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Modelling of a Hybrid-Electric Light Aircraft

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Abstract

The European Research and Innovation Agenda as well as the NASA long-term programs have set ambitious targets in terms of emission reduction for the aviation industry.

Continuous improvements of conventional technologies will not be enough to fulfil these ambitious requirements; there is a need for revolutionary aircraft concepts and/or radical innovative systems. One such concept is to use a hybrid-electric propulsion system.

The CIRA and the Department of Industrial Engineering of the University of Naples “Federico II” have started a joint program in order to develop models and technologies related to the electrification of propulsive system in aviation.

The aim of this work is, then, the exploration of possible benefits of hybrid-electric propulsion with a focus on general aviation and selecting appropriate missions.

The hybrid-electric system has been designed assembling elements/systems all commercially available, realizing a very simple parallel layout, classifiable as “minimal hybrid”. Furthermore, such hybrid-electric system, -inclusive of energy storage system, transmission system, power management system, etc.- has been conceived to fit the original ICE requirements in term of weight, volume and max power at take-off.

In this study, a simple model to evaluate the performances of a light aircraft equipped with a hybrid-electric propulsive system has been developed. The approach adopted combine the so-called 0D/1D simulation to evaluate the “single” ICE performances with a simple engineering modeling which allows the performances evaluation of the integrated power plant. The application of model for a simple transfer mission leads to fuel saving up to 20% while for classical training mission, where pilots make numerous run(lap) “touch –and-go” , the fuel saving can reach a significative 30%.

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Nomenclature

HF	Hybridization Factor
P_{EM}	Power from the Electric Motor
P_{ICE}	Power from the ICE
$P_{Propeller}$	Power to the Propeller
P_{GEN}	Power from the Electric Motor working as Generator
SoC	State of Charge

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Keywords: Hybrid-Electric Light Aircraft, 1D modeling approach

1. Introduction

The goal of the project is to demonstrate the ability to use, in aeronautical applications, a hybrid powertrain savings in terms of fuel consumption and emissions. The aviation industry is responsible for about 12% of CO_2 emitted into the atmosphere from transport. The growing awareness of the need to reduce the levels of air pollution, require both the aerospace industry that the automotive industry is increasing pressure from the company to make the transport sector more sustainable.

Although the wide use and the remarkable evolution achieved over the years, internal combustion engines are still afflicted by defects. The main ones are the non-high efficiency and the strong bond between rotation regime and optimal operation, the fuel economy and the performance. Furthermore, ICE are powered by fossil fuel also emissions need to be reduced.

In this scenario, hybrid system can achieved great widespread in the future. This solution, as known, consist of coupling in series or parallel an internal combustion engine with an electric motor linked to power battery system. Hybrids Propulsion have a higher efficiency, if compared to the conventional vehicles with internal combustion engine, and the possibility to reduce emissions in the atmosphere.

Nowadays, a great attention of the scientific community is reserved for these solutions therefore the electric vehicles are improving. The goal is to find a flexible solution that meets requirements from both points of view environmental and performance.

Over the last years, many prototypes of hybrid aircraft have been proposed. In 2012, Cui at al. [1] have modeled and optimized an aeronautical electric-hybrid engine. In this research, the traditional internal combustion engine and the electric motor are on the same shaft. The electric motor provides the surplus power to the propeller when request avoiding the ICE running/works in low yield areas/zone. In the same year, Ausserer and Harmon [2], simulated and implemented a hybrid electric engine for a small airplane piloted remotely. The extremely small size of the aircraft effects on the design of the aircraft because the mass and volume in this case are priority compared to reliability and autonomy.

More recently, Friedrich and Robertson [3] did simulations and tests on a hybrid electric motor for a microlight aircraft. The size in this case is higher than aircraft studied by [1] and [2]. The engine is the SONG Gramex Ltd, usually equipped with a 200 cm^3 Bailey V5 capable of delivering up to 15 kW. This engine has been replaced by a Honda GX160 (7.5 kW at 7000 rpm in 12 kg), coupled with a DC brushless JM1 of Joby Motors (12 kW in 2.8 kg), which can also function as a generator to recharge the batteries, if the motor is able to provide more energy than needed to meet the flight.

