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Assessment of hybrid airplane configurations based on in-flight performance

Osama M. Al-Habahbeh[1], Rami Y. Al-Khalaileh[2], Mustafa M. Daoud[3], Yaseen I. Al-sheyyab[4]
Rula D. Al-Slihat[5]
[1,2,3,4,5]Mechatronics Engineering Department, the University of Jordan, Iran
[1]o.habahbeh@ju.edu.jo, [2] hapapar@gmail.com, [3] hapapar@yahoo.com, [4] yaseen0505@gmail.com
[5] rola.alalslihat@gmail.com

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Abstract

The emergence of hybrid fuel-electric airplanes is meant to reduce the effect of oil price volatility, as well as to protect the environment by reducing exhaust gas emissions. In the present work, the feasibility of multiple hybrid configurations is investigated based on flight performance. For this purpose, a numerical model of the airplane is built and simulated. In order to find the most feasible hybrid configuration; hybridization architectures such as series, parallel, and combined series-parallel are explored. In addition, the hybrid models are compared with both conventional (all-fuel) and full electric airplanes in all flight phases; including takeoff, climb, cruise, descent, and landing. Impact on airplane weight resulting from additional equipment such as batteries, motors and inverter/converter is investigated as well. The performance of the combined series-parallel hybrid architecture is found to provide better performance than the other configurations including conventional, full electric, series hybrid, and parallel hybrid.

Keywords; *Hybrid fuel-electric airplane, Flight path performance, Parallel hybrid, Series hybrid, Combined hybrid, Airplane thrust, Electric airplane, Conventional airplane*.

I. INTRODUCTION

Since oil resources are expected to become limited and more expensive in the future, there will be a need for alternative source of energy to power air transportation. However, before the full electric air transport becomes a reality, hybridization of airplane thrust is a mandatory transition, where the design and implementation of such configuration will gain more importance in the future. This work aims at exploring the potential for air transportation benefit from new electrical components technology especially batteries. Multiple hybridization architectures are investigated; such as series, parallel, combined, and full electric. The thrust and energy consumption of these configurations will be compared in order to determine the most feasible design.

The introduction of hybrid engines into the automotive industry had succeeded due to several factors; such as reducing harmful emissions and lowering dependence on oil [1]. Initially, researchers were concerned about the high cost of using hybrids, especially in airplanes [2]. However, as technology developed further, this goal became more realistic, even with the existing challenge of limited battery capacity [3]. When hybrid systems are studied, it is necessary to consider the available designs, such as series and parallel [4]. Different configurations of airplane powertrains are shown in figures 1-5. The series design is the easiest to implement since the internal combustion engine (ICE) is not directly connected to the main thrust of the airplane [5]. The batteries are connected with the inverter and then with the main controller which in turn is connected with the electric motor. On the one hand, the electric

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system represented by the batteries will pump the necessary energy to the engine. On the other hand, the gasoline system will charge the batteries through the generator [6].

For the parallel coupling system, the fuel is used to operate the gasoline engine. While the batteries are harnessed to operate the electric motor, which in turn moves the airplane. Researchers have created some descriptions of parallel systems in order to make them simpler to understand [7]. Some of these classifications are based on the size of electric components. One key design consideration is the efficiency of the hybrid system [2]. The major component of an electric propulsion system is the battery; where one of the most important types of batteries is the Lithium-ion (Li-ion) battery. It is widely used in many applications including phones, home appliances, and automobiles [8]. It is expected that large batteries, which can provide about 750 Wh/Kg will be available before 2040 [8]. In some previous studies, the specific energy of Li-ion battery was 750-1500 Wh/Kg, battery efficiency was 95%, and electric motor efficiency was 98% [8].

Friedrich and Robertson [2] evaluated hybridization architectures for a single-seat, light aircraft; the performance of each powertrain: series hybrid, parallel hybrid, purely electric and conventional ICE is evaluated under comparable conditions. The analysis showed that the parallel-hybrid engine design is favored for aviation applications. An analysis of the energy conversion efficiency in hybrid powertrains is presented by Katrašnik et al. [7]; they reported that parallel-hybrid powertrains provide better fuel economy than the series ones for the simulated test cycles. However, the performance of the combined series-parallel hybrid configuration was not explored in the preceding literature. Therefore, in this work, this architecture will be investigated and its performance will be compared with other configurations including conventional, full electric, series hybrid, and parallel hybrid.

