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Control Oriented Modelling of a Turboshaft Engine for Hybrid Electric Urban Air-Mobility

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Abstract. The electrification of aircraft is a well-established trend in recent years in order to achieve economic and environmental sustainability. In this framework, an application particularly interesting for hybrid electric power system is represented by urban air-mobility. For this application, the authors presented a parallel hybrid electric power system including a turboshaft engine and two electric motors and proposed a quasi-stationary simulation tool. As a further step, this paper deals with the dynamic modelling of the same turboshaft engine within the framework of a hybrid electric system where the pilot command is interpreted as a power request to be satisfied by the engine and the electric machine according to the selected energy management strategy. In this work, the dynamic behaviour of the turboshaft engine is analysed with and without the help of the electric motors to satisfy the power demand.

1. Introduction

The ever-increasing number of studies concerning electrification of aircraft attests the growing interest in this topic in the aerospace field. See for example [1] for a review of concept, models, and design approaches presented in the literature.

The advantages of hybrid electric power systems for helicopters include separation of the propulsion of main and tail rotor, higher reliability, increased operational lifetime thanks to reduction in the number of devices (e.g., gear, transmission, etc.), improved maintenance workability and lower operational costs together with lower emissions, consumption, noise and vibration levels [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. In [3] the feasibility and the fuel saving potentiality of different hybridization schemes for a light helicopter are addressed. In particular, the power and energy required for different missions and emergency landings are estimated in order to size and compare the proposed hybridization schemes. This analysis shows that, with existing technologies for batteries and motors, the electrification of the tail rotor is the only scheme that can be achieved without a significant increase in the mass of the rotorcraft.

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However, there is a particular application where the limited energy density of today batteries could be sufficient for the flight i.e. aerial vehicle concepts for short-haul passenger transportation, the so-called the "urban air-mobility" (UAM). UAM is considered as a suitable way to reduce traffic congestion and pollution as well as increase mobility in metropolitan areas. This application is characterized by short trips, limited speed (compared with longer distance commuters) and altitudes up to 1000ft [4].

A quasi-static simulation tool for the hybrid electric power system of a rotorcraft for urban air-mobility is described in [5]. In this investigation, we will describe the development of a dynamic model of the turboshaft in the framework of the same hybrid electric power system.

Control oriented models of turboshaft engines are not new in literature [1,7]. However, they are referred to conventional architectures (where the engine is the only energy converter mechanically connected to the shaft of the propeller) while the proposed model is specifically developed for hybrid-electric power systems.

The final goal of this study is to develop a dynamic simulation tool for real-time simulation of the whole hybrid electric system and the development of advanced energy management strategies.

2. The turboshaft engine

The engine considered in this investigation is a two-spool turboshaft engine with the High Pressure Turbine (HPT) connected to the compressor and rotating at speed N_c. The Low Pressure Turbine (LPT) is connected to the rotor shaft and rotates at the nominal speed of 6000rpm (N_p). The efficiency maps of the compressor and the two turbines were obtained with the procedure explained in [8] starting from the desired design power P_{icenom}. Note that the details of the components of the engine cannot be reported here because of a confidentiality agreement.

2.1 Implementing the model

The three most important dynamics of a turboshaft engine to be included in the model are:

- The balance of work between the components on the same shaft;
- The mass balance between adjacent components;
- The fuel flow rate provided by the fuel control and delivery system.

The scheme of the numerical model developed in the Simulink environment is shown in Fig. 1. It consists of a block for each of the main component of the engine. The inlet (1-2) is modeled as a ram-air element with a constant efficiency (0.9). However, due to the low airspeeds of the air-taxi helicopter, this effect is quite negligible.

The compressor (2-3) and the two turbines (4-5 and 5-6) are represented as gas-path components where the values of the output streams (total pressure, temperature, density and mass flow) are calculated from their current state and values of the input streams according to their performance maps.

