

Design and Development of Hybrid-Electric Propulsion Model for Aeronautics

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Abstract. Nowadays, worldwide environmental issue, associated to reduction of pollutant and greenhouse emissions are gaining considerable attention. Aviation sector contribution to the whole CO₂ released accounts to around 2%, but it is expected to grow in the next future due to increase of demand. Probably, combustion engine design and fuel efficiency have already reached their optimum technology level and only a breakthrough as hybrid-electric propulsion could be able to satisfy the new international more demanding requirements. However, an improvement of the technology readiness level of hybrid-electric propulsion is strongly necessary and many operational and safety challenges should be addressed. In the work here reported, a hybrid-electric model was designed and developed for general aviation aircrafts, by means of the Mathworks® Matlab – Simulink 1D/0D simulation environment. Both thermal and electric energy storage units, transmission systems and power management devices were considered and the overall performances were evaluated during cruise phase and a conventional training mission, characterized by several run(lap) “touch-and-go”. Furthermore, an innovative mathematical methodology was implemented for battery pack discharge profile interpolation. Finally, reliability and accuracy of the new proposed model were evaluated through comparison with the commercial code Simcenter AMESim® software and an average bias only equal to 5% was achieved.

1 Introduction

Future Sky (FS) is a Joint Research Initiative of the Association of European Research Establishments in Aeronautics (EREA) devoted to preparing key technologies and capabilities for a green and seamless air transport in Europe. Within Future Sky, EREA promotes joining forces with the European industry and universities to design a new air transport system allowing environmentally friendly, smooth and efficient air vehicles and associated mobility.

In detail, the FS Energy is targeting new eco-friendly sources of power for aircrafts. The reduction of energy consumption in aviation leads to high social, environmental and economic benefits and will ensure air transport sustainability. The goals are improved

resource efficiency, reduction of particulate, CO₂ and NO_x emissions; the ultimate aim being the Zero Emission transport system. If no actions would be undertaken, the adverse impact of aviation on environment would significantly grow due to the expected increase of air transport traffic by 5% every year.

In order to design a system able of fulfilling the Flight-Path 2050 - FP2050 goals, *Future Sky Energy* intends to address innovative vehicles in the class of Small Aircrafts (range of 4-19 seats), Regional Aircrafts (19-75 seats) and Short-Medium Range Aircrafts (around 200 seats), with the aim of reducing the aviation environmental impact by means of breakthrough propulsion systems. Three main axes are explored:

- A1 *New solutions for energy storage and their integration in the aircraft.*
- A2 *Hybrid propulsion.*
- A3 *Electric propulsion.*

The activities presented in the paper are included within A2.

2 Model

The main goal of the modelling task was to design and develop a software - SW environment able to predict the performances of hybrid-electric propulsion systems of general aviation - GA aircrafts for assigned mission profiles. In particular, Tecnam P2010 [1] airplane was considered.

2.1 General overview

The hybrid-electric propulsion model was suitably designed in a modular way. Therefore, it can be efficiently used for investigating both the stand-alone features of every components i.e., propeller, electric motor/generator – EM/EG, battery pack, power management system, gear box, internal combustion engine – ICE and the overall behaviour of an assembled architecture e.g., serial, parallel, combined, full-electric, etc.

2.2 Mission profile

In the work here reported, two main mission profiles were considered i.e., training and cruise.

The first consists in flight segments, repeated several times just for pilot training. In particular, the flight profile is shaped in sequences of repeated climbs, cruises, base lags, descends, landings, but obviously only one take-off. This is called *touch-and-go* profile. Depending on the battery energy storage capability, the aircraft can carry out different numbers of *touch-and-go* segments.

Table 1. Training profile.

Time [s]	Altitude [m]	Power at propeller [kW]
60 (Take-off)	122	122 (90 ICE + 32 EM)
60 (Climb)	244	103 (80 ICE + 23 EM)
300 (Cruise)	244	68 (60 ICE + 8 EM)
60 (Base leg)	244	23 (35 ICE – 12 GEN)
90 (Landing)	0	23 (35 ICE – 12 GEN)

In Table 1 power is split in ICE and EM contributions. This subdivision was accomplished in order to assure maximum power at take-off. Consequently, less power during climb and a little bit of electric one during cruise can be used. Instead, during base lag and landing phases, ICE was the only motor driving the propeller. Part of its power was used also to recharge the battery through employment of EG.

Cruise profile is very different in comparison to training, especially in terms of endurance. In cruise, the maximum flight required power is guaranteed by the ICE, and only a minimum electric recovery is allowed by the EG.

Table 2. Cruise profile.

Time [s]	Altitude [m]	Power at propeller [kW]
60 (Take-off)	122	122 (90 ICE + 32 EM)
720 (Climb)	2440	93 (70 ICE + 23 EM)
8400 (Cruise)	2440	88.5 (90 ICE – 1.5 EM)
720 (Landing)	0	23 (25 ICE – 2 GEN)

The data above reported are collected in look-up tables and used in real time simulations for modelling the other components.

