International Journal of Aviation Science and Technology, Volume 3, Issue 1, (2022), 4-12

International Journal of Aviation Science and Technology

Research Article

Effect of Coordination on Transient Response of a Hybrid Electric Propulsion System

Teresa Donateo[1], Ludovica Spada Chiodo[2]*, Antonio Ficarella[3]

[1] *University of Salento, Department of Engineering for Innovation, Lecce, Italy*
teresa.donateo@unisalento.it - 0000-0001-5189-679X

[2] *University of Salento, Department of Engineering for Innovation, Lecce, Italy*
ludovica.spadachiodo@unisalento.it - 0000-0002-0320-6958

[3] *University of Salento, Department of Engineering for Innovation, Lecce, Italy*
antonio.ficarella@unisalento.it - 0000-0003-3206-4212

Abstract

Thanks to its typical limited speeds and altitudes, Urban Air Mobility represents an interesting application for electric and hybrid-electric power systems. In addition, short-range requirements are compatible with the limited performance of today's batteries, conversely to their current inapplicability for commercial aviation purposes. For the present study, a parallel Hybrid Electric Propulsion System for a coaxial-rotor Air Taxi has been implemented in Simulink and tested on four different sets of operating conditions, with a transient signal as input for the Power Lever Angle command. The goal of this investigation is to analyze the transient behavior of the hybrid-electric propulsion system in question, to underline the role of electric motors in assisting thermal engine during transients, and, in particular, focuses on the benefits deriving from the adoption of a coordination block which adapts torque split between the two power sources on the basis of actual engine response.

Keywords

Urban Air Mobility
Hybrid electric vehicles
Transient response

Time Scale of Article

Received 11 January 2022
Revised until 4 March 2022
Accepted 30 April 2022
Online date 28 June 2022

1. Introduction

During the last decade, many aerospace companies have developed solutions for Urban Air-Mobility (UAM). UAM refers to safe, efficient, and clean urban transportation systems by air, which, according to the EASA (European Aviation Safety Agency), is expected to spread in Europe within 3-5 years (EASA, 2022) and to overcome the ever-increasing ground traffic congestion (Airbus, 2022; FEV, 2022).

Generally designed in the form of VTOL, UAM vehicles can be propelled by several propulsive systems, ranging from hybrid to electric: in fact, their typical short-range requirements, limited speed (in comparison with longer distance commuters) and altitudes up to 1000ft (Uber Elevate, 2016), make UAM compatible with such propulsive systems even though to date batteries state of the art isn't satisfactory in terms of power and energy density to be employed in larger applications (Airbus, Micro-hybridisation: the next frontier to electrify flight?, 2021).

In HEPS for Urban Air Mobility vehicles, the presence of a dual-energy storage system results in an increment in endurance and range. It offers an additional advantage, the availability of electric backup in engine failure, allowing for a few minutes of extra endurance after failure occurrence.

Moreover, the electric power source represents a useful assist for the thermal engine during high power request flight phases: in parallel architecture, the engine could be operated at its nominal power, and additional power could be supplied from electric motors during take-off

---

*: Corresponding Author Ludovica Spada Chiodo , ludovica.spadachiodo@unisalento.it

DOI: 10.23890/IJAST.vm03is01.0101

or climb, while excess engine power could be spent in charging the batteries during the cruise (Rendón, Sánchez R., Gallo M., & Anzai, 2021).

However, hybrid UAM vehicles introduce necessarily disadvantages in terms of increased weight and higher complexity of the power and control systems.

The hybrid propulsive system employed in the present study will be described in the following, and the energy management strategy will be briefly summarized.

The goal of this investigation is to underline the role of the electric machines in improving the dynamic response of the system during transient operating conditions, namely when a power request variation is encountered. Besides a conventional parallel HEPS, a modified version is tested, where a coordination block is provided to boost system response during engine delays.

To the authors' knowledge, no similar study is presented in literature either numerically or experimentally, except for (Roumeliotis, et al., 2019), where a much more simplified approach is considered for the transient behavior of the system, and (Wortmann, Schmitz, & Hornung, 2014) where investigation of the transient behavior of a turbofan engine with different percentages of electric assist with a different control logic is carried out.

