Optimal Energy Management of a Hybrid Electric Helicopter for Urban Air-Mobility

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Abstract. In this study, a hybrid electric helicopter for air-taxi operations is considered. The drivetrain includes a turboshaft engine and two electric machines, fed by a lithium ion battery. In previous works, some of the authors developed a simple but thorough modelling approach for the electric path of the power system that was validated by means of experimental data from literature. In this investigation simulation results from the Gas-turbine Simulation Program (GSP) commercial environment were used to develop and validate an off design model for the turboshaft. The second innovative contribution of the paper is the application of Dynamic Programming to four different missions of the helicopter to quantify the fuel saving potentiality of hybridization and also as benchmark for future online control strategies. A constraint was considered in the investigation to allow at any time the electric backup in case of engine failure. The results of DPM showed that it is possible to obtain a reduction of fuel burn from 12% to 24% (with respect to using only the engine to move the rotor) depending on the specification of the mission and the state of health of the battery. Moreover, it was proved that charging the battery on board is not necessary in this kind of application.

Introduction
In the last decade, aircraft propulsion electrification has been earning an increasing interest due to several benefits that it could bring, especially in terms of fuel saving and emissions cutback [1]. The specific advantages of hybrid electric power systems for helicopters include also separation of the propulsion of main and tail rotor, higher reliability, increased operational lifetime thanks to reduction in the number of devices, etc. [1],[2]. As a further advantage, particularly relevant for single-engine rotorcraft, the battery pack allows for a few minutes of endurance in case of engine failure (electric back-up) [3]. These advantages need to be weighed against the increased weight and complexity of the resulting power system and are limited by the unsatisfactory performance of electric machines and storage systems [4]. While technological enhancements, in particular improvement in the energy density of batteries, are mandatory to make pure- and hybrid-electric power systems viable for heavier applications, these concepts find perfect fit in one of the today’s emerging aviation markets that is the urban air-mobility, also known as on-demand or air-taxi operations. Urban air-mobility is enabled by vertical take-off and landing capability, while the short-range requirements, limited speed (compared with longer distance commuters) and altitudes up to 1000ft [5] make them suitable for hybridization even with the limited energy density of today batteries. Hybrid Electric Propulsion Systems (HEPS) are characterized by the use of two energy storage systems: a fuel tank and an electric storage system (usually a battery). HEPS can be classified into parallel and series powertrains [6]. In the case of series configurations, the propeller (in fixed-wing aircraft configurations) or the rotor (for application of HEPS to helicopters) is moved by an electric motor while
the internal combustion engine is used to drive a generator. The current to the motor is the algebraic sum of the battery current and of that produced by the engine through the generator. In the parallel case, both the thermal engine and the electric motor are mechanically connected to the drive and their mechanical power is summed algebraically. The series configuration is suitable for low-speed, high-torque propulsion applications or distributed propulsion systems, but it is less efficient and it requires larger batteries and electric machines than the parallel one. In this investigation, a parallel hybrid electric power system is considered.

In HEPS, the power management of multi-source operation is also critical. The supervisory control strategies for hybrid electric powertrains are usually classified into four categories [6]: numerical optimization, analytic optimal control theory, instantaneous optimization and heuristic control techniques. Heuristic Control Techniques are rule based and require a very low computational cost [7]. They can be based on Fuzzy Logic controllers [8]. Other approaches use the Bellman’s Principle or, in general, Dynamic Programming to perform a global Numerical Optimization. Finally, the analytic optimal control searches for the optimal solution using a simplified mathematical model for the powertrain [9]. The application of global optimization requires fast but accurate models of the powertrain. In previous works, some of the authors developed a simple but thorough modelling approach for the electric patch of the power system that was validated by means of experimental data from literature. In this investigation simulation results from the Gas-turbine Simulation Program (GSP) commercial environment were used to develop and validate an off design model for the turboshaft. In particular, the turboshaft model predicts the engine fuel consumption when operating at loads, altitudes and speeds different from its design point. The second innovative contribution of this paper is the application of Dynamic Programming Methods to quantify the fuel saving potentiality of hybridization in this particular application and also as benchmark for future online optimal control strategies. Finally, this investigation addresses the utility of charging the battery along the mission and the possibility of the electric back-up operation in case of engine failure taking into account the degradation of battery performance due to aging effects.