II. AIRPLANE DATA

This work is based on data for Diamond DA42 Twin Star airplane. The characteristics of this airplane are listed in table 1 [9].

Table 1: Airplane characteristics

Parameter	Value
Gross weight	1,700 kg
Capacity	4 passengers including the pilot
Propulsion [10]	Twin propeller driven engine (270 HP)
Maximum speed	356 km/h
Range	1,693 km
Ceiling	5,486 m
Rate of climb	6.5 m/s
Fuel type	JET A-1
Fuel capacity	72 USG
Fuel burn	10 USG/Hr

III. POWERTRAIN CONFIGURATIONS

Possible powertrain configurations include Conventional, Full electric, and Hybrid, where hybridization architectures can be classified as Series, Parallel, or Combined series-parallel, as shown in figures 1-5 [11].

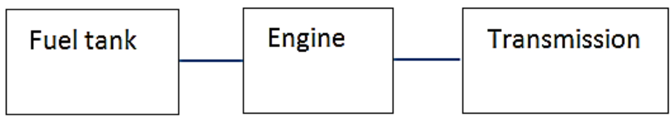

Fig. 1: Conventional powertrain

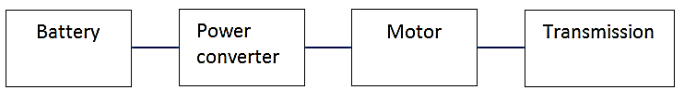

Fig. 2: Full electric powertrain

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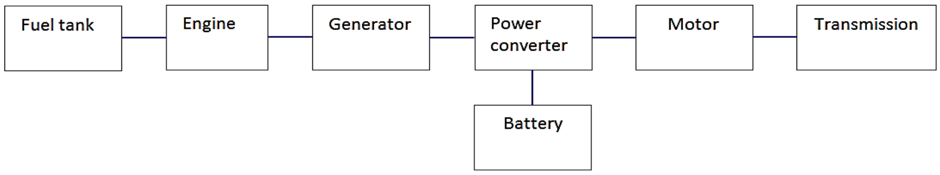

Fig. 3: Series hybrid powertrain

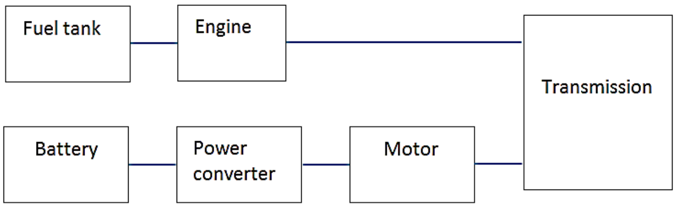

Fig. 4: Parallel hybrid powertrain

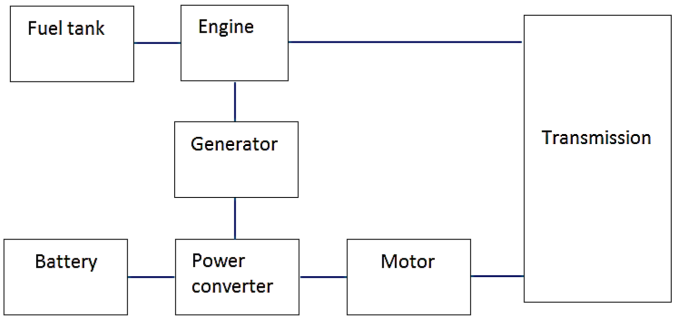

Fig. 5: Combined (Series-Parallel) hybrid powertrain

IV. POWERTRAIN MODELING

The hybrid system components that must be modeled and simulated include battery and motor models [12]. DC motor provides the best performance, where the airplane mission is to fly continuously for five hours [13]. Based on the data presented in table 2, the maximum thrust power is calculated as 250 kW, while the total energy needed is 850 kWh. Based on this data, the power demand for each flight phase is plotted in figure 6. In each flight phase, the output power should meet the power demand. Using these power values, the required fuel or battery charge can be calculated.