1.1. The Air-Taxi

In this investigation, a rotorcraft for UAM, namely a coaxial-rotor Air Taxi, with a parallel HEPS is considered (Guzzella & Sciarretta, 2007): the thermal engine and the Li-ion battery-fed electric motors are mechanically connected to the rotor shaft through a gear-box (Fig 1).

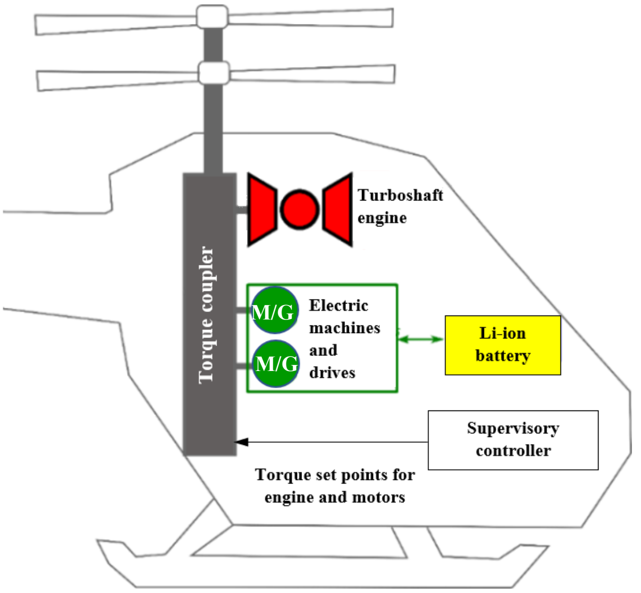

Fig. 1. Parallel HEPS for coaxial-rotor Air Taxi

Since the power management of the multi-source operation is a critical feature in HEPS, this aspect has been previously investigated by some of the authors (Donateo, Terragno, & Ficarella, 2021). In particular, the optimal curve for the discharge of the battery along the mission, denoted here as Reference State of Charge (RSOC), was found with the application of the Dynamic Programming Method.

The energy management strategy used for this investigation is based upon the application of a fuzzy logic system where the input variables are the required power at the rotor shaft and the deviation of the actual battery state of charge from the RSOC, while the output is the splitting of required power between the thermal engine and the electric machines. The constraint of keeping the battery in sufficient charge during the whole mission (to make electric backup available at any time in case of engine failure, even in the case of an aged battery) is implemented in the strategy, as explained later.

2. Methods

The behavior of the proposed power system, whose detailed description will be given in the following subsections, has been tested when a transient PLA command is given in input to the model, representing an arbitrary discontinuity in power request.

In particular, four different sets of operating conditions have been simulated, each characterized by a steady-state value of reference PLA, altitude, airspeed, and hybridization degree *k*. Such values are reported in Table 1. The choice of these operating conditions was made by considering two different missions, as shown in Fig. 2 (Donateo, De Pascalis, Strafella, & Ficarella, 2021). The value of k and the state of charge of the battery in the four operating points were set according to the results of a previous investigation (Donateo, Terragno, & Ficarella, 2021).

Then, a transient signal of the form depicted in Fig. 3 was applied to modify the reference PLA command to model an increase from 80% to full value in a time interval of 0.1 s. Such discontinuity was chosen arbitrarily to investigate the system response to a quasi-step input, which would represent the most demanding situation for the engine.

In addition, a sample case has been simulated to compare the performance of the hybrid system with a 0.5 hybridization degree to that of the same thermal engine

as standalone power source (*k* = 0).

The implemented Simulink model can be summarized by the flow chart in Fig. 4.