1. The hybrid electric power system

The hybrid electric power system considered in this investigation is a parallel configuration in which the turboshaft engine (nominal power $P_{\text{ICE, nom}}$) is mechanically coupled with two electric machines, each able to produce a nominal power $P_{\text{EM, nom}}$.

![Figure 1. Overview of the hybrid electric power systems](image1)

![Figure 2. Power request profile during electric back-up operation ($t_{AT}$: average time of flight in normal air-taxi operation)](image2)
The power hybridization degree of the system (defined as the ratio of electric power to total installed power) is equal to 0.45. The electric machines are fed by a li-ion battery designed to help the engine during the high-power phases of flight and to allow, at any time, electric back-up operation in case of engine failure. Figure 1 shows the scheme of the power system while the power request vs time assumed for the electric back-up operation is shown in Figure 2 and also described in [10]. Due to confidentiality agreement, the actual size of the components will not be reported here and all data will be shown in a dimensionless way.

To take into account the variability of flight conditions during the normal operation of the rotorcraft, four different profiles of power request, altitude and speed vs time were considered (see Figure 3). Mission #A is a schematic power request proposed by the industrial partner of the project, the other three missions were obtained, after appropriate scaling, from a previous work on a larger helicopter [3] were an accurate balance of the forces acting on the rotorcraft at any time during the mission was performed.

![Figure 3. Reference missions for the air-taxi operation (t_AT: time of flight for mission #A)](image)

2. Modelling the power system

As explained in the introduction, the analysis and the optimization of hybrid electric aircraft solutions requires appropriate models for the design and off-design analysis of each component of the power system.

To develop an empirical, fast but accurate model for the turboshaft engine, the author used the results of detailed simulations with the well-known GSP (Gas Turbine Simulation Program) [11] and found the following mathematical function:

\[
\frac{SFC}{SFC_0} = \left( \frac{P_{ice}}{P_{ice,nom}} \right)^{b_2} (z_1 Z + z_0)(m_2 M^2 + m_1 M + m_0) + b_1
\]

(1)
Where $P_{ice,nom}$ and $SFC_0$ are the nominal power and the specific fuel consumption at the design point, respectively. $Z$ is the altitude in meters and $M$ the Mach number. This equation contains seven parameters ($b_1, b_2, m_0, m_1, m_2, z_0, z_1$) whose values (Table 1) were obtained by minimizing the Root Mean Square with respect to the results of simulating mission #A (Figure 3).

| Parameter | $b_1$ | $b_2$ | $m_0$ | $m_1$ | $m_2$ | $z_0$ | $z_1$ |
|-----------|-------|-------|-------|-------|-------|-------|-------|
| Optimum   | 0.442 | -0.7  | 0.368 | 0     | $10^{-4.304}$ | 1.4   | $10^{-4.330}$ |

The “new model” was also compared with the approach proposed by Walsh for a two-spool turboshaft engine [12] which calculates the SFC in off-design conditions with a characteristic curve as a function of the corrected power ratio $BHP/BHP_0 \cdot \sqrt{\theta/\delta}$. $\theta = T_{inlet}/T_{SL}$ and $\delta = p_{inlet}/p_{SL}$ are pressure and temperature ratio, respectively, that compare the actual inlet values of temperature and pressure $T_{inlet}$ and $p_{inlet}$ with the corresponding values at Sea Level, $T_{SL}$ and $p_{SL}$. This model will henceforth called “old model” because it was also used by some of the authors in [3].

The results of the comparison between the two simplified models and the output of GSP are shown in Figure 4 in terms of RSME along the whole mission and relative error on the total fuel burn. The old model reported an RSME higher than 9% in all missions. The total fuel burn was quite underestimate (up to -10%) in all missions with respect to the results of GSP. On the contrary, the new model slightly overestimate the total fuel but both the RSME and the total fuel error are significantly better. Note that the new model was tuned on mission #A and then applied to the other three missions without any further modification of the parameters. The larger absolute values of both errors on mission #B are probably due to the effect of altitude (that is not perfectly captured by the new model). In fact, mission #B differs from the other mission for the higher altitudes in all phases of the flight.