In this paper, a Hybrid-Electric Light Aircraft is studied using a modelling technique. After a description of the hybrid propulsion layout the model built up using GT-SUITE is described and validated. The studied aircraft is the Tecnam P2010, equipped with an IO-360-M1A built by AVCO Lycoming. This engine, fueled with Avgas 100LL, has 4-cylinder opposed with an air-cooled. It is able to provide up to 130 kW of power, with a displacement of 5900 cm3 and a curb weight of about 135 kg.

This research is still in progress and it is result of a research collaboration between the CIRA (Centro Italiano Ricerche Aerospaziale/Italian Aerospace Research Center) and the Department of Industrial Engineering of the University of Naples “Federico II”.

2. Description of the Hybrid-Electric Propulsion

As has been said, this research focuses on demonstrating the convenience of a hybrid propulsion system for ultralight aircraft. The ultimate goal of the project is to design a hybrid-electric motor, with total power output of 130 kW, maximum total weight of 135 kg (including battery pack). The final motor should have dimensions to be housed on the aircraft replacing the traditional propulsion plant.

In order to respond to the working conditions, the most suitable configuration of the hybrid propulsion is the parallel architecture (in figure 1). In this way it is possible to exploit the contribution of both motors (ICE and the electrical motor) in the maximum power demand phases (takeoff) and to operate with the only ICE near the lower specific fuel consumption during the cruise phase, using the electric motor as a generator to recharge the batteries.

The chosen principle scheme is shown in figure 1.

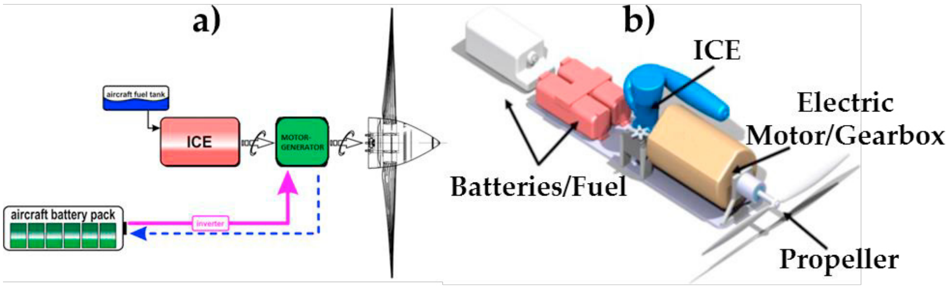

Fig. 1. a) Scheme of the Electro-Hybrid propulsion, b) Entire Electro-Hybrid Parallel Architecture

The first step of this research is the choice of the internal combustion engine. It has been chosen the CMD 22, built by the Italian Company CMD - Construction Diesel Engines. It is 4-cylinder boxer engine with a displacement of 2200 cm^3. This engine is now undergoing certification. The features are listed in table 1.

Table 1: Internal Combustion engine: CMD 22

Internal Combustion Engine	CMD 22 (Weight 82 kg)
Fuel	Gasoline
Cooling	Air
Maximum Power	102 kW (170 HP)
Maximum Torque	231 Nm
Speed (Take Off)	5500 rpm
Total Weight	82 kg

Obviously, the choice of electrical motor depends by the ICE. In this application the EM must provide the remaining energy rate of 30÷40 kW. In addition, in order to compare the new solution with the engine already equips on the ultralight, this electrical motor have limit on the maximum weight of 55 kg.

In a primary investigation, the power/weight has been fixed equal to 5 (considering the engine weight of 6-8 kg and the weight of the control and auxiliary systems), it is possible to install a battery pack up to about 40 kg. However, a battery pack of 40kg means an autonomy less than 10 minutes at full power operation of the engine. To obtain a further reduction of the weight, the electric motor can perform the function of the starter motor, saving about 15 kg.

In this application, it has been chosen the electrical motors brushless “AC synchronous “EMRAX 207”, built by ENSTROJ. Performance of the electrical engine are shown in figure 2.

