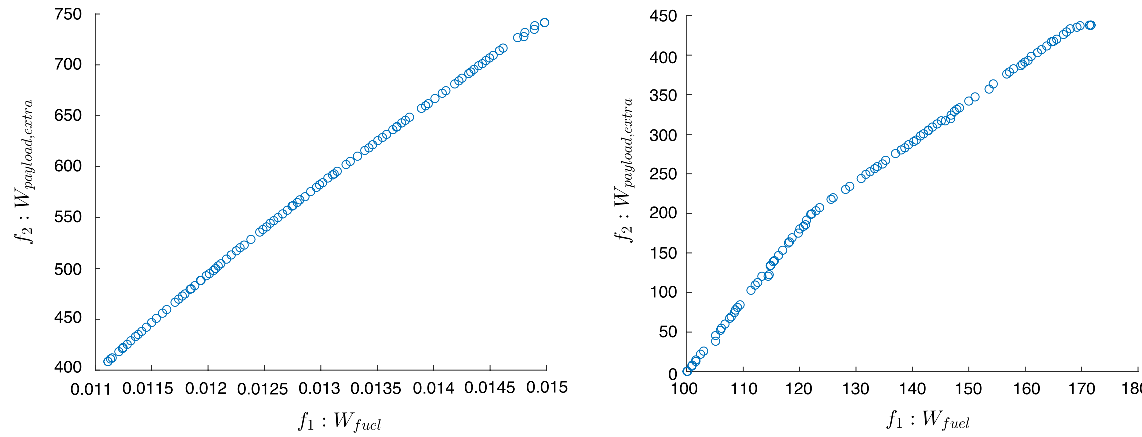
$$Cruise : \begin{cases} \left(W_{fuel}\right) \quad \text{and} \quad max\left(W_{payload,extra}\right) \\ g : V \geq 1.2V_{stall} \\ x : [n, \psi, V, W_{TO}] \\ 0 \leq n \leq 4 \\ 0.1 \leq \psi \leq 0.99 \\ 60 \leq V \leq 90 \quad [\text{m/s}] \\ 1600 \leq W_{TO} \leq 2200 \quad [\text{kg}] \end{cases}$$

The NSGA II algorithm was executed several times with a number of populations of 100, generations equal to 500, a crossover index of 20 and a mutation index of 20. Changes were also made to these parameters, but all converged to the same results. The other values of aerodynamic constants and aircraft characteristics used in the equations were extracted from Silva and Gil [36].

7 Results and discussion

The Pareto solutions or optimums of the multi-objective problems for both flight phases are shown in Fig. 6. The variations of the design variables in the solutions are shown in Table 3. For the climb phase, as the duration time is very low, the algorithm threw the solution to the highest possible degree of hybridization, that is, the greatest possible use of the battery; consequently, fuel consumption is extremely low, as illustrated in Fig. 6a. In the case of the cruise, as the duration time is longer, the algorithm balanced the best amount of battery mass and fuel consumption. Figure 6b shows a very low fuel consumption for a range of 1800 km. This is allowed by the low operating speed (closer to the minimum required power condition) and the use of batteries at a certain degree-of-hybridization.

In general, the solution found presents a good strategy to balance the mass distribution of batteries, together with the quantity, power and mass of the electric motors and the



(a) Climb. **(b)** Cruise.

Fig. 6 Pareto curve that represents the optimal solution for the two phases of the evaluated mission

Table 3 Range of design variables in the solution

Flight phase	n	ψ	V [m/s]	W_{TO} [kg]	θ [^{o}]
Climb	2	0.99	60 to 61	1600 to 2000	13
Cruise	2 to 4	0.01 to 0.21	60 to 68	1600 to 2200	–

Table 4 Range of design variables in the solution

Flight phase	n	ψ	V [m/s]	W_{TO} [kg]	θ [^{o}]
Climb	2	0.99	60	1800	13
Cruise	4	0.20	65	1800	–

internal combustion engine. This type of analysis is essential in flight planning and, even more, in the conceptual and preliminary design of any aircraft. The reduction of fuel, specifically, enables flights of the short-haul category, which are flights of short duration and distance, allowing new routes between small cities that until then were not economically attractive for airlines. In addition, a reduction of a few kilograms of fuel per flight when multiplied by the various flights performed daily and by the various aircraft from which they fly at the same time means considerable net revenue in balancing of a company. Nonetheless, the amount of greenhouse gases that is released into the atmosphere is much less.

7.1 Result in the hybrid-electric propulsive system

Choosing two points in the Pareto solutions of Fig. 6a and b, the values of the design variables present in Table 4 are obtained. From the defined degree-of-hybridization, it is possible to illustrate the equivalent hybrid propulsion system at the moment of the flight phase under evaluation, as illustrated in Figs. 7 and 8, for climb and cruise, respectively.

From Figs. 7 and 8, it is clear that the battery is much more required during the climb than during the cruise. In addition, propeller efficiencies of 0.85 and electronic equipment of 0.99 were considered. The black values represent the power in kW supplied by each component of the propulsive system, and the red values represent the power in kW lost due to the efficiency of each component.

7.2 Technical-scientific impact

Even with technological advances and, consequently, the increase in the specific energy of batteries, electrification brings with it an increase in weight due to the installation of several components associated with the chosen hybrid-electric architecture. However, a major direct effect of electrification is the partial or total replacement of fuels.