Table 2: Flight phases power demand [15]

Phase	Power demand
Takeoff	250 kW
Climb	228 kW
Cruise	150 kW
Descent & Landing	25 kW

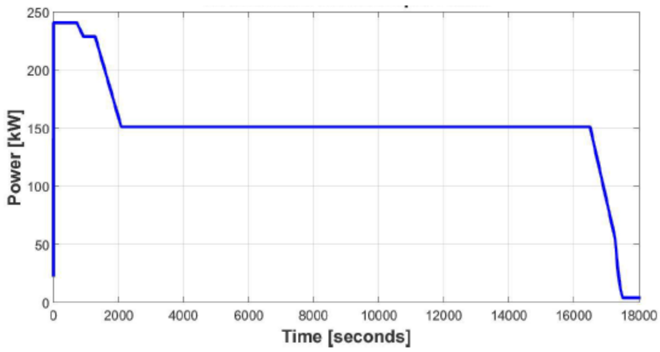

Fig. 6: Power demand during flight

4.1 Conventional powertrain

The conventional powertrain model of the airplane is shown in figure 7. Conventional airplanes rely on ICEs. In order to meet the power demand, the engine should have a power of 250 kW. Based on the figure, it is noted that the ICE consumes a fuel of 177 kg.

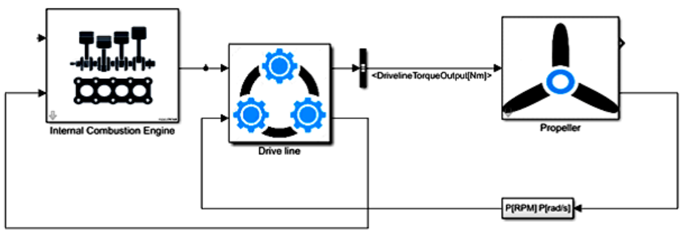

Fig. 7: Conventional powertrain model

4.2 Electrical powertrain

The electrical powertrain model of the airplane is shown in figure 8. The electrical version of the airplane is propelled by a DC Motor. To meet the power demand, a DC motor with a power of 250 kW is chosen. The DC motor is powered by a Li-Ion battery with a capacity of 850 kWh. The components of the electrical propulsion system are summarized in table 3. Based on this data, the motor power output, propellers thrust, and battery state of charge (SOC) are calculated. As shown in figure 12,

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the battery can power a 5 hours flight with a 10% remaining power at the end of the flight.

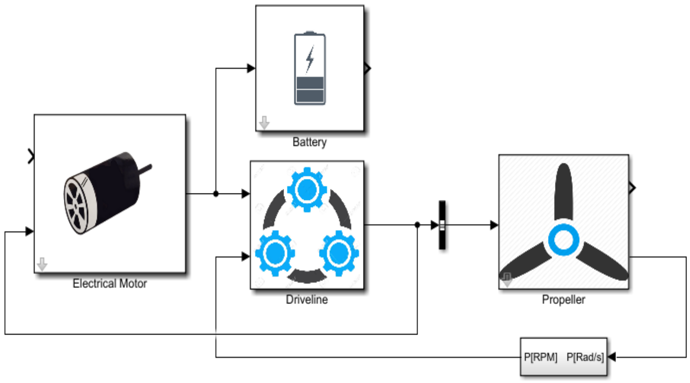

Fig. 8: Electrical powertrain model

Table 3: Electrical components parameters [15]

Parameter	Value
Motor maximum power	250 kW
Motor maximum torque	600 N.m
Battery capacity	850 kWh
Battery voltage	600 V
Battery resistance	0.001 ohm
Batter type	Li-ion
Battery energy density	410 W.h/kg
Battery weight	2000 kg
Accessories loading power	400 W

4.3 Series-hybrid

In series hybrid design, a generator is added to the system, as shown in figure 9. The generator is directly connected to ICE so as to continuously charge the battery. Therefore, the battery capacity can be reduced which would lead to cutting the battery weight. It is noted that using the series design, battery weight and capacity can be reduced. The series-hybrid components parameters are listed in table 4.