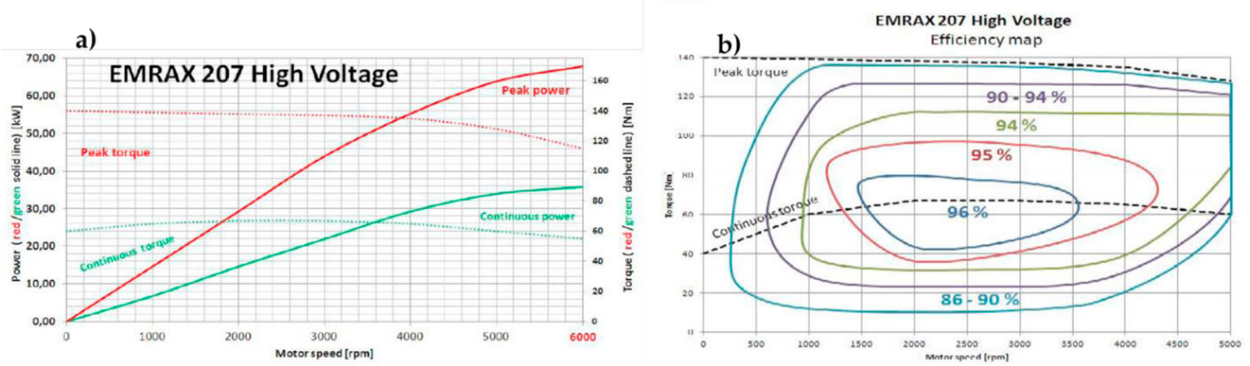

Fig. 2. a) Power vs Torque, b) Efficiency Map

The electric motor is placed directly on the shaft of the engine, upstream of the speed reducer. This solution allows a considerable saving in terms of weight, being able to accommodate the electric machine directly in the crankcase. In this way, the whole engine becomes a single block (as already shown in figure 1b). The engine has a speed reducer with a ratio of 2:1 allowing the propeller to operate at a constant speed of 2700 rpm while the engine speed therefore is of about 5500 rpm. In this point, the ICE gives about 90 kW to the propeller and the electric motor approximately 35 kW of continuous power, up to 160 kW of power peak.

These data allow calculating the hybridization factor (HF, Hybridization Factor), which classifies the hybrid in one of the three main existing categories:

- *Full Hybrid*, hybridization full, when the electric system is alone capable of advancing the vehicle on a standardized driving cycle, regardless of the autonomy of the batteries
- *Mild Hybrid*, lightweight hybridization, where the purely electric mode of operation is not able to follow for a full driving cycle normalized
- *Minimal Hybrid*, minimum hybridization, characterized by a decreasing distance in pure electric mode, and by a decreasing degree of hybridization.

This factor can easily be obtained from the following expression:

$$HF = \frac{P_{EM}}{P_{ICE} + P_{EM}} = \frac{P_{EM}}{P_{TOT}} \tag{1}$$

Where P_{EM} is the power coming from the electric system and P_{ICE} is coming from the internal combustion engine. This factor varies in the range [0 ÷ 1].

In our case, the HF is equal to 0.28 assumed a power of 35 kW for the electric motor and 90 kW for the internal combustion engine. Therefore, the entire engine falls in the last category: *minimum hybridization*. This means that the electrical motor cannot works alone in any stage a normalized cycle.

Fixing the ICE and the EM, the last choice concerns battery. However, it depends on the energy density of batteries now on the market storing as much potential energy for the same weight and obtaining autonomy benefits. Table 2 shows the energy density range of the most common batteries, with the rate of discharge.

From the table 2, it is clear that the batteries Lithium-Polymer have higher energy density and with a good value of the discharge rate. Therefore, the chosen batteries are Li-Po even if this batteries type are more expensive.

Adding battery pack the total weight of the electrical system reaches 55 kg.

