

CONFIGURATION OF HYBRID FUEL-ELECTRIC AIRCRAFT MODEL BASED ON FULL FLIGHT PATH PERFORMANCE

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Graphical abstract

FFS-PH propulsion powertrain

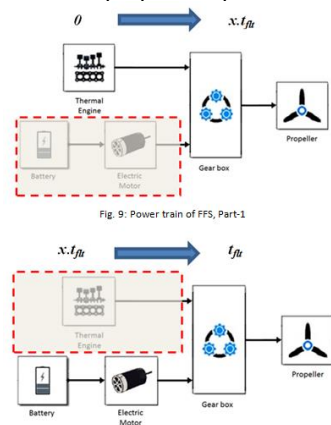


Fig. 9: Power train of FFS, Part-1

Abstract

A new approach to enhance the performance of hybrid fuel-electric aircraft is investigated. This approach adopts Fuel-first strategy (FFS) to increase the effectiveness of electrical propulsion. To illustrate the effectiveness of this method, it is compared to other propulsion types. The FFS is based on starting the electric propulsion only after the aircraft reaches the lowest weight. That is, when fuel is fully consumed. This involves inflight switching of propulsion type, where the first part of the flight is powered by fuel only and the second part is fully-electric. A hybrid version of Piper Cherokee is used to demonstrate the new concept. Modified versions of Breguet equation and Payne range strategy are used to calculate aircraft performance. Adopting FFS resulted in 10.3% fuel saving relative to conventional propulsion as well 4.2% fuel saving relative to parallel hybrid propulsion. The main theme behind this proposal is that by consuming the fuel first, the aircraft becomes lighter sooner, and this enables the batteries to power the aircraft for longer range. Upon comparing the method with other methods in the literature, it was found superior in terms of fuel consumption and performance.

Keywords: Hybrid propulsion, Fuel-Electric propulsion, Hybrid aircraft, Flight performance, Fuel-first strategy

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1.0 INTRODUCTION

The emergence of Hybrid fuel-electric propulsion is meant to reduce the effects of oil price volatility, as well as mitigate carbon footprint. Despite the existing challenge of limited battery capacity, this goal became more realistic as technology advanced further [1]. One of the main reasons for pursuing hybrid aircraft design is to reduce exhaust gas emissions, while the amount of emissions is directly related to the amount of fuel burned. Shahid *et al.* [2] reviewed efforts to reduce greenhouse gas emissions in Malaysia, especially in transport sector. They concluded that more prudent strategies are needed for climate-friendly development of transportation to achieve sustainability goals. In the literature, multiple aircraft hybridization configurations were investigated; including series, parallel, engine size reduction, and combined series-parallel. In the

meantime, different hybridization ratios were considered; Voskujil *et al.* [3] employed a constant power split strategy where the ratio of the power setting of the Engine and the Electric Motor (EM) is fixed for all flight phases. The EM provided 34% of the shaft power throughout the mission, yielding a reduction in emissions of 28%. The main types of hybrid systems that are usually investigated include series and parallel layouts [4]. Different configurations of hybrid powertrains are possible; the series design is the easiest to implement since the internal combustion engine (ICE) is not directly connected to the main thrust of the aircraft [5]. The ICE drives the generator which charges the battery, while the battery is connected to the inverter and the controller which are connected to the EM [6].

In the Parallel Hybrid (PH) configuration, the fuel is used to operate the ICE and the battery is used to operate the EM, while the aircraft is propelled by both

the ICE and the EM. One key design consideration in parallel systems is the efficiency of the hybrid system [7]. The battery is considered the main component of electric propulsion systems; where one of its most important types is Lithium-ion (Li-ion) battery. It is widely used in many applications, such as phones, appliances, and automobiles [8]. Some studies showed that the specific energy of Li-ion battery was 750-1500 Wh/Kg, battery efficiency was 95%, and EM efficiency was 98% [8]. It was reported by Katrašnik *et al.* [9] and Friedrich and Robertson [7] that PH powertrains provide better fuel economy than the series-hybrid ones. Therefore, in this work, the series-hybrid option will not be pursued. Since it is widely accepted that the PH is the most efficient architecture for aircraft hybridization, the most obvious option to improve the efficiency of the hybrid aircraft is to develop batteries with higher specific energy, as concluded by Sliwinski *et al.* [10].

Bravo *et al.* [11] reported that full-electric propulsion is not suitable for light aircraft, while piston engine is optimal for light aircraft hybrid propulsion. In addition, they concluded that parallel-hybrid propulsion is preferable to series propulsion. Rohacs and Rohacs [12] presented energy factors to evaluate the energy used per unit of work performed by aircraft. These factors can be used to compare the energy efficiency of aircraft at the conceptual design stage. They also reported that energy intensity defined for cruise can be used to compare the aerodynamic goodness of aircraft. Baharozu *et al.* [13] compared traditional, more electric, and liquid hydrogen aircraft using a multi criteria scoring method. As a result of the comparison, a future aircraft concept for long distance flights was proposed; combining the more electric concept and the liquid hydrogen concept. Brelje and Martins [14] surveyed the literature on fixed-wing aircraft propelled in whole or in part by electricity. They explored the emerging problem of aircraft thermal management. They concluded that electric aircraft design introduces new coupling between previously distinct disciplines, such as aerodynamics and propulsion, which may only become apparent with high-fidelity, physics-based analysis.