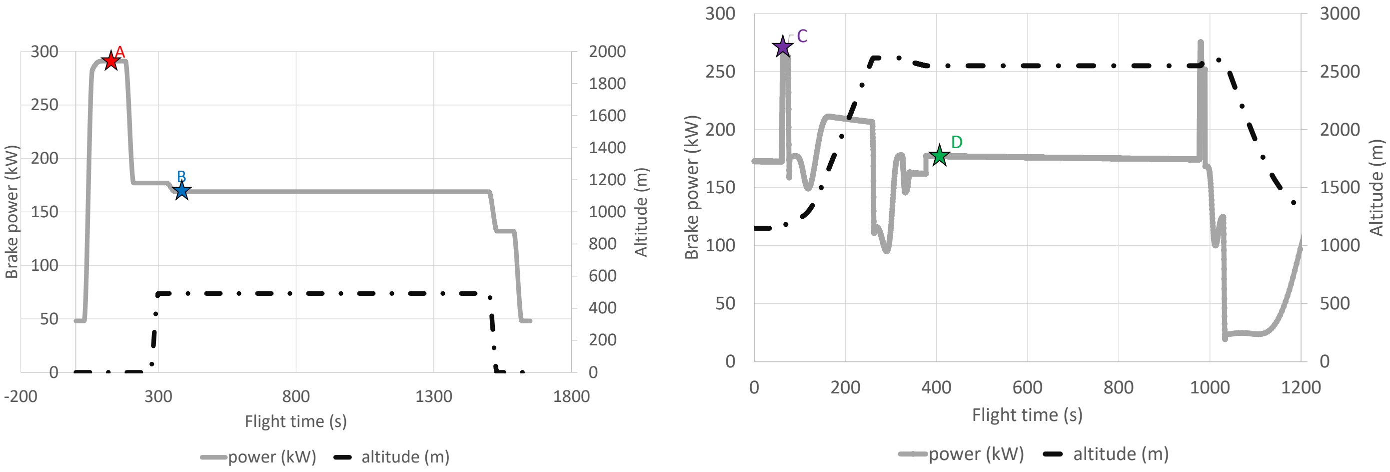

Fig. 2. Choice of the operating points.

Table 1 Operating conditions for the simulations

	Op. point A	Op. point B	Op. point C	Op. point D
PLAref (%)	65.3	50.3	68	61.5
Altitude (m)	0	492	1154	2550
True Air Speed (m/s)	30.6	30.6	4	0
Electric contribution *k*	0.4	0.7	0.47	0.6
Battery state of charge	99%	85%	99%	78%

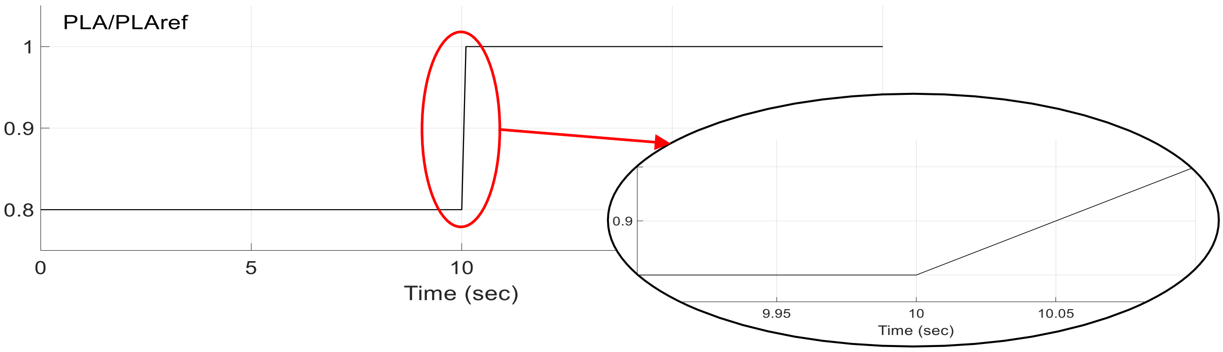

Fig. 3. Input PLA transient signal modifier.