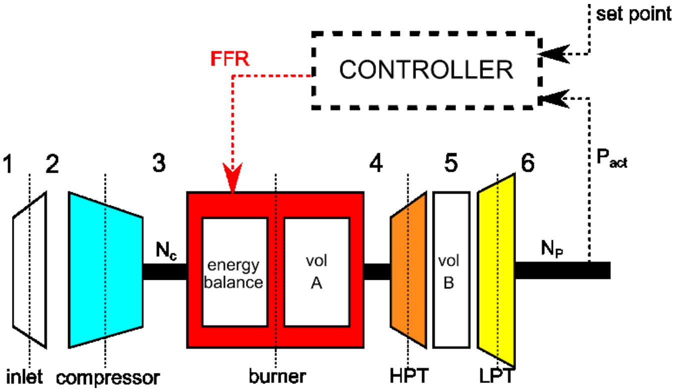


Fig. 1. Main blocks of the turboshaft dynamic model

In particular, the compressor map is used to obtain the corrected mass flow rate and isentropic efficiency as a function of the corrected rotational speed and the pressure ratio.
The burner (3-4) dynamics is represented by its temperature that is calculated with an energy balance using as input the fuel flow rate (FFR). The pressure drop across the combustion chamber is assumed equal to 2% of the input stream pressure.
The simulation of the mass balance is performed with the inter-component volume (ICV) method as applied in [10]. The dynamics of the fluid pressure in the ICV volumes A and B of Fig. 2 can be written as:

$$\frac{dP}{dt}=\frac{RT}{V}\frac{dm}{dt}=\frac{RT}{V}(\dot{m}_{in}-\dot{m}_{out}) \tag{1}$$

Where the variation of mass is due to the difference between the mass flows going into ($\dot{m}_{in}$) and out ($\dot{m}_{out}$)of the volume during transients while it is zero in stationary conditions. In equation (1), P and T are the pressure and temperature in the ICV at each time step, V is the volume and R the specific constant of the gas (universal gas constant divided by the molecular mass of the gas).
The balances of the work between the components on the same shaft can be written, for the conventional power system, as:

$$\dot{N_c}=\left(\frac{30}{\pi}\right)^2\cdot\frac{1}{IN_2}\cdot\frac{P_{HPT}-P_C}{N_c} \tag{2}$$

$$\dot{N_p}=\left(\frac{30}{\pi}\right)^2\cdot\frac{1}{IN_1}\cdot\frac{P_{LPT}-P_{load}}{N_p} \tag{3}$$

Where IN_1 and IN_2 are the inertial of the two systems, P_{HPT}, P_{LPT} and P_C are the instantaneous power of the two turbines and the compressor while P_{load} is the power of the load, i.e. the rotor in this specific application.
However, the dynamic of the power shaft has not yet been implemented (for the reasons explained later in the paper) and N_p is assumed constant.

2.1.1 The controller

In the present investigation, a PI controller is used to match the required power at each time step thus simulating the whole engine control system including the control of the shaft speed of the LPT. The output of the PI controller is the fuel flow rate (FFR) to the burner block. The PI is represented by the following equation:

$$C_{par}(t) = P + I\left(\frac{1}{t}\right) \tag{4}$$

Where C_{par} is the control variable (FFR), P is the proportional gain and I the integral gain. The input to the controller is the difference between required and actual shaft power of the LPT.

2.1.2 The static model of the turboshaft

A static version of the model was used to initialize the dynamic version and to develop the pilot interpreter for the hybrid electric case, i.e. to obtain the required power as a function of the throttle position, Mach number and altitude. To this scope, a design of experiment was used as shown in Table 1. For each combination of the input parameters, the static model calculated the nominal power of the engine in kW.