Pornet and Isikveren [15] presented a quad-fan narrow-body aircraft equipped with two Turbofans and two Electrical Fans. The performance of the concept was analyzed in terms of fuel burn and efficiency in comparison to a conventional counterpart. They concluded that the short-range market would be the most suited for the application of hybrid concepts. Hung and Gonzalez [16] presented an analysis of parallel hybrid-electric propulsion for fixed-wing unmanned aerial vehicles. They incorporated an Ideal operating line control strategy to determine the most efficient points of operation for the piston engine. They showed that the hybrid vehicle is capable of achieving a fuel saving of 6.5%, compared to the engine-only configuration.

Another method to enhance the efficiency of hybrid propulsion is to use the battery power in the

early high power-demanding phases of the flight. By doing so, it would be possible to reduce the engine size. Thereby reducing both weight and fuel consumption. This method was proposed by Ang *et al.* [17], where they introduced a strategy to manage the power in a hybrid aircraft by propelling it electrically during taxiing and providing electrical assistance during take-off and climb phases. With a climb power split of 14% electrical and the remaining mechanical, the total energy consumption is reduced. A take-off power split of 25% electrical allowed the engine to be downsized to 90% and operate close to its design point during cruise. This configuration can reduce fuel consumption by 7.5% and the total energy consumption by around 2% [17]. A similar result was reached by Hoelzen *et al.* [18], where they presented a mission profile for flight path power demand, where each flight phase is assigned with a constant power setting. They suggested a minimum battery sizing to provide energy for maximum power peak shaving of the engine power rating. In this case the battery is not used for any energy demand below this power rating. The engine can be downsized with this strategy, coherent with a decrease in aircraft weight.

It should be noted that operating the engine at less than maximum power is recognized by the industry as being beneficial to its life [19]. However, the method of reducing engine size requires the engine to operate at its maximum capacity during the cruise phase. Consequently, this mode of operation will make in-flight failure of the engine more likely, thereby, jeopardizing the flight safety. In addition to efforts to improve battery energy density, most of the previous efforts have focused on reducing engine size; however, as mentioned earlier, reducing engine size results in reducing flight safety.

In this work, a new approach to increase hybrid propulsion efficiency is investigated. This approach is called Fuel First Strategy (FFS); FFS implies operating the aircraft in fuel-only mode from the beginning of the flight up to a certain point during cruise. At that point, once fuel is fully burnt, the propulsion is switched to full-electric mode. This operational scenario enables electric propulsion at the aircraft minimum weight, thereby saving battery energy. The overall performance of this strategy will be compared to the performance of the corresponding PH configuration, which simply uses both fuel and electric propulsions throughout the whole flight.

For the purpose of illustrating the FFS, an existing aircraft model is selected and different operational scenarios are evaluated; including the baseline conventional (ICE) model, the full-electric model, the PH model, and the FF-strategy model. These models will be compared in terms of flight performance parameters including range and fuel consumption. Impact on aircraft weight due to additional equipment such as batteries, motor and power electronics will be included. The baseline model selected for this work is Piper PA-28-180 Cherokee aircraft propelled by a piston engine. Donateo and Totaro [20] proposed a hybrid version of this aircraft

powered by both an ICE and EM. Modified versions of Breguet equation are used to calculate the contribution of the ICE to the range and flight time of the aircraft. On the other hand, the range and flight time components due to electric propulsion are calculated using the Payne range strategy based on battery capacity [10].

2.0 METHODOLOGY

2.1 Conventional Propulsion

2.1.1 Aircraft Model

The baseline aircraft model selected for this work is the Piper PA-28-180 Cherokee equipped with Lycoming O-360-A, a four cylinder engine whose rated power is 180 HP (135 kW) at 2700 rpm [20]. For all cases that will be considered in this work; including conventional, PH and FFS, the same flight conditions and mission profile will be employed; which includes takeoff, climb, cruise, descent, and landing, with a total flight time of around four hours. However, because the flight is relatively long haul, it is dominated by the cruise phase. Hence, for the purpose of this work, only the cruise phase is considered. The conventional powertrain configuration is shown in Figure 1 and the model data is presented in Table 1. Most of the presented aircraft parameters are taken as constants; This approximation is done based on the fact that the cruise phase normally represents more than 80% of the total flight time [21]. Therefore, in this work, the aircraft performance over the full flight path is approximated by the performance in the cruise phase.