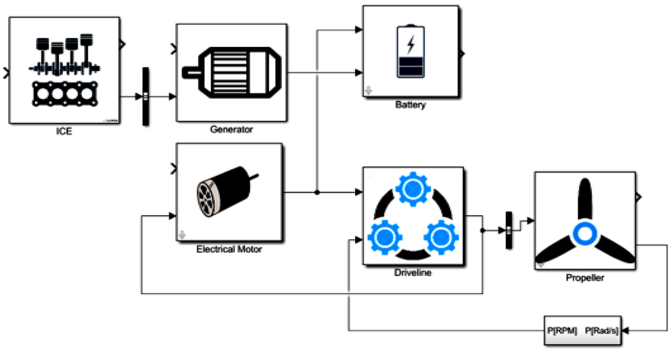

Fig. 9: Series-hybrid powertrain model

Table 4: Series hybrid components parameters [15]

Parameter	Value
Motor maximum power	250 kW
Motor maximum torque	600 N.m
Generator maximum power	100 kW
Generator maximum torque	300 N.m
ICE power	100 kW
Battery capacity	340 kWh
Batter type	Li-ion
Battery energy density	410 W.h/kg
Battery weight	829 kg
Accessories loading power	400 W

4.4 Parallel-hybrid

As shown in figure 10, this layout has two sources of power; Electric motor and ICE. These are operated at the same time so as to deliver power to the propellers. It is noted that the battery supplies the motor with the required power for the whole flight. In addition, 10% of the battery power is left at the end of the flight. On the other hand, the ICE consumes a total of 133 kg of fuel. The flight phase power demand for this configuration is shown in table 5, while the components parameters are shown in table 6.

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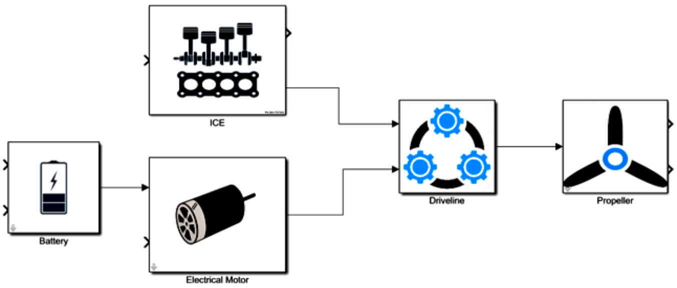

Fig. 10: Parallel-hybrid powertrain model

Table 5: Flight phases power demand [15]

Phase	Electric power demand	ICE power demand
Takeoff	99 kW	141 Kw
Climb	94 kW	134 kW
Cruise	16 kW	134 kW
Descent & Landing	25 kW	0 kW

Table 6: Parallel-hybrid components parameters [15]

Parameter	Value
Motor maximum power	100 kW
ICE power	141 kW
Battery capacity	106 kWh
Batter type	Li-ion
Battery energy density	410 W.h/kg
Battery weight	259 kg
Accessories loading power	400 W

4.5 Combined-hybrid

The combined hybrid model is shown in figure 11. It is also known as series-parallel hybrid. This design has two main power sources; the ICE and the motor. Both of them supply power at the same time. However, what distinguishes this design from the parallel layout is the link between the ICE and the generator that in turns recharges the battery during the flight. The power requirements and system specifications are shown in tables 7 and 8, respectively. It is noted that the battery provides the required power for the flight, while 30% unused power remains at the end of the flight. Moreover, the ICE consumes a total fuel of 133 kg.

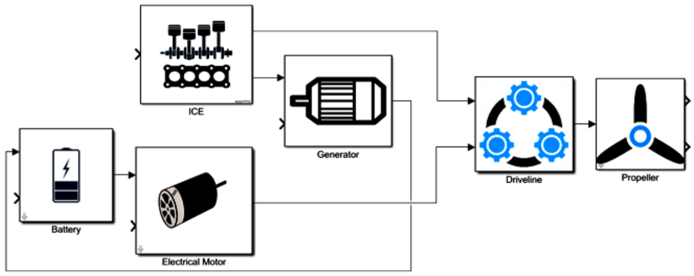

Fig. 11: Combined-hybrid powertrain model

Table 7: Flight phases power demand [15]

Phase	Electric power demand	ICE Power demand
Takeoff	117 kW	123 Kw
Climb	111 kW	117 kW
Cruise	33 kW	117 kW
Descent & Landing	25 kW	0 kW

Table 8: Combined-hybrid components parameters [15]

Parameter	Value
Motor maximum power	117 kW
ICE power	123 kW
Battery capacity	80 kWh
Batter type	Li-ion
Battery energy density	410 W.h/kg
Battery weight	195 kg
Accessories loading power	400 W

V. FLIGHT PERFORMANCE

In order to find the best hybridization configuration, the preceding systems are simulated under the same conditions. The components used in the simulation are listed in table 9. It is assumed that all configurations use the same pool of components. However, power draw from each component depends on the system power demand. As shown in figures 12-15, it is noted that the combined-hybrid configuration provides the highest thrust. In addition, it requires less battery size while the fuel consumption is similar to the parallel configuration. Based on these results it can be concluded that the most efficient configuration is the combined-hybrid.