Table 1. Design of experiments for the model validation

Parameter	**Min**	**Max**	**Step**
Altitude (m)	0	400	100
Mach number (-)	0	0.4	0.1
Throttle position PLA (%)	20	100	20

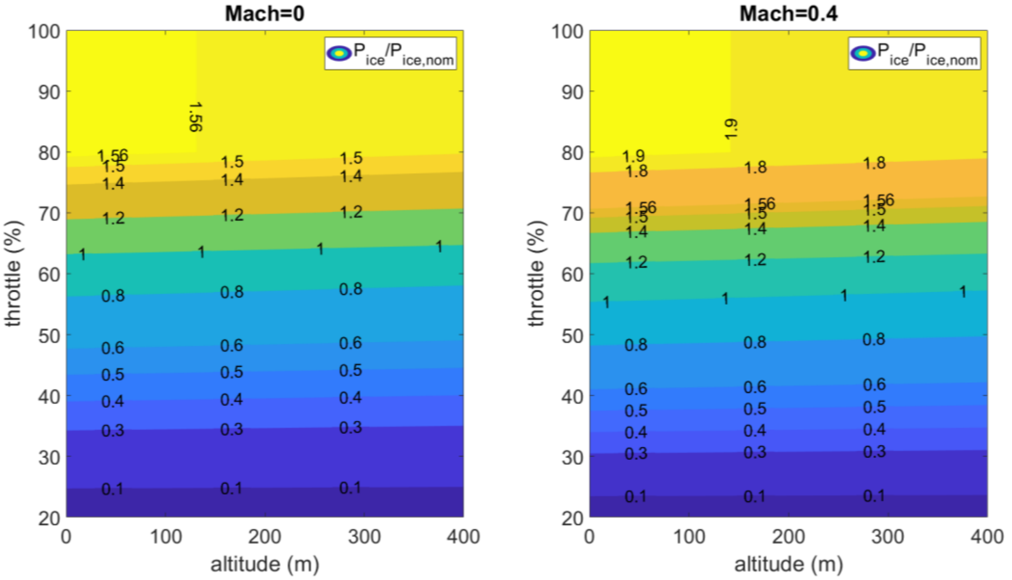


Fig. 2. Engine power as a function of throttle position, altitude and Mach number

Note that, with the same level of the throttle signal, the command power is slightly affected by the altitude due to the reduction of the atmospheric density. When increasing the Mach number, the engine produces more power due to the ram effect. However, as already explained, the proposed helicopter for air taxi operation is not expected to fly at high Mach numbers.

2.2 Discussion of the model

Unfortunately, it was not possible to perform an accurate validation of the model for the lack of experimental data and for the already mentioned confidentiality issues. However, the results of the model were compared qualitatively with those of a commercial well-known simulation tool, i.e. GSP (a Gas turbine Simulation Program). GSP is a tool developed at the Aerospace Department of Delft Technical University, capable of simulating almost all types of gas turbines (turboshaft, turboprop, turbofan, single and multi-shafts, etc.). For the exact implementation of the numerical techniques in GSP please consult [11-13].