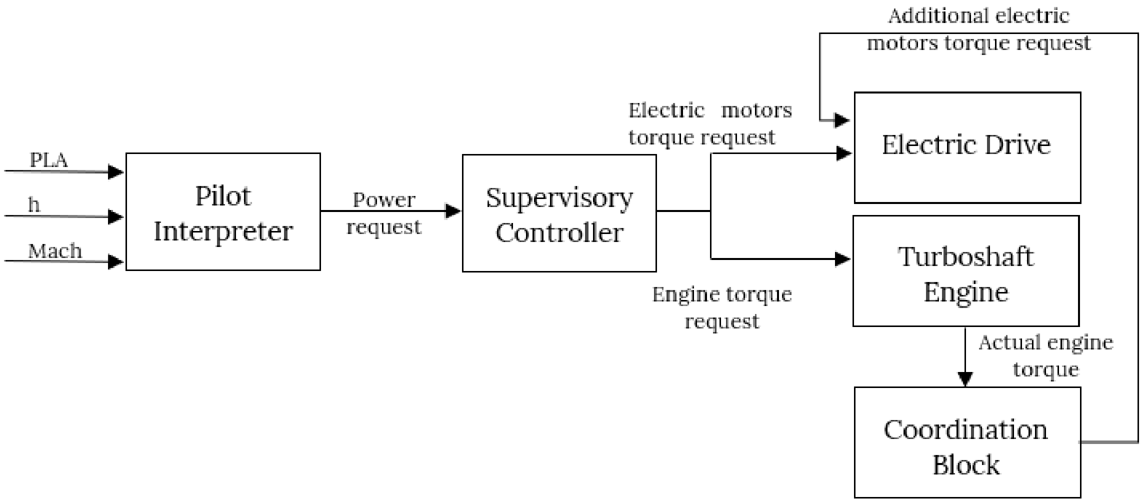

Fig. 4. HEPS model flow chart.

2.1. The Turboshaft Engine

The engine is a twin-spool turboshaft engine where the high-pressure spool connects the High-Pressure Turbine (HPT) to the compressor and rotates at the speed N_c. The Low-Pressure Turbine (LPT) is connected to the load shaft via the low-pressure spool, whose speed is assumed to equal the nominal value (N_p).

The inlet is modeled to convert the dynamic pressure of the incoming flow into static pressure with a constant efficiency of 0.9. Compressibility effects are not considered because of the typical low speeds.

Operating points are obtained from component maps available to the authors and provided in the form of lookup tables inside rotating components blocks.

A PID controller is provided to regulate fuel flow rate based on actual net LP shaft power output (since a small amount of power extraction from LP spool is considered for auxiliaries, too) and shaft power request. The controller acts to drive the power error to zero, and the automatic tuning encompassed in Matlab has been used to set its parameters, but its setting goes beyond the scope of this work. The authors intend to perform a more accurate setting of the PID controller parameters as further development of the present investigation.

The volume dynamics is taken into account by applying the inter-component volume (ICV) method as proposed in (Wang, Li, & Yang, 2017): the transient effects on fluid pressure p in the ICV volumes A and B preceding and following the HPT module (Fig. 5) are described by the following equation:

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

where the variation of mass is due to the unbalance between the volume incoming ($\dot{m}_{in}$) and outgoing ($\dot{m}_{out}$) the flow rates in transient conditions while it is zero in stationary conditions.

As for shaft dynamics, the balance of the work between the components on the same shaft is implemented to calculate the mechanical dynamic response, accordingly to Eq. (2):

$$\dot{N}_c = \left[\frac{30}{\pi}\right]^2 \frac{1}{IN_c}[P_{HPT}-P_C] \tag{2}$$

which calculates angular acceleration as a function of net power on the HP shaft, current rotational speed, and spool inertia I.

At this stage of our investigation, only HP spool dynamics has been modeled since the rotor shaft speed N_p is assumed constant at 6000rpm. However, if an LP shaft balance has to be carried out, the shaft acceleration $\dot{N}_p$ will depend on the difference between power supplied from both electric motors and engine and the load applied to the shaft.

The entire thermal engine model and its performance as a standalone power source have been previously validated through comparison with an analogous model built in the commercial tool Gas Turbine Simulation Program (GSP). This allowed to obtain a reference mapping of engine power output as a function of PLA, Mach, and altitude (thus translating a PLA input into a power request) as well as to map the power turbine discharge pressure as a function of fuel flow rate.

GSP model has also provided reference values that have been used to set inter-component volumes and shaft inertias in the Simulink model.

2.2. The Electric Drive

The employed Li-ion battery is made of 73 cells in series and has a nominal capacity of 130 Ah. A Peukert coefficient n of 1.05 is assumed, in agreement with Dubarry's results (2009), to calculate battery effective current and thus update SOC according to Eq. 3 and Eq. 4.