2.3 Propeller

Propeller is the device devoted to convert mechanical power of a rotating shaft in fluid (air) momentum change, in order to generate thrust, according to the momentum invariance principle.

In this investigation, the propeller considered was *MT Propeller* [2] with two blades and a fixed pitch. Fig. 1 illustrates the characteristic curves.

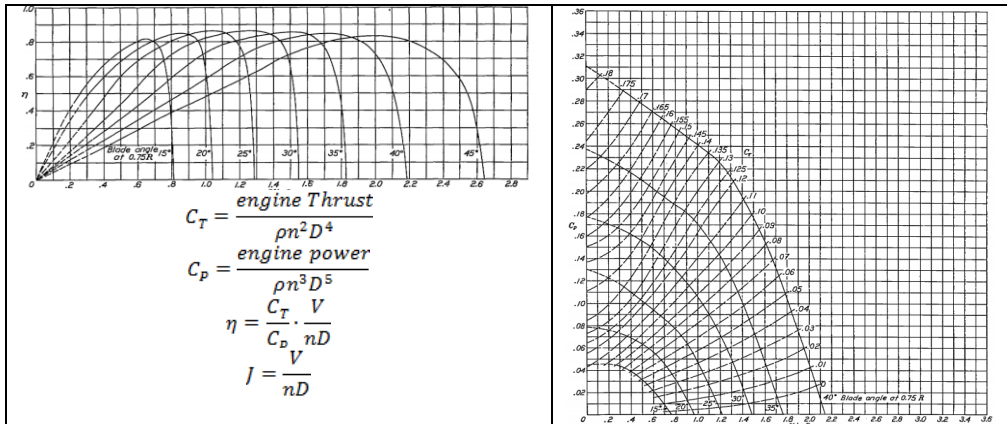


Fig. 1. Characteristic curves for propeller modelling.

Where T is propeller thrust, $\rho(z)$ density of air, n rotational speed, D diameter, V flight speed, z altitude.

Aircraft flight speed and required thrust imply the requested power; so the propeller angular speed may be inferred on the base of the maximum propeller performance.

Calculation of propeller performance can be carried out by means of Renard's equations [3], in which n is the unknown.

$$T(n) = C_T(n) \rho n^2 D^4 \quad (1)$$

$$P(n) = C_p(n) \rho n^3 D^5 \quad (2)$$

Real time solution of (1) and (2) system of equations is computationally expensive.

Therefore an alternative interpolation method was used. It is based on modification through Fig. 1 of C_T and C_p curves as function of n and on determination for two extreme values of flight speed i.e., the minimum ($V_{\min} = 15.56$ [m/s]) and maximum speed ($V_{\max} = 61.73$ [m/s])

Two thrust profiles were evaluated as a function of n . Assigning as input the mission profile in terms of thrust T and flight speed V , the number of revolutions n can be inferred. So, for every flight speed, included into the selected range, the interpolation method described by equation (3) provides the specific $n(V)$.

$$\frac{n(V_{\max}) - n}{n(V_{\max}) - n(V_{\min})} = \frac{V_{\max} - V}{V_{\max} - V_{\min}} \quad (3)$$

Where n and V are the actual mission values. Therefore, at every actual input speed the instantaneous propeller number of revolutions was obtained.

Through the number of revolutions, speed and diameter, the propeller advancement ratio ($J = V/n \cdot d$) can be determined. Entering into a look-up table of the propeller efficiency curves, previously digitized and inserted as data into a table, the propeller power was achieved.

This power is straight provided by EM, since a direct drive between propeller and EM was considered.

Analogously, through a cascade procedure, EM outputs are, at the same time, the battery inputs.

2.4 Electric Motor/Generator

Hybrid-electric propulsion systems for GA aircrafts are generally endowed with Permanent Magnet Synchronous AC Motors, which can be used also as generators.

For anisotropic EMs the electromagnetic torque T_e is expressed by the following relationship:

$$T_e = \frac{3}{2} p \Lambda_{mg} i_q + \frac{3}{2} p (L_d - L_q) i_d i_q \quad (4)$$

where p is the number of EM polar-pair number, Λ_{mg} is the maximum flux linkage per phase due to the permanent magnets, i_d and i_q are the direct and quadrature components of the armature currents, L_d and L_q the direct and quadrature stator inductances.

The motor mechanical dynamics is described by the following ordinary differential equation:

$$T_e = J \frac{d\omega_m}{dt} + B\omega_m + T_{Load} \quad (5)$$

with J the inertia moment, B the friction coefficient and ω_m the angular velocity.

The voltages and currents in the rotating frame, moving at the synchronous speed ω , can be expressed in terms of their d- and q-axes components, u_d, u_q and i_d, i_q respectively, as follows:

$$u_d = R i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \tag{6}$$

$$u_q = R i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \Lambda_{mg} \tag{7}$$

with R the stator resistance.

By starting from the knowledge of the input propeller torque and by adding a proper performance objective to be pursued by the control action, the voltages and currents can be consequently determined.

