Configuration of Hybrid Fuel-Electric Airplane Model Based on Full Flight Path Performance

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Abstract*: *The feasibility of enhancing the efficiency of hybrid fuel-electric airplane is investigated. The airplane model considered in this work is a hybrid version of Aerosonde propelled by an integrated system of internal combustion engine (ICE) and electric motor (EM). Modified versions of Breguet equation are used to calculate the contribution of the ICE propulsion to the range and endurance of the airplane. On the other hand, the range and endurance components due to EM propulsion are calculated using Payne range strategy based on battery capacity. In order to find the most feasible propulsion configuration; multiple configurations are compared; including conventional all-fuel, full-electric, parallel-hybrid and fuel-first strategy (FFS), which is based on parallel-hybrid design, where fuel is burned during the early phases of the flight then the flight is completed in the fully-electric mode. The preceding propulsion types are investigated for all flight phases including takeoff, climb, cruise, descent, and landing. Impact on airplane weight due to additional equipment is considered. It is found that by adopting the FFS, range can be extended by 7% and endurance by 6% above the parallel-hybrid case. In terms of fuel consumption, implementing FFS yields a fuel saving of 6% relative to parallel hybrid.

Keywords : Fuel-first strategy, hybrid airplane, hybrid propulsion, parallel-hybrid.

I. INTRODUCTION

The emergence of Hybrid fuel-electric airplanes results in reducing the effect of oil price volatility, as well as mitigating carbon footprint. Initially, researchers were concerned about the high cost of using hybrids [1]. However, as technology advanced further, this goal became more realistic, even with the existing challenge of limited battery capacity [2]. 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. In this regard, Voskuijl et al. [3] employed a constant power split strategy where the ratio of the power setting of the engine and the 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%. When hybrid systems are investigated, it is necessary to consider the possible designs such as series and parallel [4]. Different configurations of hybrid powertrains are possible; the series design is the easiest to implement since the ICE is not directly connected to the main thrust of the airplane [5]. The ICE drives the generator which charges the batteries. The batteries are connected to the inverter and then with the controller which in turn is connected with the EM [6].

In the parallel hybrid system, the fuel is used to operate the ICE and the batteries are harnessed to operate the EM, while the airplane is propelled by both the ICE and the EM. One key design consideration of parallel systems is the efficiency of the hybrid system [1]. Batteries are considered the main component of electric propulsion systems; where one of their most important types is Lithium-ion (Li-ion) battery. It is widely used in many applications, such as phones, appliances, and automobiles [7]. 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% [7]. It was reported by many researchers such as Katrašnik et al. [8] and Friedrich and Robertson [1] that parallel-hybrid powertrains provide better fuel economy than the series-hybrid ones. Therefore, in this work, the series-hybrid option will not be investigated. Since it is widely accepted that the parallel-hybrid is the most efficient architecture for aircraft hybridization, the most obvious option to improve the efficiency of the hybrid airplanes is to develop batteries with higher specific energy, as concluded by Sliwinski et al. [9].

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 size of the engine. Thereby reducing both weight and fuel consumption. This method was proposed by Ang et al. [10], 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%, the total energy consumption is reduced. A take-off power split of 25% allows 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% [10]. A similar result was reached by Hoelzen et al. [11], where they presented a mission profile for flight path power demand, where each flight phase (takeoff, climb, cruise, and landing) 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. Bearing in mind that most of the previous efforts focused on reducing engine size and improving battery energy density, there is still another option to increase hybrid propulsion efficiency that had not received enough attention so far; which is operating 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 airplane is switched to full-electric mode.

Revised Manuscript Received on July 20, 2020.

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This operational scenario enables electric propulsion at the airplane minimum weight, thereby saving battery energy. This scenario will be called fuel-first strategy (FFS). The overall performance of this strategy will be compared to the performance of the corresponding parallel-hybrid configuration, which simply uses both fuel and electric propulsions throughout the whole flight.