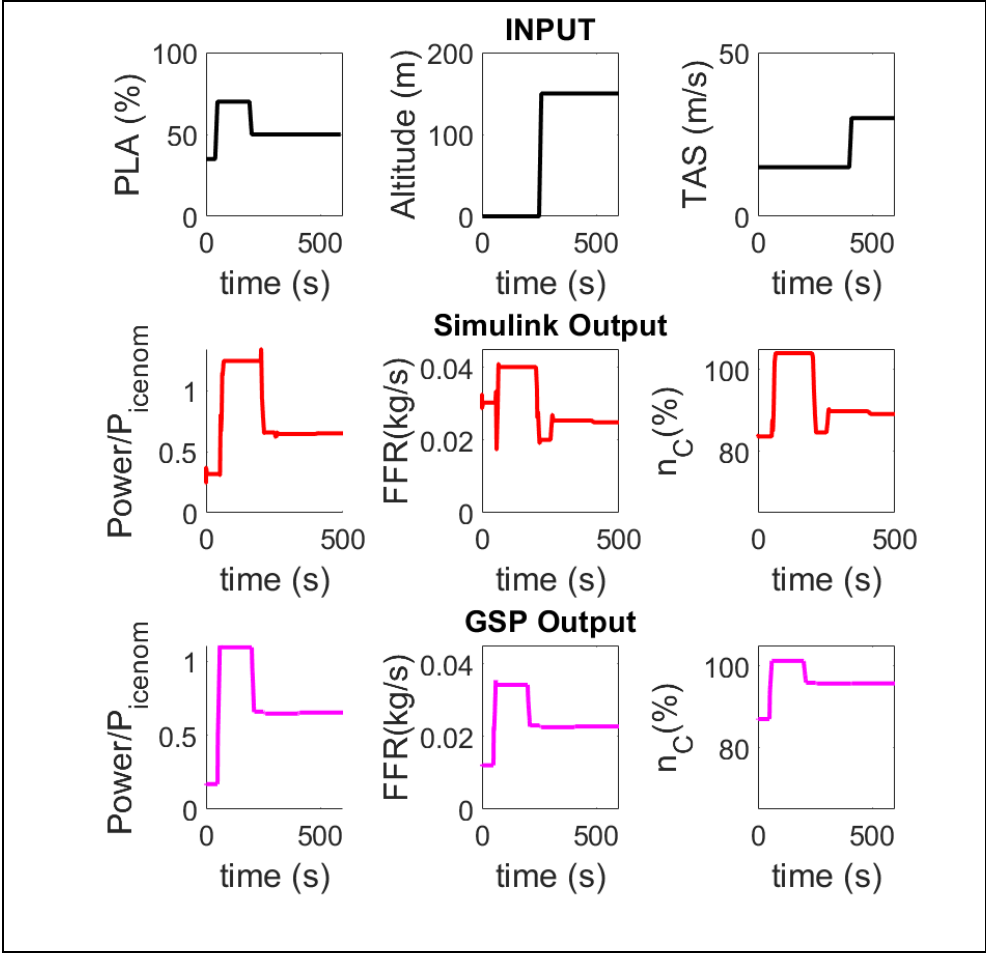


Fig. 3. Qualitative comparison between the results of the proposed method (second row) and those of the GSP simulation program (last row) to the same input signals (first row)

Note that the maps of the components used in the two models and the values of the inter-component volumes are not the same, therefore the comparison is only meant to be qualitative. Nevertheless, we can underline some issues by analysing the results of the comparison shown in Fig. 3 where the input signals are reported as black lines in the first row. These signals do not represent a real flight condition but were chosen to put into evidence the response of the models to a step variation of each of the input, i.e. PLA (Power

Level Angle), altitude and TAS (True Air Speed). The output variables chosen for the comparison are the actual engine power (scaled with respect to the nominal power of the engine $P_{ice,nom}$, the fuel flow rate (FFR) and the compressor rotation speed (also scaled with respect to the design value). The results of the proposed model are reported in the second row with red lines while the output values obtained with GSP are shown in the last row.

The qualitative comparison shows how the proposed PI predicts unrealistic oscillations of the main engine outputs with respect to the same signals obtained with GPS with the same input commands. This is due to numerical issues that still need to be fixed. To better underline the problem, the following figure shows how the setting of the PI influences the dynamic response in terms of power and FFR in correspondence of the first step in the PLA signal.