The Open Circuit Voltage is tabulated as a function of the battery state of charge.

$$I_{eff} = I\cdot\left[\frac{I}{I_{nom}}\right]^{n-1} \tag{3}$$

$$SOC(t) = SOC(t_0) - 100\cdot\int_{t_0}^{t}\frac{I_{eff}(t)}{C}dt \tag{4}$$

The electric motors are modeled using Simulink *mapped motor* block through the maps of maximum continuous torque and efficiency lines. The inputs to the maps are the torque command, the required shaft speed, and the battery voltage. The block outputs are the actual torque output and battery current.

The maximum power output of the employed motors is 120 kW, and their dynamic behavior is modeled by assigning an intrinsic time constant of 0.02 s, which is given as the default value in Simulink mapped motor, to account for both the motor and drive response.

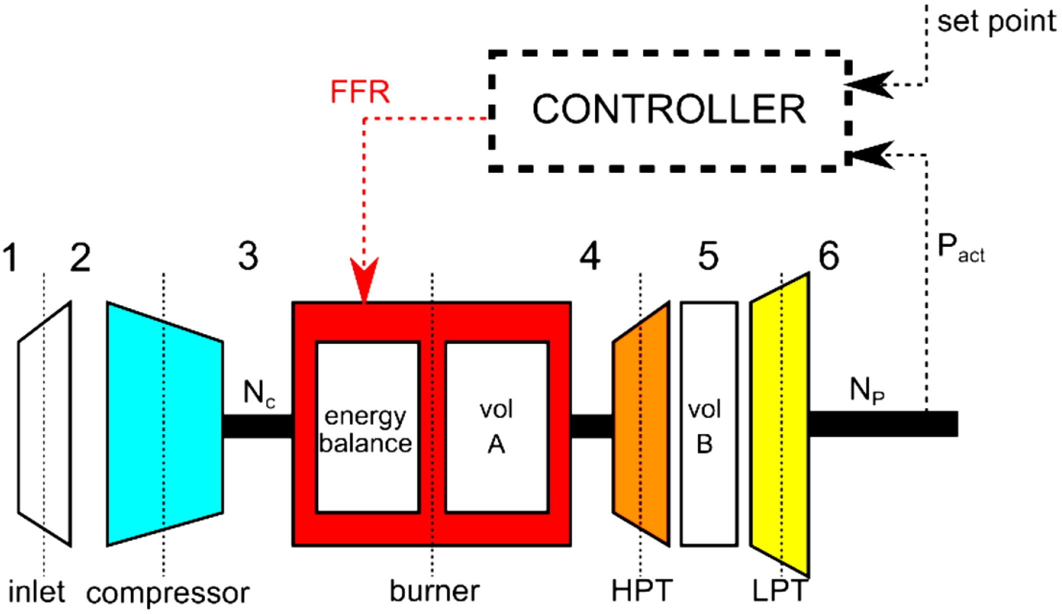

Fig. 5. Scheme of turboshaft engine with inter-component volumes.

2.3. Energy Management Strategy

The current model encompasses the capability to define an energy management strategy that is established at every time instant of the mission on the basis of current shaft power requests and battery parameters (SOC and SOH). In particular, a set of fuzzy rules is built into the supervisory controller to define the torque split between electric and thermal sources on the basis of instantaneous power demand, battery SOH and the deviation of actual SOC from the previously defined reference SOC (RSOC). Though for the present investigation, a user-defined hybridization degree is given at the beginning of its mission, and its value is held constant throughout the simulation. The selected values are those listed in Table 1.

In fact, other works from the same authors are aimed at developing and optimizing energy management strategies (Donateo, De Pascalis, Strafella, & Ficarella, 2021; Donateo, Terragno, & Ficarella, 2021) to meet the goals of fuel consumption minimization and electric backup preservation, here the focus is set on the dynamic performance improvement that can be achieved, for a fixed power split, through the activation of a coordination block: this can be defined as a device designed to account for instantaneous power difference between engine required power and engine actual power output and adjust management strategy as a consequence. Thus, when this difference is not zero, such quantity is fed as an additional load into the electric power source. In this manner, electric motors are supposed to balance power output and demand, mainly due to thermal engine response lag (suggested in (Roumeliotis, et al., 2019). That can be expressed as follows:

$$\text{If } T_{ICE}<T_{ICE,req} \tag{5}$$

$$\text{then } T_{EM} = T_{EM,req} + (T_{ICE,req}-T_{ICE}) \tag{6}$$

where T_{ICE} and T_{EM} represent actual engine and electric motors torque, and the subscript *req* refers to their respective required values.