For the purpose of illustrating the above proposal, an existing airplane model is selected and different operational scenarios are evaluated; including the baseline all-fuel (ICE) model, the full-electric model, the parallel-hybrid model, and the proposed FFS model. These models will be compared in terms of the full flight path performance that includes all flight phases; takeoff, climb, cruise, descent, and landing. Impact on airplane weight due to additional equipment such as batteries, motor and power electronics will be included as well. The baseline model selected for this work is the Aerosonde airplane propelled by a piston engine. Sliwinski et al. [9] proposed a hybrid version of this airplane 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 endurance of the airplane. On the other hand, the range and endurance components due to electric propulsion are calculated using the Payne range strategy based on battery capacity. It should be noted that the search for the most effective hybrid configuration is not limited to physical layout; it also includes logic options for operation.

II. ALL-FUEL PROPULSION

The baseline airplane model selected for this work is Aerosonde from Textron Systems equipped with modified Enya R120 4C Piston engine. The conventional all-fuel powertrain configuration is shown in Fig. 1 and the model data is shown in Table 1.

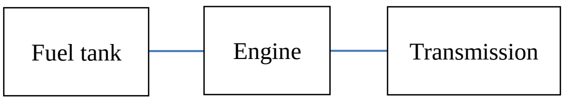

Fig. 1. **All-fuel propulsion powertrain** [12]

Table-I: All-fuel model data [9], [13], [14]

Parameter	Symbol	Value
Propeller efficiency	η_{prop}	0.9
Maximum fuel weight	$m_{f,\,max}$	4.9 kg
Shaft power	P_{max}	2.1 hp
Maximum Lift-to-Drag ratio	$(L/D)_{max}$	16.76
Airplane takeoff weight	W_0	13.1kg (128.5N)
Airplane zero fuel weight	W_I	8.2kg (80.4N)
Fuel uplift	W_f	≤ 4.9 kg
Power-specific fuel consumption (mass)	SFC	350 g/kwh = 9.7×10^{-8} kg/J
Power-specific fuel consumption (weight)	C_{SFC}	9.54×10^{-7} m^{-1}
Air density	ρ_∞	1.225 kg/m^3
Wing area	S	0.57 m^2
Lift Coefficient	c_L	1.0
Drag Coefficient	c_D	0.06

The airplane range (R) is calculated using a modified version of Breguet equation as [9]:

$$R = \frac{\eta_{prop}}{C_{SFC}} \frac{L}{D} \log \frac{W_0}{W_I} \tag{1}$$

Where

η_{prop} : Propeller efficiency
L/D : Lift-to-Drag ratio (aerodynamic efficiency)
W_0 : Airplane maximum weight (takeoff weight) (kg)
W_I : Airplane initial weight (zero fuel weight) (kg)

The power-specific fuel consumption C_{SFC} (m^{-1}) is defined as the rate of fuel consumption per unit shaft power, as shown in equation (2):

$$C_{SFC} = SFC \times g = -\left({}^{m_f}/_{P}\right) \times g \tag{2}$$

Where

SFC : Power-specific fuel consumption (kg/J)
g : Acceleration of gravity (m/s^2)
m_f : Fuel weight (kg)
P : Shaft power (W)

Prior to departure, the airplane must be fueled up to the maximum capacity, therefore, the airplane takeoff weight will be (W_0). This weight is equal to the sum of the airplane zero fuel weight (W_I) and the fuel weight (W_f), as shown in eq. (3):

$$W_0 = W_I + W_f \tag{3}$$

In eq. (1), air density is included in Lift (L) and Drag (D), while air speed is considered zero. In addition to the airplane range, the endurance time (t_{end}) (in hours) is another important parameter. It can be calculated using the Breguet endurance equation as [9]:

$$t_{end} = \frac{\eta_{prop}}{c_{SFC}} \cdot \sqrt{2\rho_\infty S} \cdot \frac{c_L^{\frac{3}{2}}}{c_D} \cdot \left(\frac{1}{\sqrt{W_1}} - \frac{1}{\sqrt{W_0}}\right) \tag{4}$$

Where

η_{prop} : Propeller efficiency
c_{SFC} : Power-specific fuel consumption (weight)
ρ_∞ : Air density
S : Wing area
c_L : Lift coefficient
c_D : Drag coefficient
W_I : Airplane zero fuel weight
W_0 : Airplane takeoff weight

