DOI: 10.13009/EUCASS2023-482

Performance Analysis of a Hybrid Thermal-Electric Turboprop Engine

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Abstract

The reduction of fuel consumption and pollutant emission have guided the aeronautic engineers in their work for decades to design always more efficient aircraft engines. Along with this, the reduction and, in the next future, the overcoming of fossil fuels has become one of the most important challenges in the engine development. Aircraft engines are responsible of about 12% of the total carbon dioxide produced by transportation, moreover, the aeronautical authorities impose for the next years stringent limits in the production of CO_2 and NO_x. These limits are quite narrow, and it is difficult to respect them using only thermal engines. The introduction of electric engines in the aircraft power system is therefore unavoidable. The possibility of the introduction of hybrid thermal-electric engine for aircraft propulsion, the architecture of the system and its consequent effects on pollution reduction, have been evaluated.

Nomenclature

P_E:	Electric Power
P_T:	Turbine power
H_P:	Power Degree of Hybridization
E_E:	Electrical Energy
EBSFC:	Equivalent Brake Specific Fuel Consumption
eP:	Equivalent Power
MTOW:	Maximum take-off Weight
η_{Etot}:	Overall Electric Efficiency

1. Introduction

It has been estimated that the aviation sector represents the 2% of the global human CO_2 emission, and the 3% of all greenhouse gases produced, and in the next years they will raise at a pace of about 4-5% per year. This fact, under the pressure of the public opinion, has moved the aircraft industry to consider with growing efforts the propulsion system electrification [1]. The aircraft engine electrification involves different kind of aircrafts, from the city taxi to wide body jet liner, and for each type there is a more indicated propulsion system. Current batteries have low energy and power density, and if the power demand and the flight length are great, their mass becomes high [2]. Two important parameters regarding the energy stored in an aircraft are the energy for unity of mass, and the energy for unity of volume. If we compare kerosene, the most used aircraft engine fuel, with Li-ion battery, we see that the mass specific energy of kerosene is about 60 times greater, and the volume specific energy 18 times greater [3]. With these numbers, it becomes difficult to think a fully electric long-range jet liner. For these reasons, while for city transport or short-range aircraft is possible to think to an all-electric solution, for greater and long-range aircrafts this solution is unfeasible at

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the current technology stage, and the hybrid thermal-electric engine seems more indicated [4-6]. Hybrid engine means that the propulsion system is partially thermal and partially electric. We are interested to investigate the performance of a turboprop engine using a combination of a gas turbine and an electric motor, and compare the main results, as performance, fuel consumption, weight, with those of a conventional turboprop.

2. Different hybrid propulsion systems

The main kind of electric propulsion systems that seem to be used for aeronautical propulsion are the all-electric, turbo electric and hybrid electric systems. In the all-electric, the energy is stored in the battery pack, and an electric motor provides the propulsion for the aircraft. The battery weight is now the most important limiting factor of this system, and for this reason it is not suitable for long range wide body aircrafts. The most attractive aspect is the reduction to zero of the pollutant emission, and a great reduction of the engine noise. For these reasons, the all-electric system is indicated for small aircrafts and short-range flights, like aero taxi, or light aircraft for short trips of about 1 or 2 hours. In Fig. 1 is shown the scheme of the system. The system configuration is very simple, consisting of an electric connection between the batteries and the electric motor, and a mechanical coupling between the motor and the propeller.

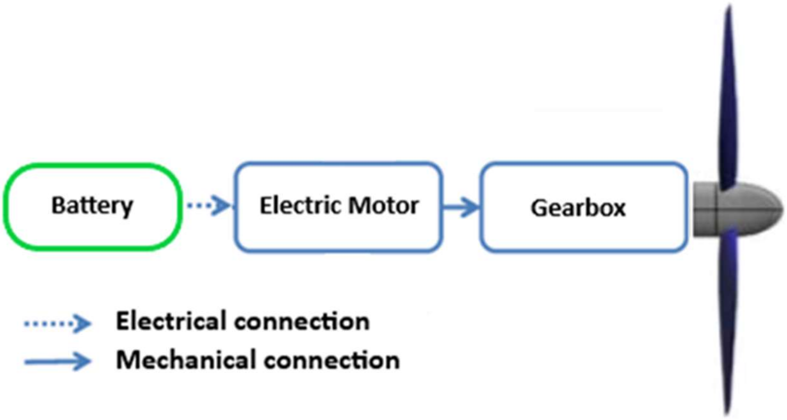

Fig. 1 All-electric propulsion system conceptual scheme.