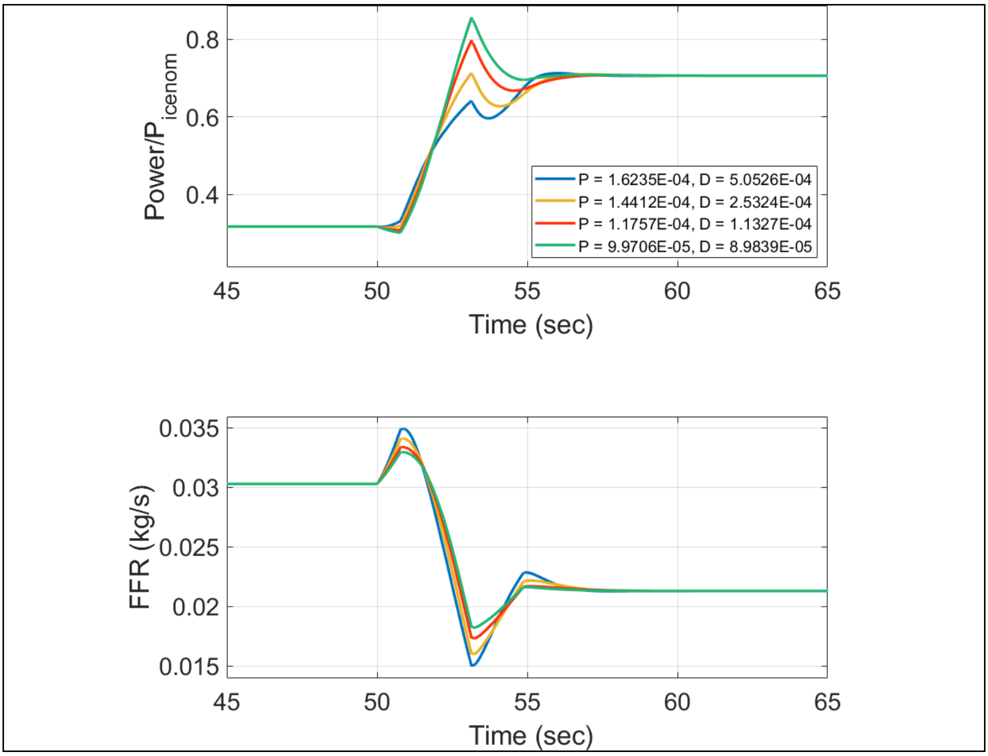
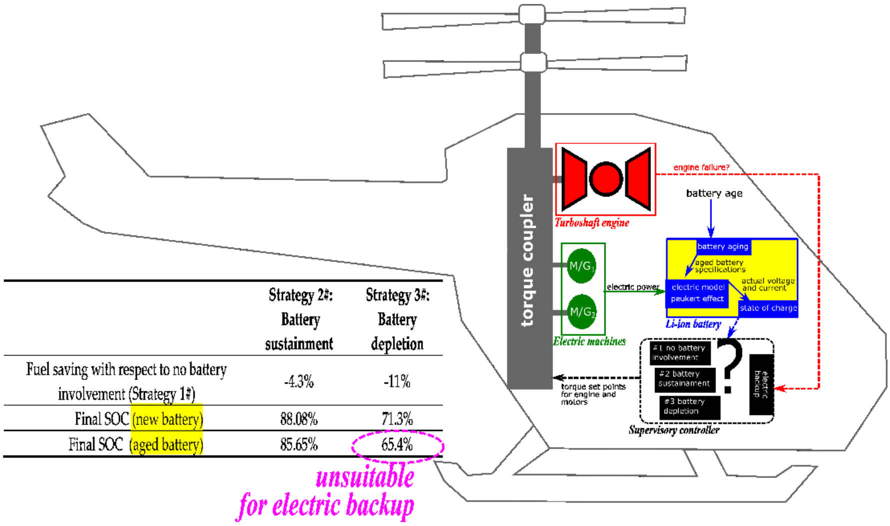


Fig. 4. Effect of PI settings of the dynamic response in in terms of power and FFR in correspondence of the first step in the PLA signal of **Fig. 3**.

3. The hybrid electric architecture

The proposed model is meant to be included in the overall dynamic simulation tool of the hybrid electric power system shown in **Fig. 5**. It is a parallel configuration in which the turboshaft engine is mechanically coupled with two electric machines, each able to produce a nominal power $P_{EM,nom}$.



	Strategy 2#: Battery sustainment	Strategy 3#: Battery depletion
Fuel saving with respect to no battery involvement (Strategy 1#)	-4.3%	-11%
Final SOC (new battery)	88.08%	71.3%
Final SOC (aged battery)	85.65%	65.4%

Fig. 5. Overview of the power systems and of the previous work [5].