A fundamental design goal in unmanned aerial vehicles (UAV) is to prioritize endurance over range and reliability [9]. One reason for this is that the UAV is used to perform a mission then comes back to origin; therefore, endurance is more meaningful than range. On the other hand, a transport or a passenger aircraft flies from origin to destination to deliver goods or passengers. Therefore, it is desired to maximize the range and minimize the endurance which is basically the flight time. Since this work aims to configure a hybrid airplane model based on full flight path performance, the range and endurance for all flight phases should be studied. Equations (1) and (4) are used to calculate the values shown in Table 2, where all flight phases are shown including takeoff, climb, cruise, decent, and landing. The numbers in parentheses after each phase are shown on the flight path in Fig. 3. As the distances of takeoff and landing rolls are too small compared to the other phases, they are added to climb and descent, respectively. In Table 2, each phase consumes a certain fuel quantity proportional to its power demand [14]. For each phase, the range segment is shown in nautical miles, while the endurance segment is shown in hours.

Table-II: Flight phases for all-fuel propulsion

Phase	Fuel Mass (kg)	Range (nmi)	Endurance (hr)
Takeoff & Climb (1-2)	1.25	49	1.2
Cruise (2-3)	3.60	292	7.9
Descent & Landing (3-4)	0.15	33.7	1.0
Total	5.00	374	10.1

The full flight path of the airplane is shown in Fig. 2 [14]. It shows the altitude variation with time, as well as the different flight phases; where takeoff and climb are shown in section A of the figure, cruise is shown in section B, and descent and landing are shown in section C. The same flight path is shown in Fig. 3 [14], but it manifests the variation of altitude with distance, as well as the different flight phases; where takeoff and climb are represented by the line 1-2, cruise is represented by the line 2-3, and descent and landing are represented by the line 3-4. The purpose of showing the details of the mission profile is to investigate all flight phases for possible ways to save energy while completing the required mission.

For the purpose of validating the method used in this work, the obtained range and endurance results (374 nmi and 10.1 hr) are compared to previous results (376.2 nmi and 10.1 hr) reported by Sliwinski et al. [9]. The difference is less than 1% which proves the validity of using the modified Breguet range equation in this work.

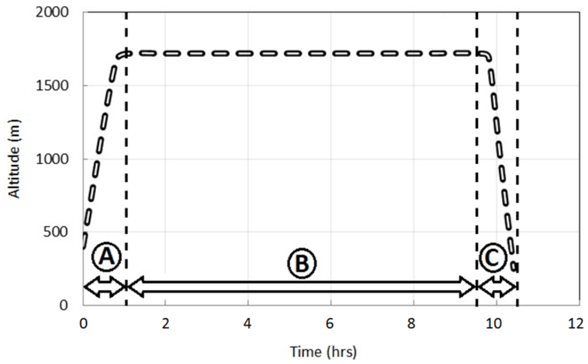

Fig. 2. **Airplane flight phases**

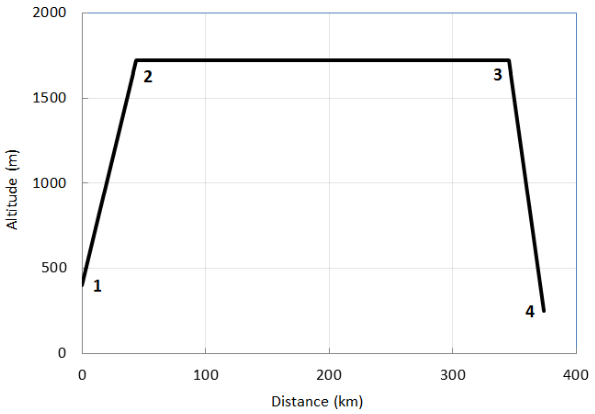

Fig. 3. Airplane flight path

III. FULL-ELECTRIC PROPULSION

A full-electric version of the selected airplane powered by an EM was proposed by Sliwinski et al. [9]. In this work, this version will be investigated further especially in regards to the performance of the different flight phases. The powertrain of the full electric model is shown in Fig. 4, while the data for the Plettenberg HP320/30 Brushless DC motor and the Thunder Power Li-Po air battery 8-cell pack is shown in Table 3 [9]. The electric version simulation will be limited to 5 battery packs because if an additional one is added the airplane weight will exceed the maximum takeoff weight.