### 2.1 Modelling the electric path

The electric machine is modelled with a simple Willans line as proposed by [6]. As for the battery, the simulation approach used in this investigation (see also [10]) is to evaluate the actual current of the battery according to the power request $P_{batt}$:

$$ I(P_{batt}) = \frac{OCV}{2R} - \sqrt{\frac{OCV^2}{4R^2} - \frac{P_{batt}}{R}} $$

Where the Open Circuit Voltage $OCV$ is a function of the battery state of charge, while the internal resistance $R$ depends on the specification of the battery and varies along the battery life. The model takes into account the Peukert effect (i.e. the reduction of the battery actual capacity when increasing
the discharge power). The actual capacity, the internal resistance and the Peukert coefficient are calculated along the battery life (number of discharge/charging cycle) as in explained in [10].

3. The energy management

The energy management strategy proposed in this investigation has two main goals:
- Keep the battery sufficiently charged during the whole mission so to allow electric back-up at any time in case of engine failure;
- Minimize the overall fuel burn during the mission in order to save money but also to reduce the environmental impact of the flight.

To reach the first goal, the authors studied the discharge of the battery during the OEI mission with different values of the initial state of charge and at different stages in the battery life in a previous work [10] finding that the minimum SOC to be allowed is 60% for the battery at the beginning of its life and 70% for the aged battery.

For the development and the analysis of the strategy, we will consider constant the take-off mass (i.e. saved fuel is converted in payload) and we will neglect the effect of the energy management on the weight of the rotorcraft along the missions. This hypothesis is reasonable because the fuel consumption in all missions is negligible with respect to the take-off mass of the rotorcraft.

The problem is addresses as a typical optimum control problem where the design variable is defined as:

\[
u = \frac{P_{\text{mot}}}{P_{\text{mot,nom}}}, \text{ with } 0 < u < 1 \text{ (battery in discharge)}\]

\[
u = \frac{P_{\text{batt}}}{P_{\text{batt,charging}}}, \text{ with } -1 < u < 0 \text{ (charging)}\]

where \(P_{\text{mot,nom}}\) is the nominal power of the electric machine and \(P_{\text{batt,charging}}\) is the maximum power that the battery can sustain in charging (according to its specification).

The control problem is described with Eq. (5) to Eq. (12).

\[
\min_u J = \int_0^T m_{\text{fuel}}(u) \, dt
\]

subject to

\[
\dot{x}(t) = f(x(t), u(t))
\]

for \(x(t) = (SO\text{C}(t), fu\text{el})\)

\[
SO\text{C}(0) = 100\% \]

\[
f\text{uel}(0) = 0 \text{ [kg/h]}
\]

\[
-1 < u(t) < 1
\]

\[
60\% < SO\text{C}(t) < 90\%
\]

\[
0 < f\text{uel}(t) < 200 \text{ [kg/h]}
\]

\[
P_{\text{powertrain}}(t) = P_{\text{req}}(t) \forall t
\]

The problem is solved with the well-known Dynamic Programming Method (DPM) [13],[14]. The common elements of a DP include:
- a set of steps (N steps) that in this case corresponds to the discretization of the mission;
- a set of decision stages (N-1 stages);
- a set of \(H\) possible controls (values of \(u\)) and \(K\) states at each stage;
- a set of transitions between states \(s_{k+1} = f(s_k, u_k)\): system dynamics equations;
- a cost function \((J)\).

The set of steps number, possible controls and states constitutes the so-called DPM grid that was defined before running the optimization with an appropriate sensitivity analysis.

4. Results of the DPM
The proposed DPM method with the baseline grid was applied to the four missions of Figure 3 with and without the option of charging the battery during the mission. Moreover, the results of the DPM were compared with these cases:

- “Engine only”: The engine gives the required power in any time of the mission and the battery is never used during the normal operation of the vehicle.
- “Rule based with charging”: the battery is used to help the engine when the required power $RP(t)$ is higher than $RP_{hi}$ and is charged when $RP(t) < RP_{low}$.
- “Rule based without charging”: the engine is turned off and the power request is satisfied by the electric motor (after checking that the battery is sufficiently charged).

The results of the different strategies proposed in this investigation are summarized in Table 2 in terms of fuel saving using as reference the “engine only” case. Note that the rule based strategy without charging is quite successful on mission #B where it allows a fuel saving of about 8% compared with the “engine only” mode but gives negligible improvements on missions #C and #D. In all cases, charging the battery during the flight is not useful and actually deleterious on mission #C where it causes a slight increase in the fuel burn. This is due to the fuel consumed to charge the battery that is not compensated by an improvement of the fuel consumption. In fact, the engine works at a higher load (i.e. closer to its design point) in order to charge the battery and give the required power to the aircraft.