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. For more details, see [5]. Note that the dynamic of the electric drive will not be treated in this investigation that deals with the transient behavior of the turboshaft only.

3.1 Control-oriented model of the hybrid system

The dynamic model of the overall system has been developed in analogy with a typical supervisory control systems used in a hybrid electric vehicle as explained by Guzzella and Sciarretta [14]. It consists of a first block named "pilot interpreter" which translates the pilot command (i.e. the PLA) into a specific power request according to the actual values of Mach and altitude. In a conventional power system, this command is the torque to be delivered by the engine and can be used to set the reference values for the compressor speed and the air-fuel ratio. In the case of a hybrid electric power system, the same value of torque can be obtained in an infinite number of ways.

The degree of freedom of a parallel hybrid electric power system is usually expressed with the torque split ratio:

$$u = \frac{T_{EM}}{T_{EM} + T_{ICE}} \tag{5}$$

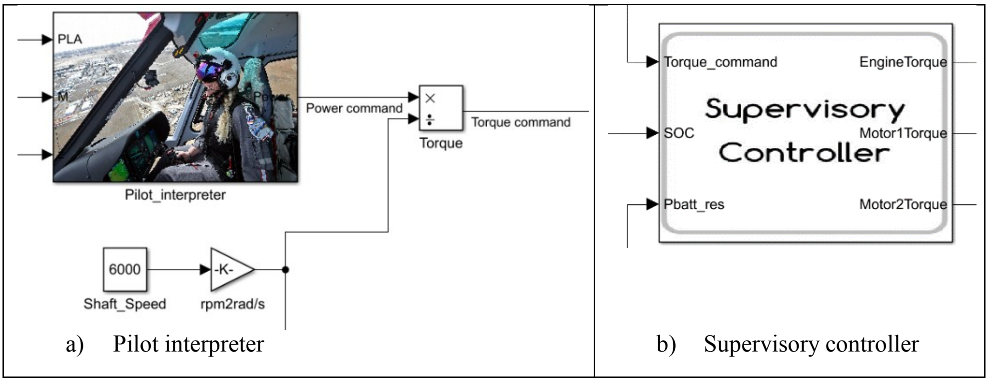
According to the value of u, a parallel hybrid electric power system can work in different modes: electric ($u = 1$), ICE ($u = 0$), power assist ($0 < u < 1$) and battery recharge ($u < 0$).

In our application, T_{EM} is the total torque of the electric machines that is equally distributed between the two electric motors. The charging of the battery is not considered in the proposed power system.

The desired engine torque is selected during the mission according to the energy management strategy that selects the set points for the engine and the motors.

3.1.1 *Selection of the engine set point*

The selection of the engine set point is the results of the two blocks shown in Fig. 6. The pilot interpreter block is implemented as a multi-dimensional look-up table that takes as input the position of the PLA , the actual flight conditions (Mach and altitude) and calculates the torque demand. The pilot command is interpreted as it were a conventional turboshaft engine (no hybrid) using the maps of Fig. 2.



a) Pilot interpreter

b) Supervisory controller

Fig. 6. Selection of the engine set point

The supervisory controller defines the set points for the engine and motors torque according to the pilot request and the battery status (residual energy and available power). Some examples of rule-based strategies for the same powertrain are presented in [5]. In the present investigation, the engine is used as the only power converters in the following cases:

- When the battery state of charge is below 70% (to allow electric back-up operation as explained in [5]);
- When the torque request is below a pre-fixed threshold value.

When the battery is sufficiently charged and the torque request is higher than the threshold value, the engine works at the threshold value and the remaining torque is provided by the two electric machines.