As mentioned, the weight of the batteries is the main limit to the use of large all-electric airplanes and on long distances. The main types of batteries currently available are Lithium-Ion batteries. They can be produced, with current technologies, quite cheaply, and can be sized and grouped to provide several hundred kWh. Now the energy per unit mass that can be reached is of about 200 Wh/kg, but soon it will be possible to reach values up to 250 Wh/kg. In addition to Lithium-Ion batteries, other types of Lithium-based batteries are being developed, such as Lithium-Sulfur and Lithium-Oxygen, which promise significantly higher values of energy per unit mass. However, these batteries will not be available for at least a decade. In table 1 are reported the values of energy per unit mass of the different types of battery currently available, and, for comparison, the specific energy of kerosene, the currently most used fuel in aviation.

System	Specific energy [Wh/kg]
Li-Ion	150-250
Li-S	500-1250
Li-O_2	800-1750
Kerosene	12000

Tab. 1 Specific energy density of current and future chemical battery systems, and kerosene as reference.

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The serial hybrid turbo-electric system essentially consists of a gas turbine that, using a conventional fuel, produces mechanical power that is converted into electrical power by a generator. The generator is coupled to one or more electric motors that provide the power necessary for propulsion to one or more propellers or fans. The system can also provide for the presence of batteries to store a certain amount of electric energy. Figure 2 shows the conceptual scheme of this type of propulsion system.

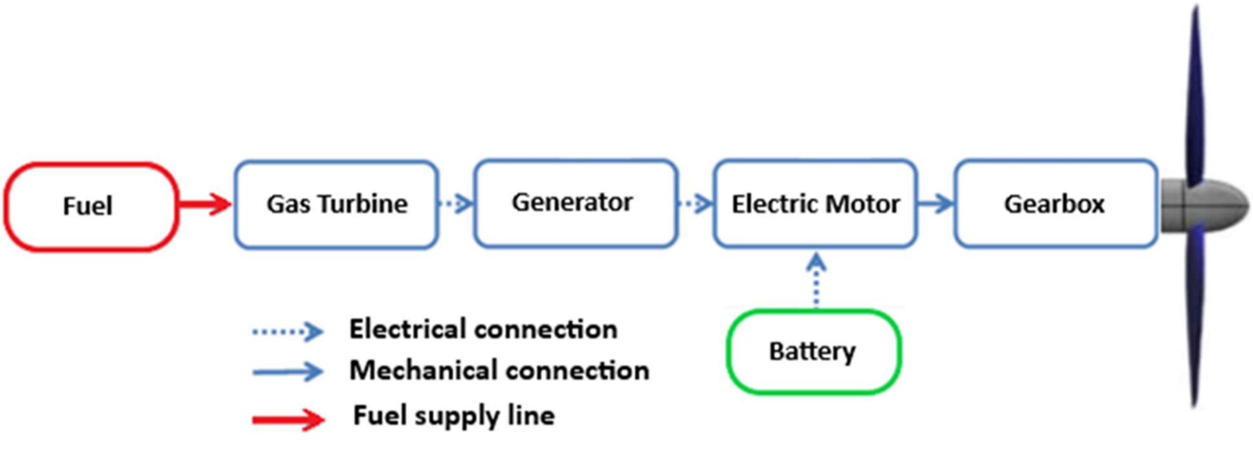

Fig.2 Serial hybrid turbo-electric propulsion system conceptual scheme.

The batteries supply energy to the system through an electrical branch and can be recharged during phases of flight that require low power, such as cruising. One of the main advantages of this configuration is that the turbine, not being directly connected to the propeller or fan, and therefore not having to vary the power or speed characteristics related to the different phases of flight, can always operate at its maximum efficiency, thus reducing fuel consumption. In addition, in case of high power required, the extra power is supplied by the batteries, allowing a smaller gas turbine.

In the parallel configuration (Figure 3), a battery-powered motor and a conventional motor are mounted on a shaft that drives a fan so that one or both can provide power at any given time. Here, too, as in the series, the accumulators can be recharged directly from the conventional engine without having to resort to other elements that would only represent additional weight. Compared to the series configuration, however, the parallel one enjoys a reduction in weight due to the absence of the generator and a greater level of safety thanks to the intrinsic redundancy of the structure that has two independent power sources. This configuration also has disadvantages: there is a high mechanical complexity due to the coupling of the two parallel supply lines; there is a great difficulty in controlling the system because the power flow must be regulated and mixed from two different sources.