Table 2: Battery typical energy density range and discharge rate

Type	Energy Density [Wh/kg]	Discharge Rate [C]
Lead	30-50	0.1
Ni-Cd	48-80	20
Ni-MH	60-120	5
Li-ion	110-160	5
Li-Po	130-200	12

For simplicity of calculation and as a precaution, it has been assumed a weight of the battery pack 40 kg. The energy density of the batteries Lithium Polymer varies from 130 to 200 Wh/kg. It has been used a value of 150 Wh/kg. Therefore:

$$\frac{\text{PWR Density}\left[{}^{\text{Wh}}/_{\text{kg}}\right]\times\text{Battery Weight [kg]}}{1000} = \text{PWR Available [kWh]} \qquad (2)$$

Using the above equation, a battery pack of 40 kg is able to provide 6.0 kW continuously for an entire hour and consequently 12 kW continuously for 30 minutes. The main limitation is related to the maximum discharge. The discharge rate for this type of batteries is about 12 C, which means that the stored energy is discharged in not less than 1/12 of time (5 minutes).

The maximum power can be evaluated as following:

$$\text{Maximum Power [kW]} = \frac{\text{PWR Available [kWh]}}{\frac{1}{\text{Discharge Rate [c]}}} \qquad (3)$$

In this case, the maximum power is of 72 kW that are available only for the first 5 minutes of operation of the battery to the maximum state of charge. Therefore, the discharge rate is another important parameter for the battery pack choice. It is known, that the maximum charge of these accumulators is about 2 C, which means that the battery cannot be recharged fully in less than 30 minutes. In addition to a time limit, there is another one because 40 kg of batteries cannot receive from the ICE more than 12 kW (evacuated by equation 3).

If the SoC is equal to 100%, it is possible to use both motors at full power getting the required 130 kW only for 5 minutes.

The minimum recharge the battery pack is about 30 minutes, requiring approximately 12 kW to the thermal engine, with a difference of 80 kW (ICE). Obviously, it is possible, if required, to give less power to recharge the batteries and more power to the rotating axis. In this case, the duration of the batteries charging increases.

3. 1D model of the Hybrid-Electric Propulsion

The described Electric-Hybrid propulsion has been modelled using the commercial code GT-SUITE developed by Gamma Technologies. A first model of the only ICE has been built up and validated using data of CMD (the engine manufacturer) and then it has been coupled with the EM [4].

The ICE has been analyzed for all the rotating speeds. The model has been built up giving as input the features of the engine CMD 22.

All the geometrical characteristics are implemented in the model to run simulations. Simulations have been run in the engine speed range [2000 ÷ 7000] rpm, in figure 3 model results are shown.

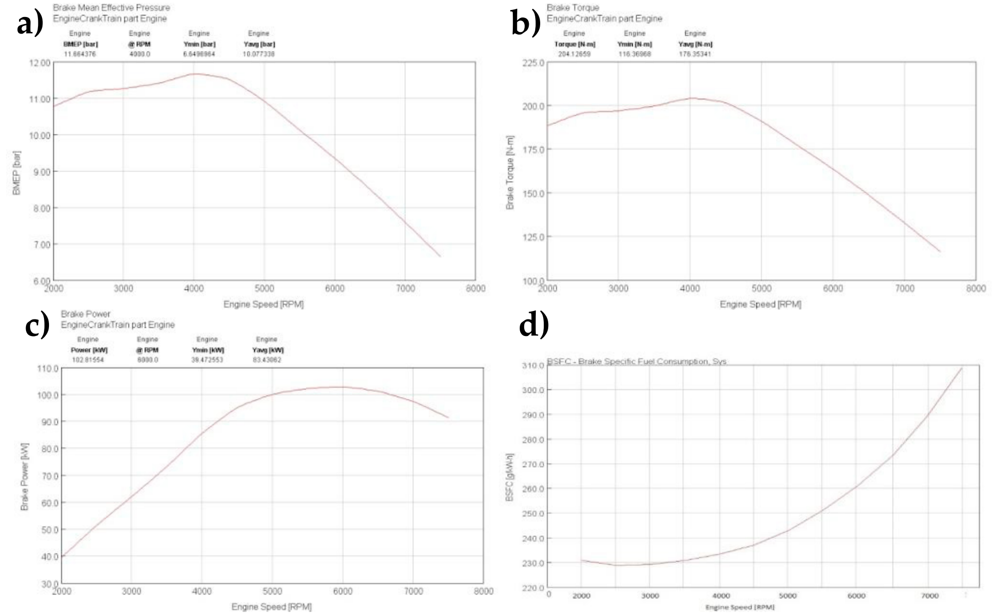

Fig. 3. Model results: a) PME vs rpm, b) Brake torque vs rpm, c) Brake power vs rpm, d) BSFC vs rpm.