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Table 9: Propulsion components parameters [15]

Parameter	Value
Motor maximum power	250 kW
Generator maximum power	30 kW
ICE power	250 kW
Battery capacity	850 kWh
Battery energy density	410 W.h/kg

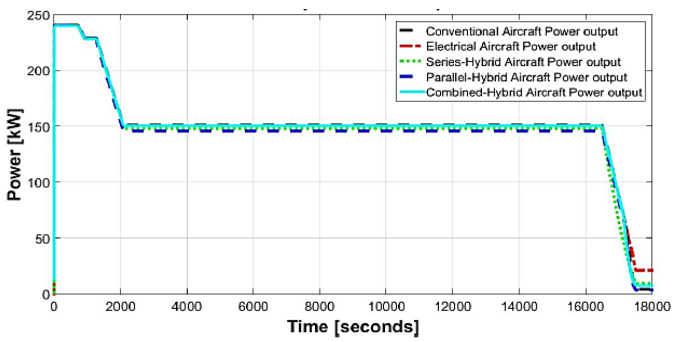

Fig. 12: Full flight power for different configurations

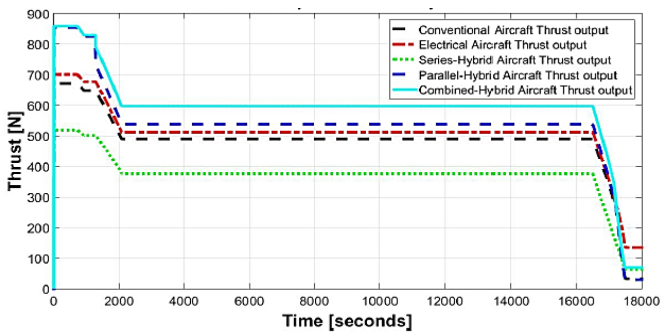

Fig. 13: Full flight thrust for different configurations

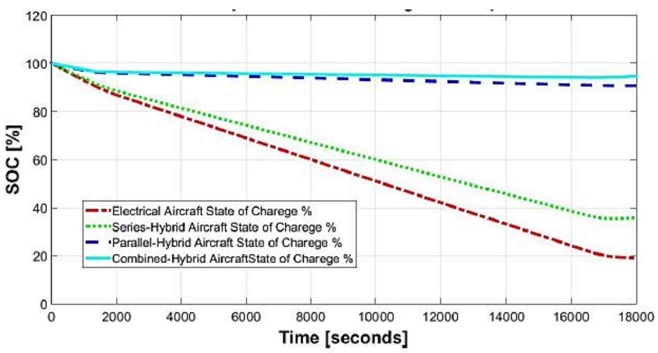

Fig. 14: Full flight battery SOC for different configurations

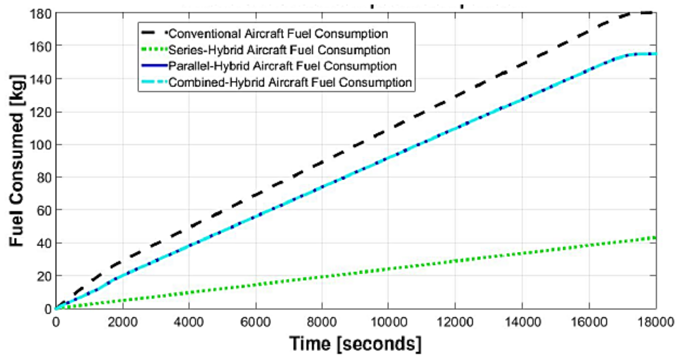

Fig. 15: Full flight fuel consumption for different configurations

VI. CONCLUSION

The flight performance of multiple hybrid configurations is studied using a numerical model based on data for Diamond DA42 Twin Star airplane. Multiple propulsion configurations including series-hybrid, parallel-hybrid, and combined series-parallel hybrid, as well as conventional and full electric models are simulated for all flight phases; including takeoff, climb, cruise, descent, and landing. The results show that the combined hybrid configuration is the most successful approach. It provides the airplane with the highest speed, torque, and thrust, along with the minimum battery charge. However, a large amount of fuel is still needed as it provides high specific energy.

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