Two cases are compared: in the first one, the energy management is simply obtained as output from the supervisory controller module (user-defined in this case), and the resulting torque split *k* is given in input to both the thermal engine and electric machine; in the second one, the coordination block is added, following the supervisory controller, to take advantage of the faster dynamics of the electric machines, so that *k* will be slightly altered from the predefined value if condition **(6)** is true.

3. Results

If a steep variation in power demand was encountered, the turboshaft engine would not be able to rapidly fulfill the new requirement because of its typical high inertia.

This is supposed to be quite evident, particularly in part-load applications, as suggested by (Wortmann, Schmitz, & Hornung, 2014).

To alleviate the impact of such behavior on global system performance, at every time instant, the difference between engine torque command and actual engine torque is loaded onto the electric module in the manner described in the previous section as a result of the coordination block activation, which is intended to leverage fast electric motor response in favor of a more respondent propulsive system as a whole.

For each of the four test cases, the parameters of Table 1 combined with the PLA modifier of Fig. 3 have been given in input to the HEPS Simulink dynamic model.

In the following pictures (Fig. 6), the power request and power output of the turboshaft engine, the electric motors, and the hybrid system is plotted for the system with both the coordination block on and off.

As it can be seen, after a fast power request increase from 80% to full value in 0.1 seconds, the overall system output achieves its target after 0.15 s on average when the coordination block is active, which means 0.05 s after the stabilization of the input signal, while it requires an additional time interval of about 0.15 s for the system without coordination to attain its nominal request, with a delay of 0.2 s for the response stabilization. So, the uncoordinated system response lags behind that of the coordinated system in all four cases, requiring four times the time needed from the latter to get the new steady condition.

More in general, the performance improvement made possible by hybridization of the system combined with the beneficial effect deriving from the activation of the coordination block can be evinced from Fig. : here, the higher slope of hybrid system response during transient is visible, in contrast with looser thermal engine response, which is characterized by a larger interval of instability, too.

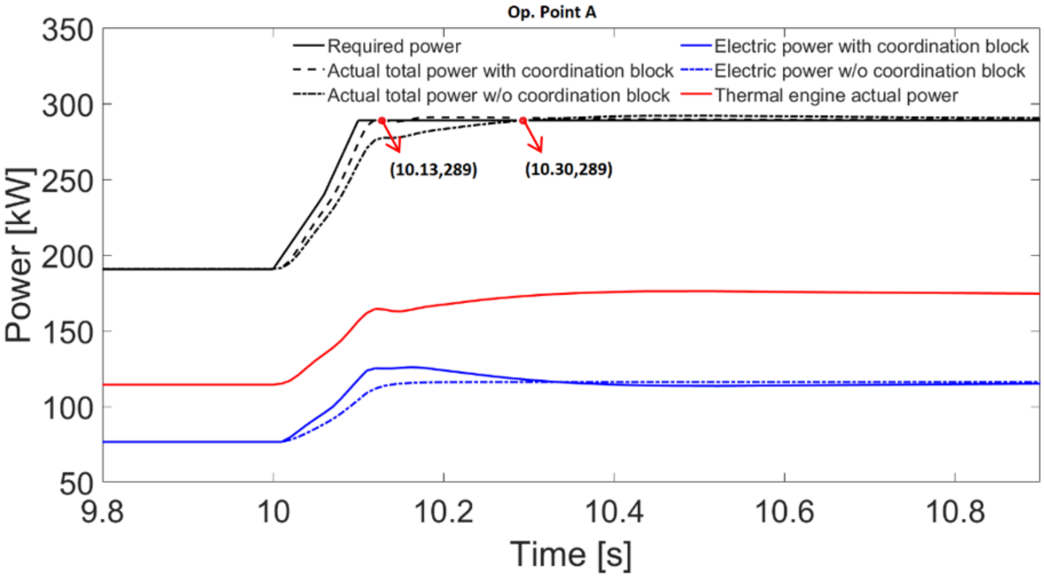

Fig. 6a. Effect of coordination on transient response, Op. Point A.