3.1.2 *The shaft dynamics*

Taking into account the presence of the two electric machines, the balances power shaft becomes:

$$\dot{N}_p = \left(\frac{30}{\pi}\right)^2 \cdot \frac{1}{IN_1} \cdot \frac{P_{LPT} - P_{EM1} - P_{EM2} - P_{load}}{N_p} \qquad (6)$$

However, this dynamics has not yet been implemented because it depends also on the electric machines and on the load variation. Therefore, N_p will be assumed constant also in the hybrid electric case.

3.2 Results

The plots of Fig. 7 show how the power demand obtained by the interpreter is translated in specific set points for the engine and the motors that changes in time according to the energy management strategy (continuous lines). For each component, the actual scaled power, as resulting from the dynamic processes taken into account in the paper, is also presented (dotted lines). Even if the dynamic of the motors is not addressed here, it is reported in Fig. 7 to explain the behaviour of the total actual power (dotted black line).

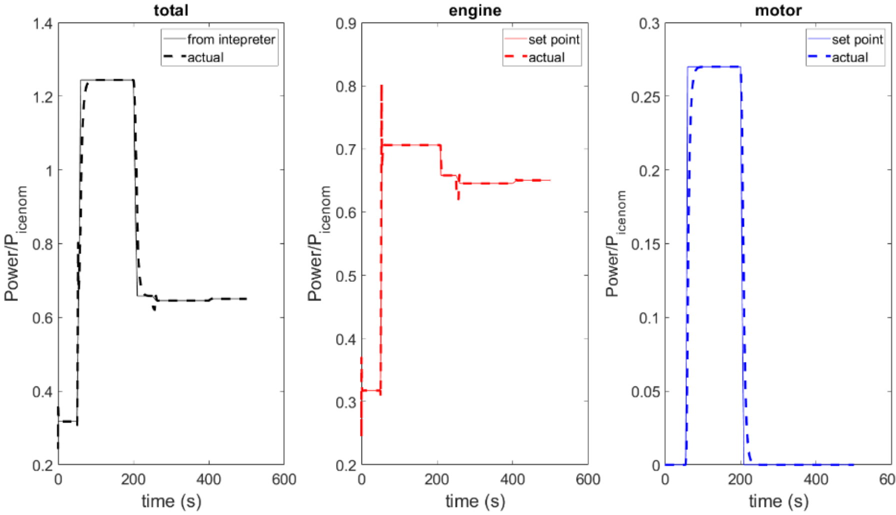


Fig. 7. Actual power of the hybrid system compared with the power request obtained from the interpreter and distributed between engine and motor from the energy management strategy.

The fuel flow rate, the compressor speed and the battery state of charge are shown in Fig. 8. Comparing these plots with the results of Fig. 3, we can notice a quite lower fuel flow rate in the region where the motors help the engine and a less varying compressor speed

