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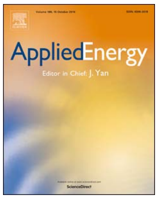

Fuel economy of hybrid electric flight

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HIGHLIGHTS

- A formulation of fuel economy/endurance for a hybrid electric aircraft.
- Amendments to existing battery discharge models and experimental validation.
- A battery charging model for lithium batteries and its experimental validation.
- Effect of battery specifications and the engine working points on fuel economy.
- Application to a parallel hybrid electric unmanned aerial vehicle.

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ABSTRACT

The present investigation addresses the problem of evaluating the endurance of hybrid electric aircraft and discusses the effect of battery specifications and the engine working points on fuel economy. In particular, the endurance per unit mass of fuel of a hybrid power system is calculated by assuming a constant power-level flight performed with alternate cycles of battery charging and discharging (ON-OFF strategy). The computation of the fuel economy requires accurate models for the time, the power and the energy associated with battery charging and discharge processes. In order to reach this goal, two approaches proposed in literature to evaluate electric endurance were discussed, amended and validated through comparison with experimental data. A model for constant-current/constant voltage battery charge was also presented and validated with literature experimental data. In order to explain how these models can be applied to real applications, a parallel hybrid power system was sized and analyzed for a medium-altitude long-endurance unmanned aerial vehicle. Lithium polymer batteries and two stroke diesel engines were considered and three different hybridization degrees were analyzed. The results showed a trade-off between electric flight time and overall endurance per unit mass of fuel and an improvement up to 12% in fuel consumption with respect to a non-hybrid case with the same engine.

1. Introduction

In conventional aircraft powertrains with thermal engines, the amount of energy stored on board is not a limiting factor because of the very high gravimetric and volumetric densities of liquid fuel [1]. For these systems, endurance is usually evaluated in conditions of level flight using the well-known Breguet formulas [2]. Breguet formulas cannot be applied to battery powered aircraft because of the complex behavior of electric storage systems that makes arduous to establish the actual energy available during the flight and the overall efficiency of electric flight.

Even if some formulas for electric steady rectilinear level flight were proposed in literature [3,4], the problem is not trivial because of the dependence of battery capacity on several parameters including current drawn, temperature, aging and cycling. Another problem is the lack of useful experimental data since batteries are usually tested at constant current (see for example [5,6]). For this reason, Traub [7] and Avanzini et al. [8] performed specific constant power discharge tests that attempted to reproduce the power request in a steady level flight. However, the approaches of these authors do not take into account the technological limits to the power drawn from the battery, and in particular its maximum continuous current that also affects the energy density.

To evaluate electric endurance, *EE*, Donateo et al. [9] proposed a mission-based approach that can take into account the variability of power request for both propulsion and auxiliaries (payload, avionic, etc.). A similar approach is also used by Fuller [10]. During the preliminary design of an electric or hybrid electric power system, however, it could be more useful to have a simple formula for endurance than a detailed simulation tool.

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Nomenclature

bC_{rate}	burst discharge current of the battery/C
BHP	brake horse power
$bsfc$	brake specific fuel consumption of the engine
C	nominal capacity
c_{D0}	zero lift drag coefficient
C_{rate}	nominal discharge current of the battery/C
DOD	depth of discharge
E	energy
EE	electric endurance
E_0, J, H, P	parameters of the Sheperd-Peukert model
G	flow rate
GED	gravimetric energy density
h	parameter of the proposed charge model
HD	hybridization degree
I	current
I_0	charging rate
K	induced drag factor
k	parameter of the proposed charge model. Final current of the battery charge = kI_0
L	percentage of the battery maximum power drawn from the battery
M	mass
n	Peukert coefficient
Ns	number of battery cells in series
OCV	open circuit voltage
P	power
R	internal resistance of the battery
rC_{rate}	maximum recharge current/C
S	wing area
SE	specific endurance
SOC	state of charge
t	time
THP	thrust power
U	true air speed
V	voltage
W	weight
η	efficiency
ρ	atmospheric air density

Subscripts

$batt$	battery
$burst$	burst
c	conventional (non hybrid) power system
CC	constant current
$cell$	battery cell
CV	constant voltage
d	discharge
E	empty
Eff	pseudo-effective
f	fuel
fin	final
G	electric machine in generator mode
h	hybrid power system with the ON-OFF strategy
ICE	internal combustion engine
in	initial
inf	lower bound value (ON-OFF strategy)
M	electric machine in motor mode
max	maximum value
min	cutoff value
mR	modified Ragone approach
mT	modified Traub formula
nom	nominal
P	propeller
r	recharge
R	Ragone approach
sl	sea level
sup	upper bound value (ON-OFF strategy)
t	hybrid power system in thermal mode
T	Traub formula
to	takeoff

In this work, amendments to the approaches of [3,11] are suggested to improve their accuracy and to put into evidence the effect of battery specification. Moreover, the proposed formulations for battery discharging time are expressed in terms of datasheet specifications to make easier the application to real cases. Their accuracy is experimentally validated over a wide range of batteries versions and discharging conditions.

As for the time and the energy required for charging the batteries, the authors couldn't find an appropriate model but some experimental data are reported in [12]. Therefore, another original contribution of the paper is the development and the validation of a model to estimate the time, the energy and the power required to charge a battery according to the selected charging current. Such a model is essential in the study of a hybrid electric airplane where batteries can be recharged in flight when excess propulsive power is available (for example in cruise or during the plane's descent).

All in all, fuel economy in a hybrid electric aircraft cannot be calculated with a universally valid equation because it depends on the architecture (series or parallel), the hybridization degree (electric power to total power), the engine design and the energy management strategy of the power system [13]. This work describes a methodology to evaluate the endurance of a hybrid power system that assumes a

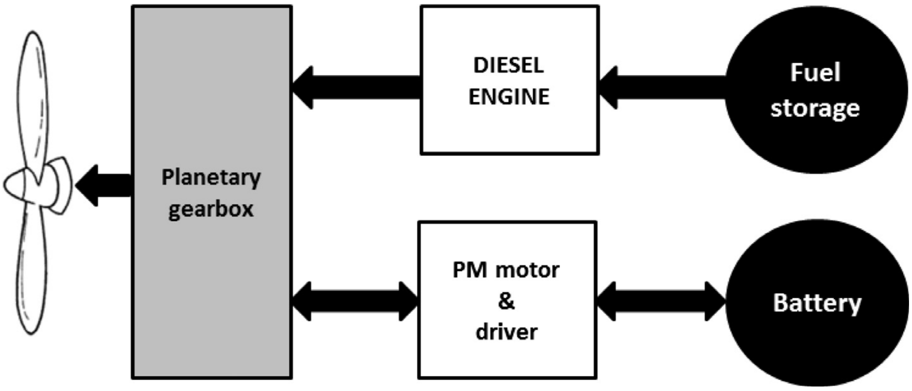

Fig. 1. A parallel hybrid power systems.