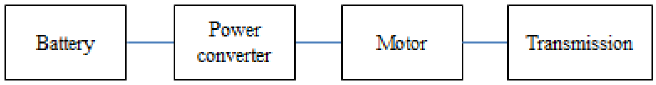

Fig. 4. **Full-electric propulsion powertrain**

Table-III: Electric propulsion parameters [15]

Parameter	Symbol	Value
Propeller efficiency	η_{prop}	0.9
Battery energy density	E^*	158-460 Wh/kg
Total propulsive efficiency	η_{total}	0.77
Maximum Lift-to-Drag ratio	$(L/D)_{max}$	16.76
Mass of battery pack	$m_{battery}$	0.93 kg
EM mass	m_{motor}	0.415 kg
Total mass	m	13.1 kg
Voltage	V	29.7 V
Current	I	25 A
Power in	P_{In}	1366.2 W
Power out	P_{out}	1229.58 W
Battery efficiency	η_{Batt}	0.9
DC/AC conversion efficiency	η_{Conv}	0.95
Range	R	Km
Acceleration of gravity	g	m/s^2

The range (R) of a battery operated aircraft can be calculated using the following equation [9]:

$$R = E^* \eta_{total} \frac{1}{g} \frac{L}{D} \frac{m_{battery}}{m} \tag{5}$$

Where,

E^* : Battery energy density (Wh/kg)
η_{total} : Total propulsive efficiency (%)
L/D : Lift-to-Drag ratio (aerodynamic efficiency)
$m_{battery}$: Battery mass (kg)
m : Total mass (kg)

The range and endurance for the full-electric propulsion are shown in Table 4. These values were calculated using Equation (5) for all flight phases. The numbers in parentheses after each phase are shown on the flight path in Fig. 3. For each phase, the range segment is shown in nautical miles, while the endurance segment is shown in hours.

Table-IV: Flight phases for full-electric propulsion

Phase	Range (nmi)	Endurance (hr)
Takeoff & Climb (1-2)	19	0.3
Cruise (2-3)	115	2.3
Descent & Landing (3-4)	13.3	0.3
Total	148	2.9

IV. PARALLEL-HYBRID PROPULSION

The parallel-hybrid propulsion powertrain is shown in Fig. 5. This version of the airplane is basically a combination of the two previous versions; the baseline all-fuel version and the full-electric version. It is powered by both an ICE and EM as proposed by Sliwinski et al. [9]. The implemented hybridization factor is 50%, which corresponds to 3 battery packs and 1.8 kg of fuel. In this work, this version will be investigated further especially in terms of the performance of the different flight phases.

The range and endurance for this version are shown in Table 5. These values were calculated based on 50% hybridization across all flight phases. The numbers in parentheses after each phase are shown on the flight path in Fig. 3.

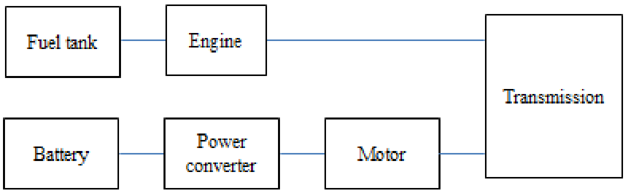

Fig. 5. **Parallel-hybrid propulsion powertrain**

Table-V: Flight phases for hybrid propulsion

Phase	Fuel Mass (kg)	Range (nmi)	Endurance (hr)
Takeoff & Climb (1-2)	0.4	26	0.55
Cruise (2-3)	1.3	159	3.57
Descent & Landing (3-4)	0.1	18	0.46
Total	1.8	203	4.58