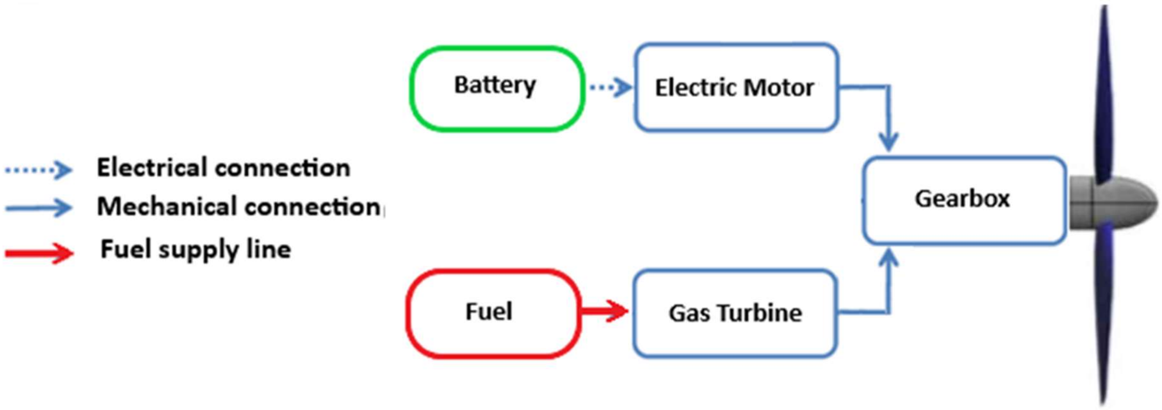

Fig.3 Parallel hybrid turbo-electric propulsion system conceptual scheme.

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3. Hybrid turboprop engine simulation

To evaluate the effect of the introduction of an electric motor on the characteristics of an aeronautical propulsion system, the behavior of a hybrid turboprop engine was simulated, and compared with that of a conventional turboprop engine [7], and highlighted the potential advantages in terms of efficiency, fuel consumption, pollutant emissions and overall weight of the system. The aircraft chosen to study the case is a regional aircraft for about 50 passengers, powered by two turboprop engines. The mission profile consists of three phases: take-off, climb, and cruise. The descent and landing phases are not considered, as they are less significant from the engine point of view. The mission profile is shown in fig.4.

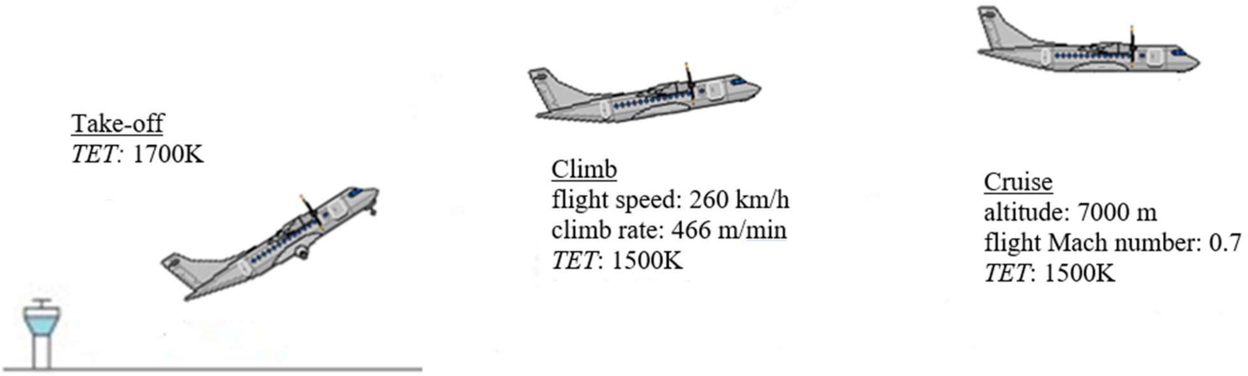

Fig. 4 Simulated mission profile: the three phases considered are take-off, climb and cruise.