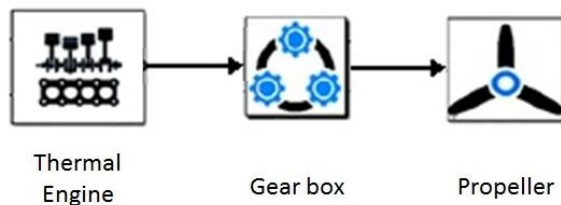


Figure 1 Conventional propulsion powertrain [22]

Table 1 Conventional model data [23], [20], [24], [25]

Parameter	Symbol	Value
Propeller efficiency	η_{prop}	0.8
Maximum Lift-to-drag ratio	$(L/D)_{max}$	10
Maximum takeoff mass	m_0	1,091 kg
Maximum zero fuel mass	m_1	960 kg
Maximum fuel weight	m_f	131 kg
Aircraft basic weight	m_b	492 kg
Maximum payload	m_p	468 kg
Specific fuel consumption	C_{SFC}	$6.8 \times 10^{-7} \text{ m}^{-1}$
Air density	ρ_∞	1 kg/m ³
Wing area	S	14.86 m ²
Lift Coefficient	c_L	0.36
Drag Coefficient	c_D	0.036
Cruise speed	v_C	123 kts
Fuel density	ρ_f	0.721 /l

2.1.2 Thermal Engine Operation

The fuel flow rate in the engine is calculated as:

$$\dot{m}_f = BSFC \cdot BHP_e \quad (1)$$

Where BSFC is the engine brake specific fuel consumption and BHP_e is the engine power.

2.1.3 Gear Box Operation

As shown in Figure 3, the gearbox is the key element of the hybrid system. It permits the addition of the power produced by thermal engine to the power of the electric motor.

2.1.4 Propeller Operation

The power absorbed by the propeller can be expressed as a cubic called "Propeller load curve":

$$BHP = K_p \cdot n^3 \quad (2)$$

Where K_p is a constant and n is engine speed.

2.1.5 Aircraft Range

The conventional aircraft range (R_C) is calculated using a modified version of Breguet equation as [10]:

$$R_C = \frac{\eta_{prop} L}{C_{SFC} D} \log \frac{m_0}{m_1} \quad (3)$$

Where

- η_{prop} : Propeller efficiency
- C_{SFC} : Specific fuel consumption
- $\frac{L}{D}$: Lift-to-drag ratio (aerodynamic efficiency)
- m_0 : Takeoff weight
- m_1 : Zero fuel weight

Specific fuel consumption (C_{SFC}) is defined as the rate of fuel consumption per unit shaft power, as shown in equation (2):

$$C_{SFC} = \left(\frac{\dot{m}_f}{P} \right) \quad (4)$$

Where \dot{m}_f is the fuel flow (kg/h) and P is the shaft power (W). Prior to departure, the aircraft must be fueled up to a certain amount, therefore, the aircraft takeoff mass will be (m_0). This weight is equal to the sum of the aircraft zero fuel mass (m_1) and the fuel mass (m_f), as shown in eq. (3):

$$m_0 = m_1 + m_f \quad (5)$$

Moreover, m_1 can be calculated by adding the aircraft basic mass (m_b) to the payload (m_p) as follows:

$$m_1 = m_b + m_p \quad (6)$$

In addition to aircraft range, flight time (t_{flt}) (in hours) is an important parameter. It can be calculated using the Breguet flight time equation as [10]:

$$t_{flt} = \frac{\eta_{prop}}{c_{SFC}} \cdot \sqrt{2\rho_{\infty}S} \cdot \frac{c_L^{\frac{3}{2}}}{c_D} \cdot \left(\frac{1}{\sqrt{W_I}} - \frac{1}{\sqrt{W_0}} \right) \quad (7)$$

Where

η_{prop}	:	Propeller efficiency
c_{SFC}	:	Specific fuel consumption
ρ_{∞}	:	Air density
S	:	Wing area
c_L	:	Lift coefficient
c_D	:	Drag coefficient
W_I	:	Zero fuel weight (N)
W_0	:	Takeoff weight (N)

2.2 Full-electric Propulsion

Using the current battery technology, full-electric propulsion for the Piper aircraft is not feasible, as the flight would be too short; the energy density of aviation fuel is about 16 times more than that of the current battery. However, the efficiency of electric motors is about double that of thermal engines. Therefore, the net fuel energy will be reduced by half which makes it 8 times larger than the current battery. Nonetheless, this is a large difference. However, when counting for the expected future battery technology, this type of propulsion would be possible. A full-electric version of the selected aircraft powered by an EM is simulated using the Payne range strategy based on battery capacity Sliwinski *et al.* [10]. This version will be investigated especially in regards to the flight performance. The powertrain of the full-electric model is shown in Figure 2, while the electric propulsion parameters are listed in Table 2. The electric version simulation will be limited to 7 battery packs due to weight and volume constraints; The aircraft has five seats, and assuming a passenger weight of 80 kg, the total will be 400 kg. On the other hand, the total mass of electric propulsion system including seven battery packs is 66.6 kg as shown in Table 2, adding it to the weight of the passengers yields 466.6 kg, which closely matches the maximum payload of 468 kg, as shown in Table 1. This means adding more batteries will reduce the number of passengers, which was avoided in this work. Therefore, the number of batteries was limited to seven.