V. FUEL-FIRST STRATEGY (FFS)

The powertrain for the FFS is the same as the one for the parallel-hybrid propulsion shown in Fig. 5. Even though the physical layouts of both hybrid configurations are the same, the logic of operation for each one is different. In this strategy, the hybridization factor is still 50%, which corresponds to 3 battery packs and 1.8 kg of fuel. As explained earlier, the focus of this work will be on the performance of the different flight phases. The range and endurance for the FFS are shown in Table 6 and Table 7, respectively. These values were calculated based on FFS hybridization, which means the fuel is burnt first then the batteries are used till the end of the flight. This means the flight starts using the ICE only until the fuel is fully burnt, which will happen during cruise. At that point the electric motor is started and the batteries power the remaining part of the flight.

Table-VI: Flight phases for FFS

Phase	Fuel Mass (kg)	Fuel Range (nmi)	Electric Range (nmi)	Total Range (nmi)
Takeoff & Climb (1-2)	0.85	28	0	28
Cruise (2-3)	0.95	87	83	170
Descent & Landing (3-4)	0.00	0	20	20
Total	1.80	115	103	217

Table-VII: Flight phase endurance for FFS

Phase	Fuel Mass (kg)	Fuel Endurance (hr)	Electric Endurance (hr)	Total Endurance (hr)
Takeoff & Climb (1-2)	0.85	0.58	0	0.58
Cruise (2-3)	0.95	2.26	1.53	3.79
Descent & Landing (3-4)	0	0	0.49	0.49
Total	1.8	2.84	2.01	4.85

This strategy is illustrated in Fig. 6 and 7, where Fig 6 shows the distribution of the range covered by fuel (fuel portion) and the distribution of the range covered by electricity (electric portion) over all flight phases. It also shows the total of the two contributions over the same flight phases. Similarly, Fig 7 shows the distribution of the endurance powered by fuel (fuel portion) and the distribution of the endurance powered by electricity (electric portion) over all flight phases. It also shows the total of the two contributions over the same flight phases.

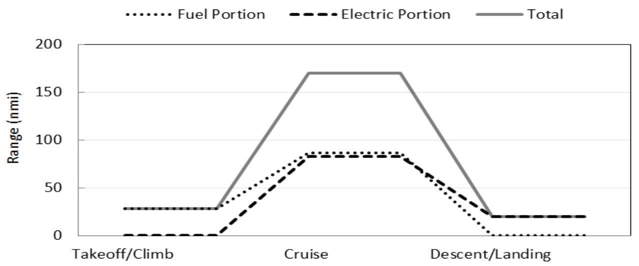

Fig. 6. FFS range portion vs. flight phase

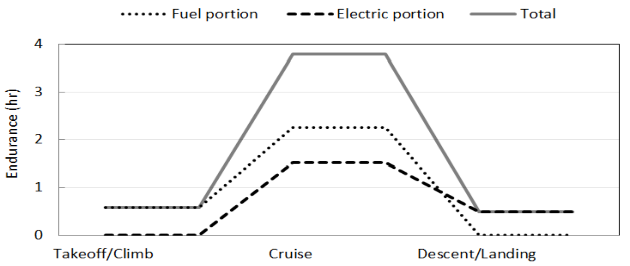

Fig. 7. FFS endurance portion vs. flight phase

VI. PROPULSION PERFORMANCE COMPARISON

In the preceding sections, the performance of different propulsion architectures was presented in terms of fuel burnt, range, and endurance, distributed over all flight phases. In this section, these results will be compared graphically so as to reveal the relative advantage of each propulsion method. In Fig. 8, the fuel used is plotted against all flight phases, for all-fuel, Parallel-hybrid, and FFS. It is shown that the all-fuel propulsion consumes the highest fuel quantity followed by the parallel-hybrid and FFS. During takeoff and climb, the FFS method consumes more fuel than the parallel-hybrid. However, during cruise, the parallel hybrid consumes more fuel than the FFS method. Finally, during descent and landing, no fuel is consumed in the FFS method, while little fuel is consumed in parallel hybrid method, since there is an electric power component.