Through a numerical program that simulates the behavior of a turboprop engine in off-design conditions, the main performances during the three phases of the mission described above were evaluated [8]. The program allows to calculate the specific power, the thermodynamic efficiency, and the specific fuel consumption according to the different engine characteristics, such as compression ratio, turbine inlet temperature, efficiency of the different components, etc., and the external operating conditions, essentially defined by the altitude and the flight Mach number. The aircraft considered is of the regional type, a twin-engine turboprop, with take-off power of the single engine equal to 1350 kW. Table 2 shows, following the off-design study, the different characteristics during the three mission phases.

Mission part and length	***Z* [m]**	**Flight speed [km/h]**	**Flight Mach number**	***TET* [K]**	***eP* [kW] (2 engines)**	**EBSFC [kg/h/kW]**	**Fuel flow [kg/h]**	**Fuel consumption [kg]**
Take-off (2 minutes)	0	122	0.1	1700	2700	0.247	666.9	22.2
Climb (15 minutes)	0-7000	260	0.216 (average)	1500	1462 (average)	0.242 (average)	353.8 (average)	88.4
Cruise (90 minutes)	7000	786	0.7	1500	1417	0.213	301.8	452.7

Tab. 2 Main characteristics of the reference turboprop engine, computed through a thermodynamic numerical program that simulates the behavior of the engine in off-design conditions (take-off, climb and cruise).

The configuration chosen for this case study is the parallel hybrid of fig. 3. In this case the aircraft is still twin-engine, but each propulsion system that powers the single propeller consists of a gas turbine and an electric motor.

The electric motor can be used in two ways: in all phases of the flight or used only in the phases of maximum power required, such as take-off and climbing. In the first case there is the maximum reduction in the use of the gas turbine, with excellent results in terms of reduction of pollutants related to the combustion of a hydrocarbon, and with the possibility of using a smaller gas turbine. However, the continuous use of the electric motor would lead to a strong

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increase in the weight of the batteries, as the specific energy of current batteries is much lower than the specific energy of fossil fuels (see Table 1). For this reason, it seems unlikely now to use high-power electric motors for high flight lengths. The use only in the phases of greater power demand, typically during take-off and climb, would lead to a reduction of pollutants in these phases in which their formation is very high, and the possibility of using a smaller engine during the phases of the mission in which less power is required, such as cruising and descending, with advantages in terms of plant engineering and cost. The electric motor could also be used during ground operations (taxis) given the modest power required, without a large increase in weight by the batteries.

Therefore, let's assume to use two smaller turboprop engines, and compensate for this reduction in power with two electric motors during take-off, climb and cruise. As an example, let's imagine that the chosen turboprop (the single engine) develops a power of 900 kW at take-off instead of 1350 as the reference engine. The missing 450 kW, as shown in Table 2, will have to be supplied by an electric motor. Referring to the same table, and scaling the powers with the same ratio, during the climb the single thermal engine will provide 487 kW and the difference, equal to 244 kW, will be provided by the electric motor. Even in cruise, the percentage of power supplied by the electric motor remains the same, therefore the gas turbine will provide about 474 kW, while the remaining 234 kW will be supplied by the electric motor.

To define the contribution in terms of power of the electric motor to the propulsion system composed of a thermal/electric engine, the power degree of hybridization H_P is used, defined as the ratio between the electric power and the total installed power:

$$H_p = \frac{P_E}{P_E + P_T}$$

In this case, H_P is 0.33.

In this first phase of the study, we want to calculate the reduction in fuel consumption linked to the use of the electric motor, and the consequent reduction of polluting emissions, in particular CO_2, in itself not considered a polluting agent, but a greenhouse gas, and therefore attributed to global warming. The formation of NO_x is not considered, as it depends not only on the quantity of fossil fuel used, but also on the combustion characteristics, therefore not uniquely referable to the degree of hybridization of the propulsion system.

During take-off the amount of fuel used by the thermal engines would be 22.2 kg (Table 2). If we consider the combustion in oxygen of a single component of kerosene (n-decane, $C_{10}H_{22}$):

$$\mathrm{C_{10}H_{22} + 15.5O_2 \rightarrow 10CO_2 + 11H_2O}$$

we obtain that the ratio between the mass of CO_2 produced, compared to the mass of kerosene used, is equal to about 3.1. Therefore, it is possible to estimate the the reduction of the fuel used and the CO_2 produced by the hybrid configuration in the three phases of the mission analyzed. Table 3 shows the results.