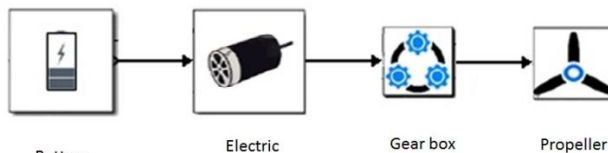


Figure 2 Full-electric propulsion powertrain

Table 2 Electric propulsion parameters Donateo and Totaro [20]

Parameter	Symbol	Value/Unit
Number of battery packs	n_b	7
Battery energy density	E	750 Wh/kg
Mass of battery packs	m_B	59.3 kg
Total mass of electric propulsion system	m_{te}	66.6 kg
Voltage	V	274 V
Current	I	45 A
Battery power density	P_B	7.7 kW/kg
EM power	BHP_m	40 kW
EM efficiency	η_{EM}	0.91
Mass of (motor, inverter, driver)	m_{total}	7.3 kg

2.2.1 Battery Model

The battery is fully charged prior to the flight, while discharging occurs during the flight. The discharge process will be modeled using the Shepherd model, where the state of charge (SOC) in percentage is defined as [26]:

$$SOC = 1 - \frac{1}{Q} \int_0^t i(t) \cdot dt \quad (8)$$

Where Q is Maximum capacity (Ah), t is time (s) and i is electric current (A).

2.2.2 Electric Motor Model

The electric motor is sized according to the power requirement which is based on the engine size. It is assumed that it has the same speed as the engine. It should be noted that the power and energy densities are related to the discharge current of the battery. The output power of the motor is defined as:

$$BHP_m = \eta_{EM} \times P_B \times m_B \quad (9)$$

Where η_{EM} is the motor efficiency, P_B is the battery power density and m_B is the mass of battery packs.

2.2.3 Electric Aircraft Range

The electric range (R_E) of a battery operated aircraft can be calculated using the following equation [10]:

$$R_E = E\eta_{total} \frac{1}{g} \frac{L}{D} \frac{m_{battery}}{m} \quad (10)$$

Where,

E^* : Battery energy density (Wh/kg)

η_{total} : Total propulsive efficiency (%)

g : Acceleration of gravity (m/s^2)

L/D : Lift-to-drag ratio (aerodynamic efficiency)

$m_{battery}$: Battery mass (kg)

m : Total mass (kg)

2.3 Parallel-hybrid (PH) Propulsion

This version of the aircraft is basically a combination of the two previous versions; the baseline conventional version and the full-electric version. It is powered by both an ICE and EM as proposed by Donateo and Totaro [20]. The powertrain of the PH propulsion is shown in Figure 3 while the data for the reference hybrid model is presented in Table 3. The hybrid model can be configured to have 1-7 battery packs along with a corresponding fuel mass as shown in Table 4.

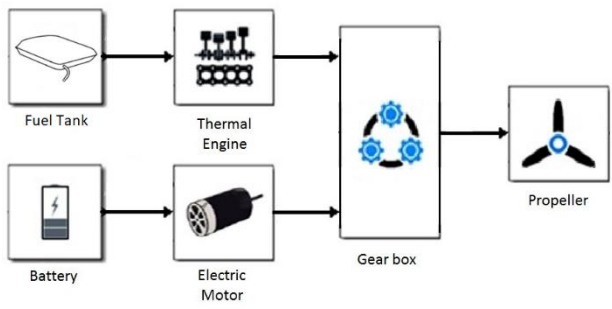


Figure 3 PH propulsion powertrain

Table 3 Hybrid model data [20]

Parameter	Symbol	Value/Unit
Battery energy density	E	750 Wh/kg
Mass of battery pack	$m_{battery}$	37 kg
EM mass	m_{motor}	40 kg
Aircraft total mass	m	1,039 kg
Voltage	V	274 V
Driver efficiency	η_D	0.88
EM efficiency	η_{EM}	0.91
Electric drive mass	m_{ED}	52 kg

2.4 Fuel-first Strategy (FFS)

The powertrain of the FFS is similar to the PH propulsion. However, Part-1 of the FFS is shown in Figure 4 where only the thermal engine operates; it runs from time $(t) = 0$ (the beginning of the flight) to $t = x.t_{fit}$, where x is the fraction of the flight time covered by part-1, and t_{fit} is the total flight time. Part-2 of the FFS is shown in Figure 5 where only the electric motor operates; it runs from $t = x.t_{fit}$ (which marks the end of Part-1) to t_{fit} . Even though the physical layouts of PH and FFS are the same, the logic of operation for each one is different, as explained earlier.