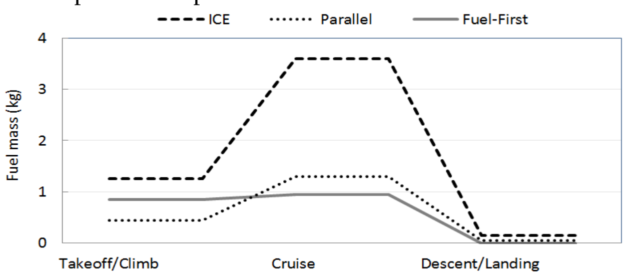

Fig. 8. Fuel burned vs. flight phase

The range segments over each flight phase are shown in Fig. 9, where it is clear that the maximum range is achieved by the all-fuel propulsion, followed by the FFS, then the parallel-hybrid, and finally the electric propulsion. Similarly, the endurance times for each flight phase are shown in Fig. 10. Again the maximum endurance is achieved by the all-fuel propulsion, followed by the FFS, then the parallel-hybrid, and finally the electric propulsion.

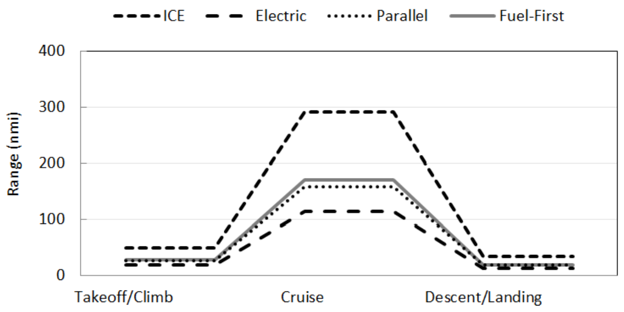

Fig. 9. **Range vs. flight phase**

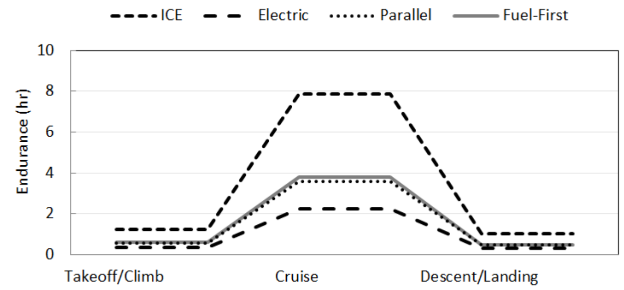

Fig. 10. **Endurance vs. flight phase**

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 civil aviation authorities. From the above results it is clear that the all-fuel propulsion provides the highest range and endurance. However, it consumes the maximum amount of fuel. It would be the natural choice if fuel price was low and emission restriction was relaxed, which is the first extreme case. The other extreme case would be having high fuel price and/or tough emission restriction; in this case, the full electric propulsion would be the natural choice. For cases that fall in between i.e. medium fuel price combined with moderate emission restriction; the parallel-hybrid option would be appealing. As a summary of the above discussion, recommended propulsion types for different fuel price and emission restriction scenarios are summarized in Table 8.

A comparison between parallel-hybrid and FFS for various degrees of hybridization that depend on the number of battery packs is presented in Table 9. The compared parameters include fuel mass used and range. A similar comparison of endurance is presented in Table 10. For clarity the results are plotted in figures 11 and 12. From these figures, it is evident that applying the FFS would make the hybrid option even more attractive, as it provides 7% more range as well as 6% more endurance than the parallel-hybrid. Furthermore, the fuel savings achieved using the FFS can be calculated using the data presented in Table 9; for 3 battery packs, taking equal range for both parallel-hybrid and FFS as 203 nmi and calculating the fuel used for the FFS as 1.7 kg, the resulting fuel saving is 6%. The corresponding endurance results for Parallel-hybrid and FFS is shown in Table 10.