Mission part	**H_p**	**Fuel consumption [kg]**	**CO_2 Production [kg]**
Take-off	0	22.2	68.82
	0.33	14.8	45.88
Climb	0	88.4	274
	0.33	58.9	182.5
Cruise	0	452.7	1403.3
	0.33	298.7	926.2

Tab. 3 Fuel used, and CO_2 produced, by the hybrid configuration in the three phases of the mission.

As shown in Table 3, the mission part where CO_2 savings would be maximum is cruise, given its length in terms of time. However, as previously mentioned, the batteries needed to provide the power at this stage would be very heavy. As a first approximation we can calculate the electrical energy E_E necessary for the 2 electric motors to provide the power for the required time:

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$$E_E = \frac{P_E t}{\eta_{Etot}}$$

Assuming a total electrical efficiency (η_{Etot}), which considers all energy losses from batteries to propeller equal to 75%, the amount of energy coming from the batteries would be equal, just for cruise, to about 940000 Wh. If we consider, at the state of the art, an energy density of Li-ion batteries of 200 Wh/kg, the battery pack weight to provide the energy needed for cruise would be about 4700 kg. Considering that this engine could be used by a regional turboprop of about 50 seats, with a payload weight of about 4800 kg, a fuel capacity of about 5000 kg, and a maximum take-off weight (MTOW) of about 15000 kg, it is clear that, despite having chosen a value of H_p equal to 0.33, not too high, the battery weight, if the electric motor were also used in cruising, would be too large.

4. Conclusions

In this work the possibility of using a hybrid propulsion system in a regional turboprop aircraft of about 50 seats was evaluated, instead of the traditional turboprop engine. The propulsion system, which must provide a power of 1350 kW at take-off for each engine, is of the parallel type, with a thermal engine and an electric engine that provide power to the propeller. In this way, fuel savings and a consequent reduction in CO_2 production were highlighted. The most important aspect, from the point of view of the possibility of realizing the system, is given by the weight of the batteries necessary to supply the energy to the electric motor. In fact, considering that the system would provide the maximum advantage during cruise, as it is longer lasting, however, the batteries needed to provide the required energy would be too many and, considering the use of Li-ion batteries, currently the most suitable for this type of application, their weight too high. Therefore, at the state of the art, such a hybrid system is not suitable for large aircraft and long-duration flights, but for smaller aircraft and shorter flights. The development of this study will be the analysis of other hybrid configurations, to evaluate the differences and the improvement solutions, monitoring the development of higher energy density batteries.

References

[1] Fly the Green Deal, Europe's Vision for Sustainable Aviation, Report of the Advisory Council for Aviation Research and Innovation in Europe (ACARE), 2022.

[2] G.V. Brown, "Weights and efficiencies of electric components of a turboelectric aircraft propulsion system", 49th AIAA Aerospace Sciences Meeting, Orlando, FL, USA, 4–7 January 2011.

[3] Martin J. Hepperle, "Electric Fligth-Potential and Limitations", Conference: AVT-209 Workshop on Energy Efficient Technologies and Concepts Operation, October 2012.

[4] P. Juretzko, M. Immer, J. Wildi, "Performance analysis of a hybrid-electric retroft of a RUAG Dornier Do-228NG"., CEAS Aeronaut. J. 11(1), 263–275 (2019)

[5] D.F. Finger, C. Bil, C. Braun, "Initial Sizing Methodology for Hybrid-Electric General Aviation Aircraft", J. Aircr. 2020, Vol.57 N.2 , 245–255.

[6] M.C. Cameretti, A. Del Pizzo, L.P. Di Noia, M. Ferrara, "Preliminary analysis of Hybrid-Electric propulsion system integrated in a regional aircraft", AEIT Congress, Bari, Italy, 3–5 October 2018.

[7] J. Thauvin, G. Barraud, X. Roboam, B. Sareni, M. Budinger, D. Leray, "Hybrid propulsion for regional aircraft: A comparative analysis based on energy efficiency", ESARS-ITEC 2016, Toulouse, France, 2–4 November 2016.

[8] R. Andriani, U. Ghezzi, F, Gamma, A. Ingenito and A. Agresta, "Performance of a Turboprop Engine with Heat Recovery in Off-Design Conditions", Int. J. Turbo Jet-Engines 2013; 30(3): 249 – 259.