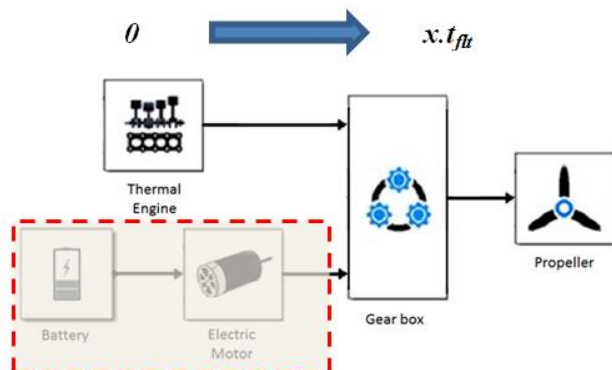


Figure 4 Power train of FFS, Part-1

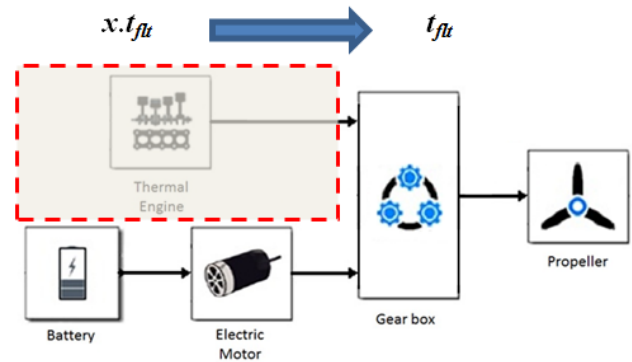


Figure 5 Power train of FFS, Part-2

3.0 RESULTS AND DISCUSSION

3.1 Model Validation

In order to validate the method used in this work, the conventional propulsion range results are compared to real-world flight profiles reported by Donateo and Totaro [20]. The comparison is done for the same conditions including takeoff weight of 1,039 kg and range of 221 nmi. Excellent agreement is found between the two methods. On the other hand, the comparison between the two hybrid methods (engine size reduction and PH) showed a difference of only 4%, which is acceptable bearing in mind that the two methods are basically different methodologies and are not expected to be identical. The parameters used for benchmarking are shown in Tables 1 and Table 2. Consequently, the foregoing outcomes validate the use of the modified Breguet range equation in this work.

3.2 Performance Simulation

The aircraft conventional model is simulated using the preceding equations in conjunction with the data in Table 1. Figure 6 shows the flight range versus fuel mass. As expected, the range increases with the fuel mass, while the relationship is linear. On the other hand, Figure 7 shows the variation of the flight time with the fuel mass; similarly, flight time increases with fuel mass in a linear fashion. In both cases the fuel mass reaches the maximum fuel capacity.

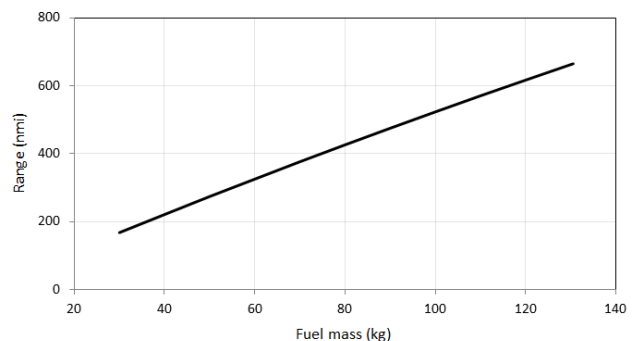


Figure 6 Range of the conventional model

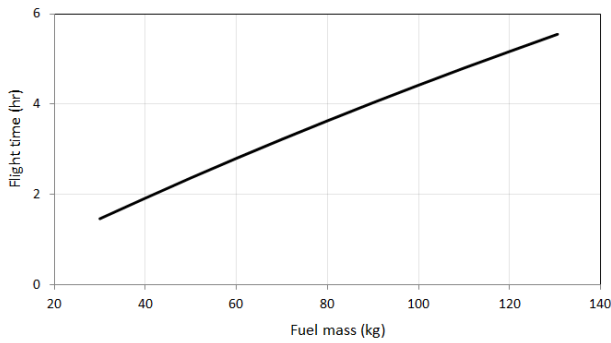


Figure 7 Flight time of the conventional model

The range and flight time for the full-electric propulsion are shown in Figure 8 and Figure 9, respectively. The relationship in both cases is almost linear, where the maximum number of batteries is 7. The reason for that is the small battery mass-to-aircraft mass ratio. It is noted that the range and flight time in this case are far less than those for conventional propulsion shown in Figure 6 and Figure 7. If the 7 battery packs option is selected together with 64 kg fuel, as shown in Table 4; the configuration will correspond to a hybridization factor of 24%, as shown in Figure 10, where it is noted that the hybridization factor is constant throughout the flight.