Table-VIII: Propulsion type adoption scenarios

Fuel cost	Emission restriction		
	Tough	**Moderate**	**Relaxed**
High	Full-electric	High electric hybridization	High electric hybridization
Medium	High electric hybridization	Medium electric hybridization	Low electric hybridization
Low	High electric hybridization	Low electric hybridization	All-fuel

Table-IX: Parallel-hybrid vs. FFS (Range)

Number of Battery Packs	Parallel Fuel Mass (kg)	Parallel Range (nmi)	FFS Fuel Mass (kg)	FFS Range (nmi)
0	4.6	335	4.6	335
1	3.7	284	3.7	296
2	2.7	241	2.7	256
3	1.8	203	1.8	217
4	0.9	171	0.9	180
5	0.0	148	0.0	148

Table-X: Parallel-hybrid vs. FFS (Endurance)

Number of Battery Packs	Parallel Fuel Mass (kg)	Parallel Endurance (hr)	FFS Fuel Mass (kg)	FFS Endurance (hr)
0	4.6	8.9	4.6	8.9
1	3.7	7.2	3.7	7.4
2	2.7	5.8	2.7	6.1
3	1.8	4.6	1.8	4.9
4	0.9	3.6	0.9	3.8
5	0.0	2.9	0.0	2.9

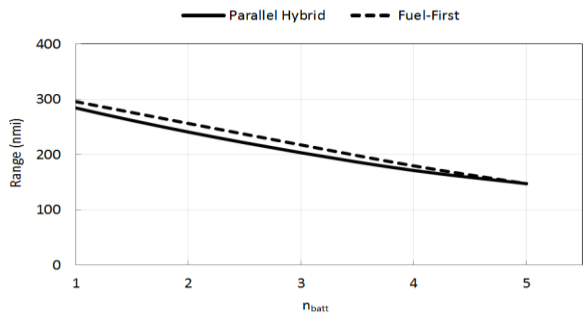

Fig. 11. Range of FFS and Parallel-hybrid models

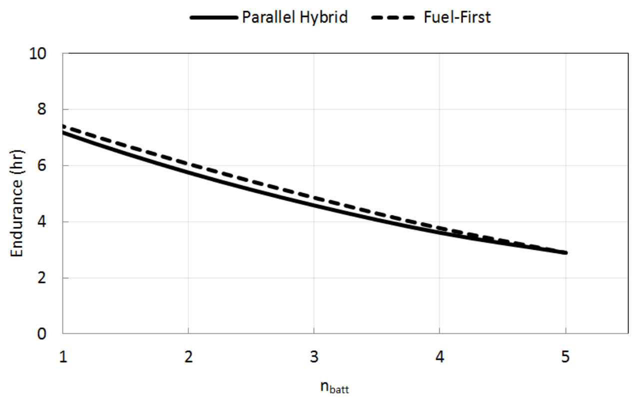

Fig. 12. Endurance of FFS and Parallel-hybrid models

VII. CONCLUSION

An operational approach to enhance the performance of hybrid fuel-electric airplane was introduced; this approach is named "Fuel-first strategy (FFS)", where the airplane starts the flight in all-fuel 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 all-fuel part which includes takeoff, climb, and part of the cruise, and the full-electric part, which includes the rest of the cruise, descent, and landing. 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 airplane would be at minimum weight. Therefore, the available battery energy can power the airplane for longer time. In terms of fuel savings, implementing FFS yields a fuel savings of 6% relative to parallel hybrid.

The advantage of the FFS is verified by comparing it with other propulsion types such as all-fuel, full-electric and parallel-hybrid for all flight phases, including takeoff, climb, cruise, descent, and landing. FFS was found to consume the least amount of fuel, followed by parallel hybrid, then all-fuel propulsion. In addition, it was second best in terms of range and endurance performance after all-fuel propulsion, parallel-hybrid was third and electric propulsion was last. Finally, the decision to operate any propulsion type depends on the fuel cost as well as the imposed emission restriction; All-fuel propulsion can be selected if fuel price is low and/or emission restriction is relaxed, while full-electric propulsion can be selected if fuel price is high and/or emission restriction is tight. Furthermore, FFS or parallel-hybrid can be selected if fuel price is medium and emission restriction is moderate. By adopting FFS the range can be extended by 7% and the endurance by 6% above the parallel hybrid case.

ACKNOWLEDGMENT

This research was conducted while on Sabbatical leave granted to the author by the University of Jordan.

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