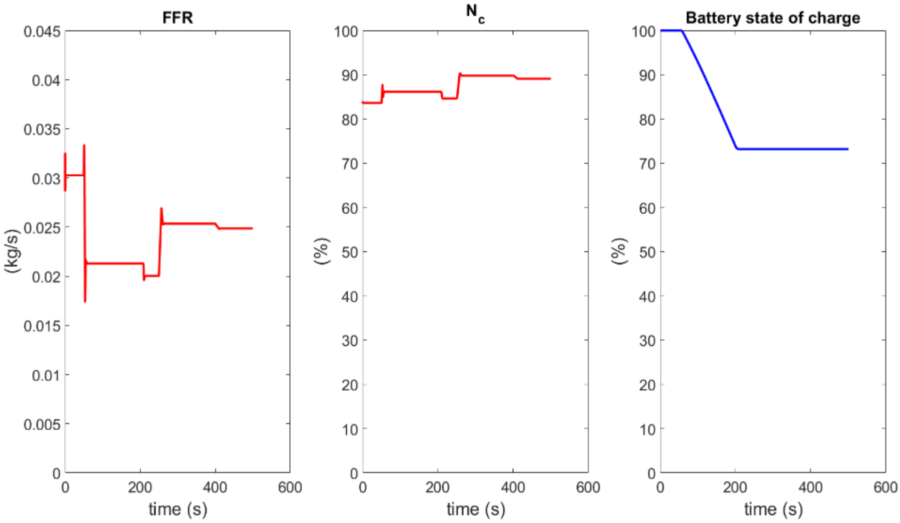
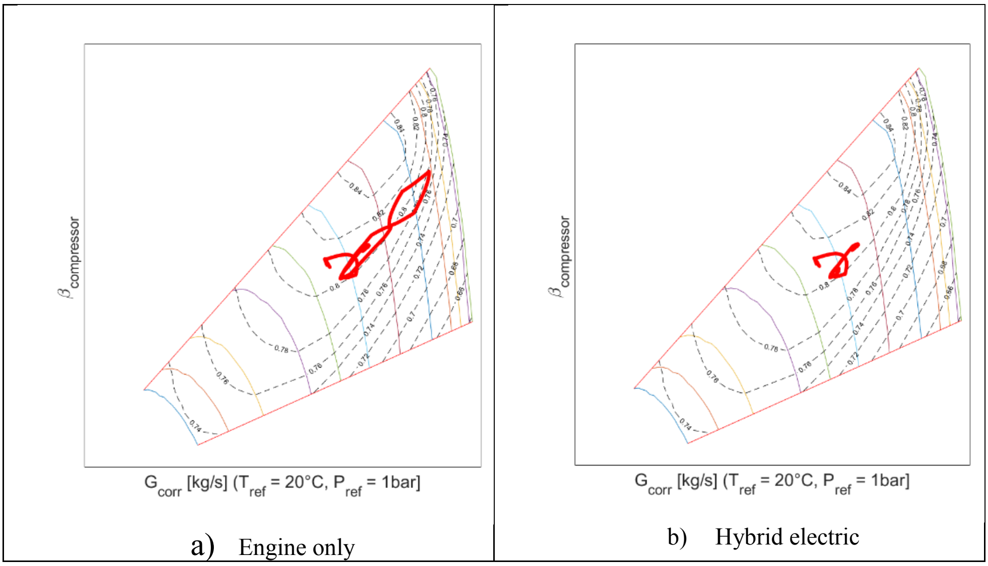


Fig. 8. Fuel flow rate, compressor speed and battery state of charge

The integral of the fuel flow rate was used to obtain the overall fuel consumed in the mission. In this way, it was possible to put into evidence that the hybridization allowed a fuel saving of 18% with respect to using only the engine, with the same power request. In fact, the sizing of the components, with their additional mass and encumbrance, is not considered in this investigation. Moreover, the fuel saving was obtained at the expenses of an electric consumption because the battery is partially discharged as shown in Fig. 8.



a) Engine only

b) Hybrid electric

Fig. 9. Compressor working points

It is interesting to notice that one of the advantages of the hybridization is that the compressor working point remains in the central part of its performance map (see Fig. 9). This means that, with an appropriate management strategy, it would be possible not only to avoid working near the surge line but also to guarantee a high compressor efficiency in all the flight phases.

Conclusions

The present investigation describes the implementation of a dynamic model for a two-spool turboshaft that takes into account the balance of work between the components on the same shafts, the mass balance between adjacent components and the fuel flow rate provided by the fuel control and delivery system. More specifically, the model takes as input the power request along the flight (depending on throttle, altitude and speed) and describes the dynamic behaviour of the engine. Among the several possible outputs of the model, the authors selected the actual engine power, the fuel flow rate, the compressor speed and the compressor working point. A qualitative comparison with the results of a commercial software (GSP) showed the reasonability of the results even if some improvements to the model are still needed. The engine was then included in the framework of a parallel hybrid electric configuration where its power request is the results of a pilot interpretation and a supervisory controller that implements a simple rule based energy management strategy.
The engine dynamic behaviour in the hybrid electric propulsion system was analysed and the advantages of hybridization put into evidence.

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