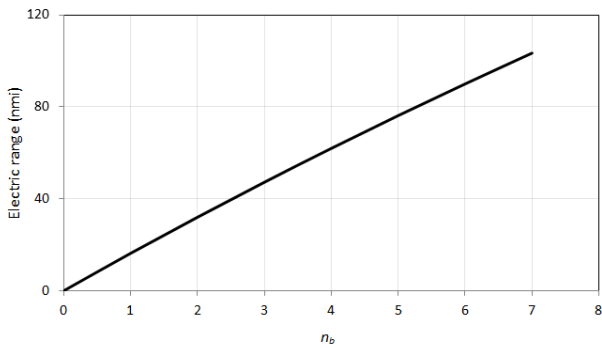


Figure 8 Fully-electric range vs. number of batteries

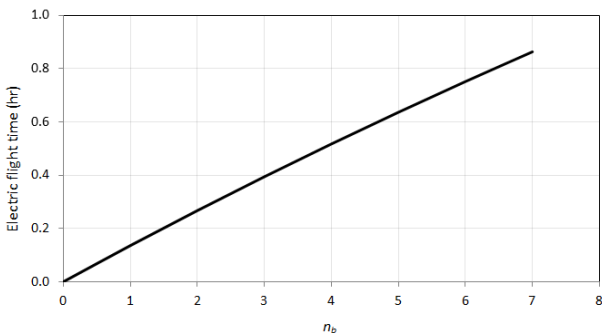


Figure 9 Fully-electric flight time vs. no. of batteries

Table 4 Hybridization ratios in PH configuration

No. of Battery packs	Fuel mass [kg]
1	115
2	106
3	98
4	89
5	81
6	72
7	64

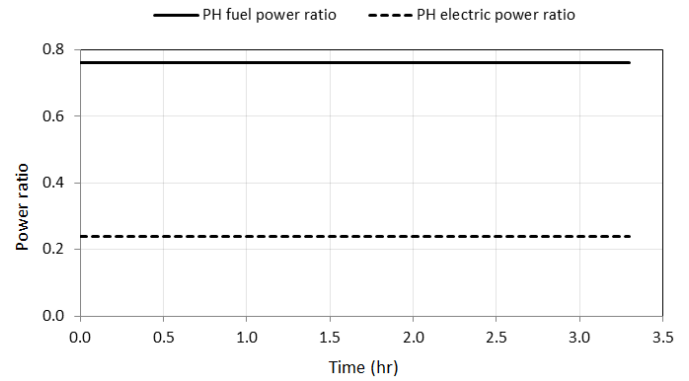


Figure 10 PH hybridization factor vs. flight time

In the FFS, the hybridization model still has 7 battery packs and 64 kg of fuel as shown in Table 4. However, this configuration alternates between hybridization factors of 1 and 0, as shown in Figure 11, where it is noted that the hybridization factor starts as zero and stays constant for 2.7 hours, i.e., fuel portion. At 2.7 hours flight time, the onboard fuel would be fully consumed and the thrust is switched to fully-electrical mode, where the hybridization factor becomes 1, and the flight is continued using battery power only, i.e., electric portion. This means the ICE propels the aircraft from the start of the flight until the point at 2.7 hours flight time. At that point, the ICE is switched off, simulating total fuel burn. At the same point, the EM is started to propel the aircraft and the batteries power the remaining part of the flight.

In terms of the total propulsion energy, the fuel portion contributes 80% of the total flight energy, while the electric portion contributes 20% of the total flight energy. On the other hand, the impact of changing payload on the power ratios is shown in Figure 12. In this scenario, 7 batteries and 117 kg of fuel are used. The fuel portion slightly decreases with payload because the aircraft becomes heavier and therefore consumes the fuel sooner. In the meantime, the electric portion "appears" slightly increasing with payload because it is less sensitive to the effect of aircraft higher weight, i.e., it actually decreases at a slower rate than the fuel portion, therefore it appears as if it is increasing relative to the total flight power.