In table 3, there is a comparison between data supplied by the engine manufacturer and the model results. In figure 4a, the simulated torque is compared to the experimental one while in figure 4b the simulated and experimental pressure vs crank angle for the first cylinder are shown.

Table 3. Performance comparison: Experimental vs Model results Engine CM22

Engine Speed [rpm]	Experimental Data	Model Results	Error %
4000 (Max. Torque)	231 [Nm]	204 [Nm]	-11.69%
4500	102 [kW]	95 [kW]	-6.86%
5500	103 [kW]	102 [kW]	-0.97%
	256 [g/kWh]	251 [g/kWh]	-1.95%
Min. BSFC	225 [g/kWh]	229 [g/kWh]	1.78%

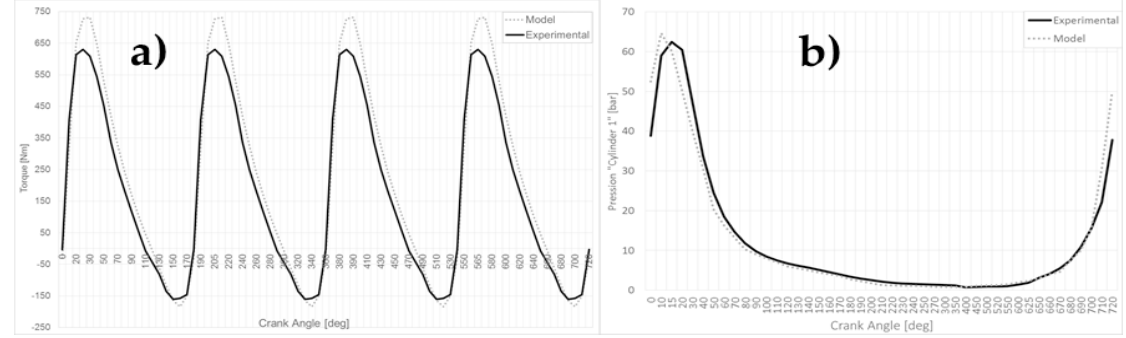

Fig. 4. Comparison: Experimental vs Model: a) Torque, b) Pressure vs crank angle for the first cylinder.

The validated model of the ICE has been coupled with an electrical motor. Input to the engine have been set are the current, the toque coefficient, the windings temperature, the equivalent resistance and the equivalent inductance.

The entire/completed model has been validated comparing, with experimental data, the torque and the power as function of the engine speed. This comparison is shown in figure 5.

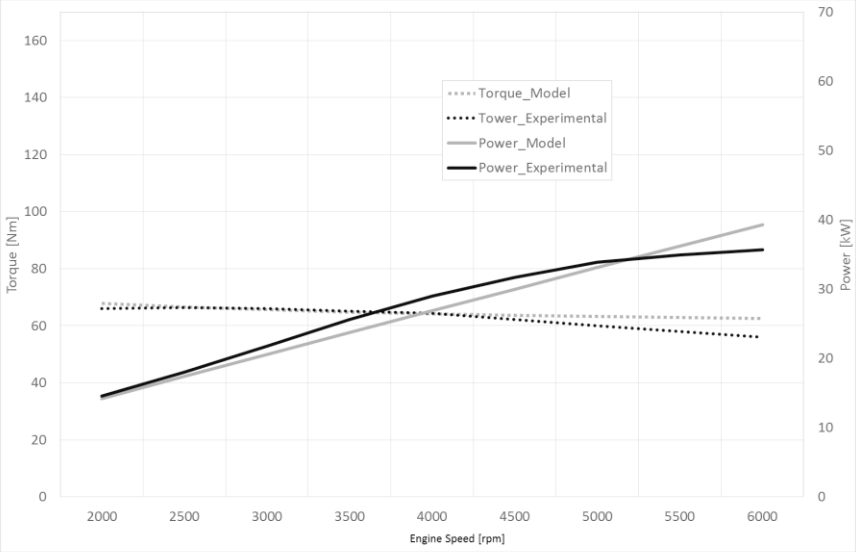

Fig. 5. Comparison: Toque and Power.