The optimal control obtained with the DPM allows fuel saving ranging from 12% for missions #A and #C up to about 26 and 24% for mission #D for the cases with and without battery charging, respectively.

**Table 2.** Fuel saving obtained with the proposed strategies with respect to using only the engine during the whole mission (“engine only” mode) with the battery at the beginning of its life.

| mission | DPM with charging | Rule based with charging | DPM without charging | Rule based without charging |
|---------|-------------------|--------------------------|----------------------|-----------------------------|
| #A      | 13%               | 13%                      | 2.9%                 | 4.5%                        |
| #B      | 21%               | 21%                      | -1.0%                | 7.8%                        |
| #C      | 12%               | 12%                      | 0.6%                 | 0.6%                        |
| #D      | 26%               | 24%                      | 0.3%                 | 0.3%                        |

The higher performance of the DPM is due to the ability to discharge the battery in an optimal way so to reach the minimum allowed state of the charge (60%). This can be put into evidence from the data reported in Table 3 that refers again to the battery at the beginning of its life.

**Table 3.** Final state of the charge of the battery (at the beginning of its life).

| mission | Engine only | DPM with charging | DPM without charging | Rule based with charging | Rule based without charging |
|---------|-------------|-------------------|----------------------|--------------------------|-----------------------------|
| #A      | 100%        | 60.4%             | 60.7%                | 86.1%                    | 83.0%                       |
| #B      | 100%        | 60.5%             | 60.5%                | 98.9%                    | 88.4%                       |
| #C      | 100%        | 60.4%             | 60.6%                | 97.3%                    | 97.3%                       |
| #D      | 100%        | 60.4%             | 67.8%                | 98.6%                    | 98.6%                       |

At the end of its life, the battery is subject to a faster discharge (at the same power request) due to the worsening of nominal capacity, internal resistance and Peukert coefficient. Moreover, to ensure the electric backup is necessary to set a minimum state of charge of 70% as already discussed. This determines a reduced fuel saving with all strategies on all missions as shown in Figure 5 that reports (in a dimensionless way) the kg per km of fuel burn for the four missions obtained with the “engine only” mode and the strategy found with the DPM method with the new and the aged battery, respectively.
4.1 Lessons learnt from the DPM

The DPM is an off-line optimal control method that allowed us to find out the best usage of the battery in each mission in order to minimize fuel consumption while keeping the battery at the desired state of charge. However, this result cannot be achieved in the practice unless the power request profile is fully known before starting the mission. On the other hand, the results of DPM can be used to derive suggestion on how to implement online energy management strategy. First of all, let’s compare the usage of the engine on mission #A according to the “rule based” and the DPM, both without charging (see Figure 6). Note that the energy management strategy found with the DPM can be easily translate as a system of simple rules even if these rules are different from those considered in this study.

The second lesson learnt from the results of the DPM is that it is possible to obtain the same fuel saving either charging or not the battery. Since charging the battery on board requires a higher complexity of the control systems, we can easily conclude that it is better not to implement this option in the powertrain.

Conclusions

In this investigation a simple but accurate model for a turboshaft engine was developed and validated through comparison with detailed analysis performed with a commercial software. The model is able to predict the Specific Fuel Consumption of the engine when operating at loads, altitudes and speeds different from its design point with an error lower than 3% on the total fuel burn in a typical mission. The model was incorporated in a simulation tool for whole hybrid electric powertrain that include an electric equivalent model for the battery that takes into account also battery aging.
The simulation tool allowed the execution of off-line optimizations with the Dynamic Programming Method over four different flight missions. The fuel saving found with DPM with the new battery ranged from 12% to 24% according to the specification of the mission (while allowing electric back-up at any time). The results of the investigation showed that recharging the battery during the flight can be avoided without compromising fuel economy and that the results of DPM can be used to develop online line energy management strategies as further development of this work. Moreover, the authors will address in future works the synergies between static design optimization and on-line dynamic optimization, the transient behaviour of the powertrain and the effect of degradation of other components like the engine.

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