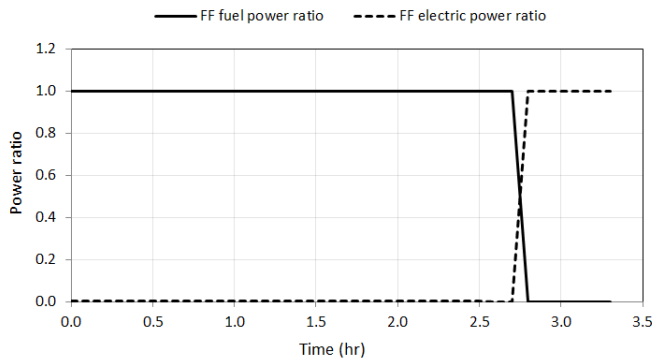


Figure 11 Hybridization factor vs. flight time for FFS

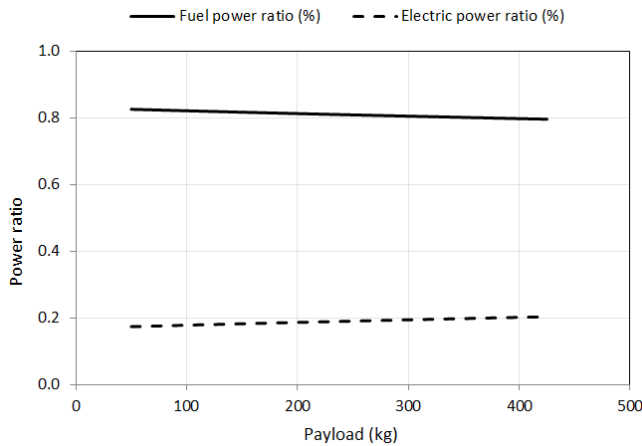


Figure 12 FFS fuel and electric energy ratios vs. payload

3.3 Comparison of Propulsion Types

In the preceding sections, the performance of different propulsion architectures was presented in terms of fuel burned, range, and flight time. In this section, the performance of the different propulsion schemes is compared based on range and flight time measurements at the same air speed and weight configuration. The performance results will be compared graphically. An expected trend of decreasing range with increasing payload is shown in Figure 13. It is noted that the FFS range drops below the ICE range at lower payloads because the electric equipment weight is constant and becomes more significant compared to the lower payload.

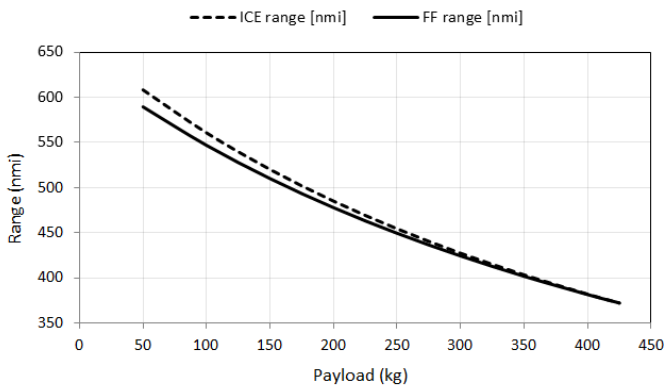


Figure 13 Range vs. payload for ICE and FFS propulsions

As illustrated in Figure 14, the flight time decreases with payload. In this case ICE continues to provide more flight time for most of possible payloads. However, for the highest payloads, FFS will slightly exceed the ICE. The same reason as explained in Figure 13 applies here, which has to do with the effect of the constant weight of the electrical components at lower payloads. Another reason is that when the aircraft is too heavy, the fuel is consumed faster, which will limit the flight time, especially for the ICE case. In this plot the FFS uses 7 battery packs and 117 kg of fuel, while the ICE fuel mass considered is 130.5 kg.

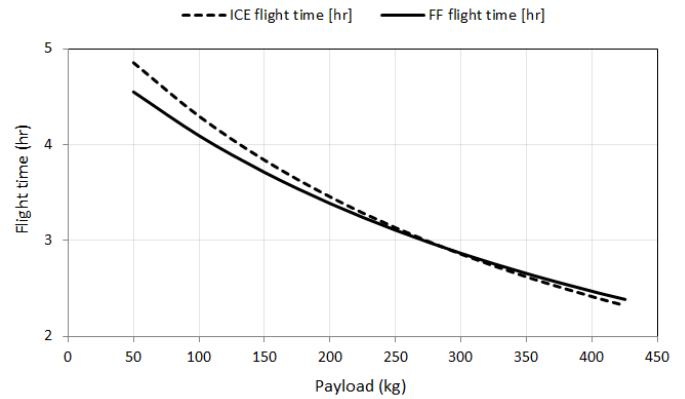


Figure 14 Conventional and FFS flight times vs. payload

Figure 15 shows the PH and FFS ranges vs. number of batteries; In this Figure, it is evident that applying the FFS would provide more range than the PH for the same conditions. The fuel savings achieved using the FFS is calculated using an equal range of 428 nmi for both PH and FFS, along with 7 battery packs. The fuel used is calculated for both methods, which is found to be 69 kg and 66 kg, respectively. It is found that FFS will provide a fuel savings of 4.2% relative to PH. Figure 16 shows the PH and FFS flight times vs. number of batteries. In this Figure, it is evident that applying the FFS would provide longer flight time than the PH for the same conditions.