2.5 Battery

At the moment, especially for aeronautical applications, the best available rechargeable batteries in terms of specific energy and power and long shelf-life, belong to lithium-ion polymer – LiPo family.

The battery time-dependent behaviour can be conveniently described by electric circuital models. Indeed, they are more detailed than the experimental schemes and less computationally expensive than the electrochemical ones, so they are very suitable for numerical simulations.

Among the various circuital approaches, reliable results [4-6] are obtainable by the following relationship:

$$V_{batt} = E_0 - K \frac{Q}{Q - it} - Ri + A \exp(-B it) - K \frac{Q}{Q - it} i^* \tag{8}$$

Where E_0 is the voltage constant component, K the polarization constant, i.e., equivalent to polarization resistance, R internal cell resistance, Q battery capacity, A reference electric potential, B the inverse of time constant, related to discharge in exponential regime, i current, i^* the filtered current, and t the time.

Some simplified hypotheses are assumed i.e., cell internal resistance is not affected by current intensity during both charge and discharge cycles, voltage parameters are equal for charge/discharge profiles, battery capacity is not influenced by current intensity (no Peukert effect), self-discharging and memory effects are neglected.

2.6. Internal Combustion Engine

In a serial configuration of hybrid-electric propulsion system, ICE can be used as range extender, while for a parallel architecture battery pack was sized with the average power and all the possible load oscillations are addressed by ICE.

For the simulation of this component, the engine characteristic curves in terms of power, torque and specific consumption, as function of the rotational speed, were considered by previously collected look-up tables.

Fig. 2 shows block diagram of the ICE model in Mathworks® Matlab Simulink SW.

In Fig. 3 and Fig. 4 plots, associated to training mission profile are reported and it can be noticed that the average percentage bias between the two considered models is about 4%, while the maximum absolute bias is about 32 V.

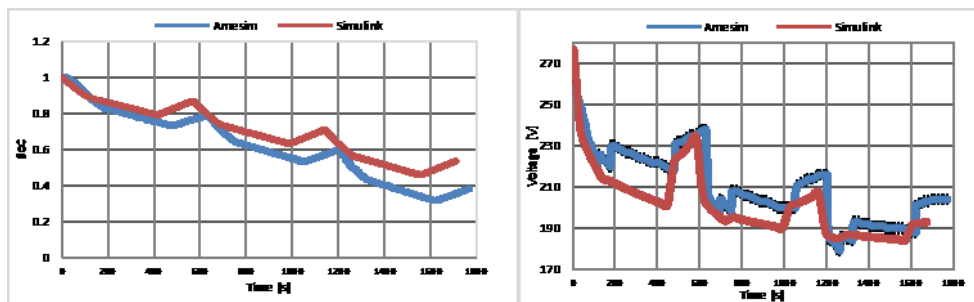


Fig. 3. Comparison between Simulink and AMESim[®] plots for training mission profile.

So, for the training profile, the two plots of the state of charge show a mismatch in terms of power and voltage of about 18% while the maximum absolute bias is about 0.18. This is in agreement with the deviation between the actual current profiles obtained for the two simulations examined and reported in Fig. 4.

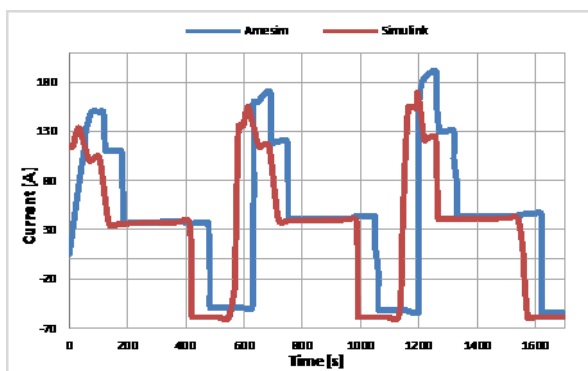


Fig. 4. Comparison between Simulink and AMESim[®] plots for training mission profile.

4 Conclusions

Aim of the proposed SW is to conveniently simulate different hybrid electric propulsion architectures and configurations, with the capability to compare several mission profiles, in terms of battery charge and discharge and to evaluate the performances of the main components.

Models were conceived and implemented for every subsystem, either as look up tables either as electrical-mechanical physical models. Particular emphasis was paid to the innovative battery model, which uses a parametric equation with a Kalman filter to accurately simulate several regions of the battery discharge curve.

To test the overall model, electrification of GA Tecnam P2010 aircraft was considered in an electric hybrid parallel configuration. Two mission profiles were analysed i.e., cruise with a duration of about 2 hours and training with repeated cycles of *touch-and-go* segments of about 10 minutes each.

After a preliminary validation of the main components against the technical specifications arising from the commercial data-sheets, the results of the overall model were compared with the achievements, obtained in a previous work [8] using the commercial software Simcenter AMESim[®]. Comparison with the reference data [7-8] shows a satisfactory agreement within a slight deviation of about 15%.

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