The final validated model has been run in the typical speed range. Results are shown in figure 6.

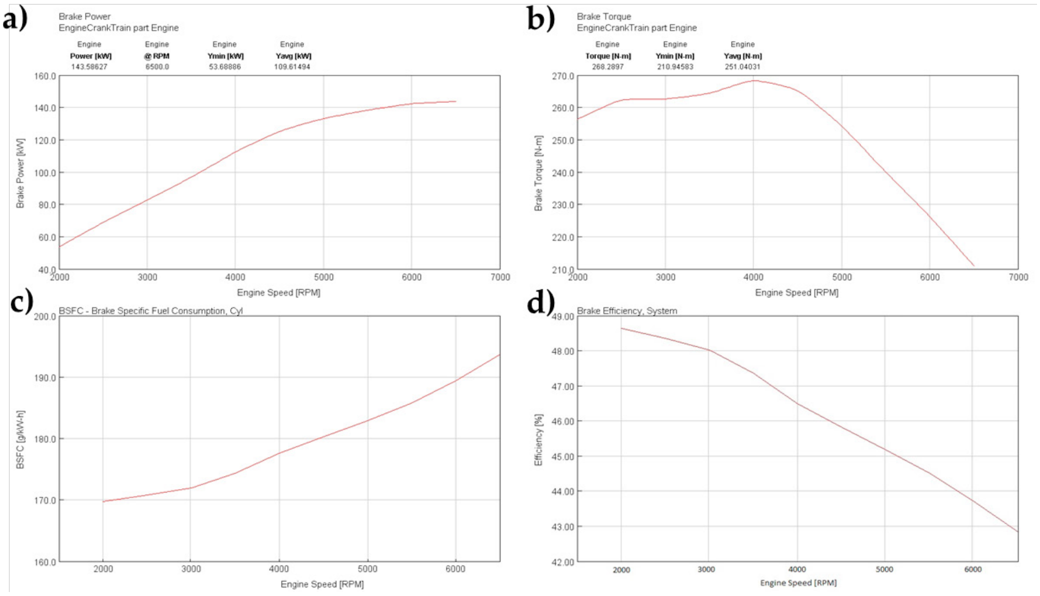

Fig. 6. Model results: a) Brake Power, b) Brake Torque, c) BSFC, d) Efficiency.

It’s obvious that the electrical motor can give a surplus of power and torque. The requested power of 138kW has been achieved at the rotational speed of 2750 rpm of the impeller (5500rpm of the ICE). Both torque and efficiency increase.

It is important to underline that the model does not include the production and the storing of the electrical energy, it considers an infinite amount of energy available for the electrical machine.

However, as already said, this model is the first step of this research.

The efficiency increment is due to the reduction of the specific consumption. This means that a higher output power is available for the same fuel consumption. Obviously, these considerations effect to the emission.

4. Conclusions

In this paper, a preliminary study of an innovative Hybrid-Electric Propulsion for a Light Aircraft has been presented. The ultimate goal of the project is to design a hybrid-electric motor, with total power output of 130 kW, maximum total weight of 135 kg (including battery pack).

In order to respond to the working conditions, a hybrid propulsion with a parallel architecture has been chosen with a Hybridization Factor equal to 0.28 (assumed a power of 35 kW for the electric motor and 90 kW for the internal combustion engine). Therefore, the entire engine falls in the last category: *minimum hybridization*. This means that the electrical motor cannot works alone in any stage a normalized cycle.

The final propulsion consists of an internal combustion engine CMD 22, manufactured by the company CMD and an electrical motor brushless "AC synchronous "EMRAX 207", built by ENSTROJ. The batteries pack as a weight of the battery pack 40 kg and are Lithium Polymer.

Before the only ICE and then the coupling of ICE and EM have been modelled using the commercial code GT-SUITE, developed by Gamma Technologies. Both models have been validated comparing data with experimental ones. This research is still in progress and it is result of a research collaboration between the CIRA (Centro Italiano Ricerca Aerospaziale/Italian Aerospace Research Center) and the Department of Industrial Engineering of the University of Naples "Federico II".

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