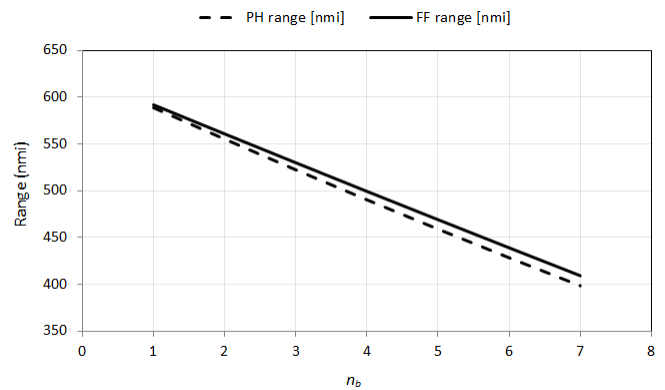


Figure 15 PH and FFS ranges vs. number of batteries

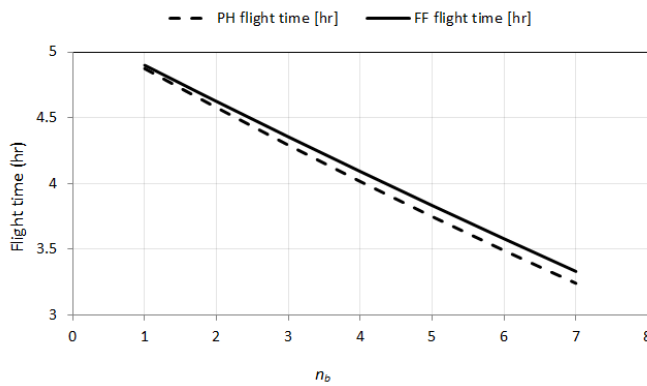


Figure 16 PH and FFS flight times vs. number of batteries

A trend of increasing fuel savings with increasing payload is shown in Figure 17. It shows fuel savings of FFS relative to conventional ICE propulsion. It is noted that FF propulsion provides more fuel savings for high payloads (up to 10.3%). However, for lower payloads fuel savings will drop down. This behavior is due to higher ICE fuel consumption at higher aircraft weights. Whereas for FF case, the second part of the flight will be powered by batteries, therefore, the effect of the constant weight of the electric equipment will be more pronounced as compared to the lower payload.

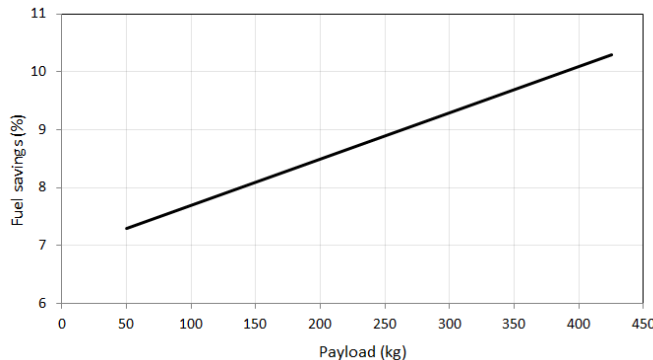


Figure 17 Fuel savings of FFS relative to conventional propulsion

The decision to operate any of the presented propulsion architectures would be contingent upon the cost of fuel as compared to that of electricity. Another important factor is the possible restrictions on emissions imposed by the concerned authorities. From the above results it is clear that conventional propulsion provides the highest range and flight time. However, it consumes the maximum amount of fuel. It would be the preferred choice if fuel price was low and emissions restrictions were relaxed, which is the first extreme case.

The other extreme case would be having high fuel prices and/or tough emissions restrictions; in this case, the full-electric propulsion would be the preferred choice. For cases that fall in between, i.e. medium fuel prices combined with moderate emissions restrictions; the FFS option would generally be preferred, followed

by the PH option. After all, a price calculation based on the presented energy quantities is needed to confirm which configuration is the cheapest. However, the environmental effects must be considered.

4.0 CONCLUSION

An operational approach to enhance the performance of hybrid fuel-electric aircraft was introduced; this approach is named "Fuel-first (FF) strategy", where the aircraft starts the flight in conventional ICE mode until the fuel is fully burned, at that point, switching is done to full-electric propulsion. This means the flight will be divided into two parts, the conventional part and the full-electric part. The two parts are divided by the switching point which happens during cruise. The reason for saving fuel this way is that after the switching point, the aircraft would be at minimum weight. Therefore, the available battery energy can power the aircraft for longer time. In terms of fuel savings, implementing FFS yields a fuel savings of up to 10.3% relative to conventional ICE propulsion, for the same range.

The advantage of the FFS is verified by comparing it with other propulsion types such as conventional, full-electric and PH for the whole flight. FFS was found to consume the least amount of fuel, followed by PH, then conventional propulsion. In addition, it was second best in terms of range and flight time performance after conventional propulsion, PH was third and electric propulsion was last. Finally, the decision to operate any propulsion type depends on the fuel cost as well as the existing emissions restrictions; Conventional propulsion can be selected if fuel price is low and/or emissions restrictions are relaxed, while full-electric propulsion can be selected if fuel price is high and/or emissions restrictions are tight. Furthermore, FFS or PH can be selected if fuel price is medium and emissions restrictions are moderate. It is found that FFS would provide a fuel savings of 4.2% relative to PH propulsion. In addition, a trend of increasing fuel savings as the payload increases is observed when applying FFS.

The FFS is particularly suitable for aerospace applications because the flight is already planned in terms of route, distance, fuel, speed and time. Therefore the FFS can be applied as part of the flight planning phase. On the other hand, applying the FFS to automotive applications would be difficult due to the irregular nature of car usage. Further research is needed to implement the FFS on representative aircraft categories in order to find out which aircraft size and/or configuration would be the best candidate for implementing the FFS.

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