For short flights and smaller aircraft, the specific energies of the current batteries are already able to partially meet the requirements, generating good results. In this way, as this specific energy increases, it is possible to further incorporate electrification in the design of large aircraft, which requires a large amount of energy per mission. In addition, if electricity becomes cheaper than aviation fuel per unit of energy, then there will be a big reduction in operating costs, which is a great advantage of this type of technology. Depending on how this electricity is produced, that is, if renewable electricity generation is assumed, there is a direct reduction in carbon emissions.

Fully-electric aircraft still have the advantage of not dealing with problems related to the thermal cycling of engines. In this case, since only batteries are installed, if the aircraft uses superconducting wires and new power electronics, the electrical efficiency can reach values close to 1. Additionally,

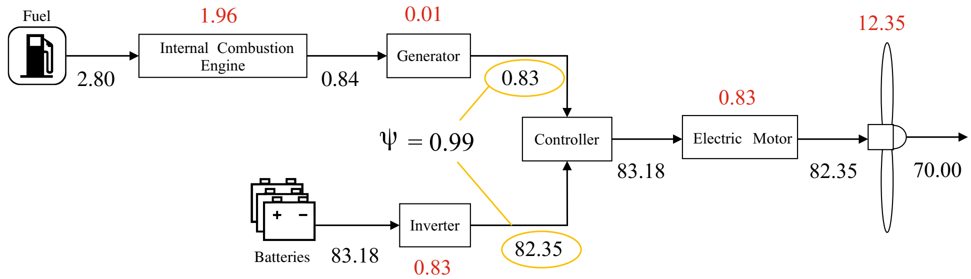


Fig. 7 Propulsive system during climb. Values in kW

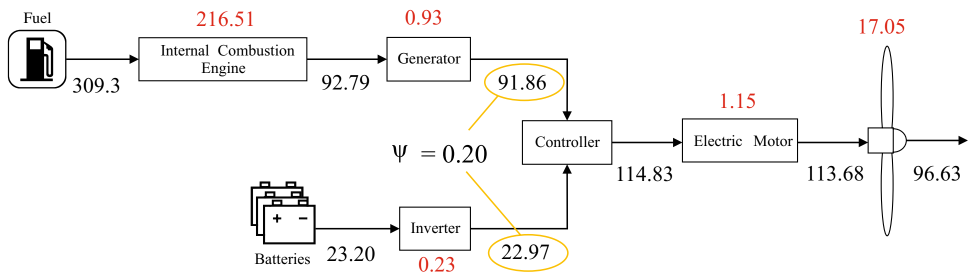


Fig. 8 Propulsive system during cruise. Values in kW

in the case of turboelectric aircraft, there is the presence of gas turbines, which experience thermodynamic losses. However, if the aircraft has only batteries installed and an external ground engine is used to recharge them, that engine will be more efficient, as it is not dealing with the effects of altitude. In addition, it is possible to reduce the maintenance cost by replacing combustion engines and fossil fuels with electric motors and batteries, since this set of equipment would have fewer moving parts than its combustion counterpart. This would make the operation of the aircraft more consistent and predictable.

8 Conclusions

This work approaches a multi-objective optimization study of two phases of flight (climb and cruise) of a hybrid-electric aircraft. In this context, NSGA II was used to minimize fuel consumption spent on missions and maximize the extra payload. The optimization variables involve the number of electric motors arranged on the wings, the degree of hybridization, the airspeed of operation, the takeoff weight and also the angle of climb. After executing it several times, it was noticed that the algorithm was able to find Pareto's optimal solutions and the results showed low fuel consumption levels, which was enabled by the low operating speed and the use of the maximum possible of battery in each phase.

Moreover, considering only the climb phase, since its duration is relatively small with respect to cruise, the impact of weight of battery is very small, leading the optimizer to the greatest value of degree-of-hybridization ($\psi = 0.99$). The velocity kept near 60 m/s because at this condition the required power is smaller and, consequently, less energy is spent, what implies in less fuel consumption, which is one of the objective-function of the optimizer. The takeoff weight varied from 1600 kg to 2000 kg, i.e., the requirements are fulfilled for any weight in the range. The angle θ kept at 13^o because at a higher climb angle, less time is needed to reach the cruise altitude, then reducing the fuel consumption, even though the required power is may be higher.

On the other hand, considering only the cruise phase, the degree-of-hybridization varied from 0.01 to 0.21. This happens because since the duration of the cruise is greater, if a high ψ was set, a great amount of battery would be needed, what would result in a much heavier aircraft. Therefore, the optimizer counted for it e made the balance among the benefits of burning less fuel or carry more baggage.

Notwithstanding, it is worth mentioning that the specific energy of the batteries is crucial to enable the electrification of the project. In other words, if the battery presents a greater specific energy, the aircraft is capable of carrying out longer missions, but keeping the same weight, which is a big challenge. Thus, the advancement of technologies is the main factor that will determine the progression of fully-electric and hybrid-electric aircraft projects. In addition, electrification brings many benefits, but also many problems, including effects of electrification on propulsion, aerodynamics, sizing, weights, system safety, noise and thermal signature. Therefore, it is important to highlight the current challenges and future needs for research and technology, where most of them have been discussed in debates and panels of congresses and international commissions.

The performance analysis strategy addressed allows a range of operations for different categories of aircraft, which generates a field of research that is still quite vast to be explored. As a sequence of this work, it is intended to integrate all phases of the typical flight mission in order to obtain a minimum fuel consumption for the entire mission, in addition to including in the project variables parameters such as altitude and range.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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