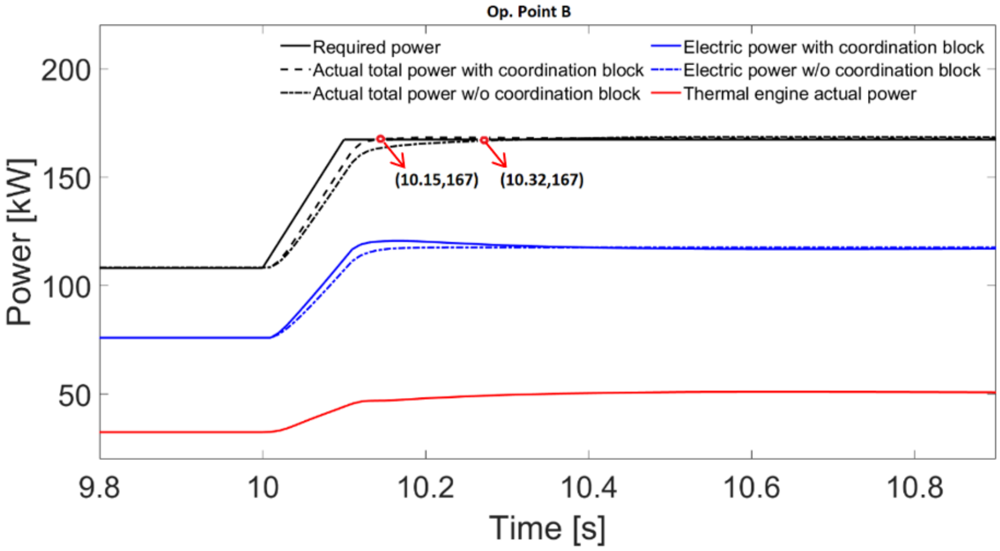

Fig. 6b. Effect of coordination on transient response, Op. Point B.

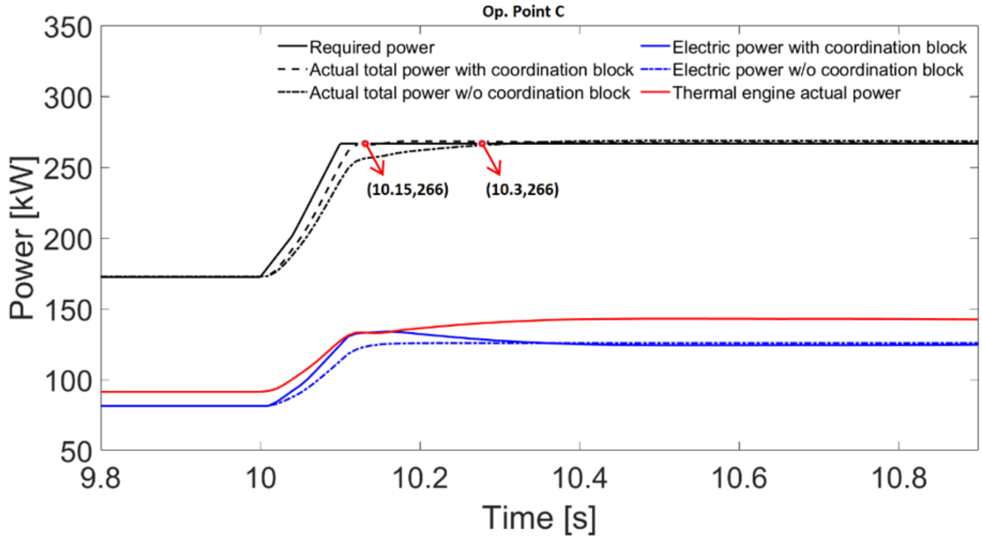

Fig. 6c. Effect of coordination on transient response, Op. Point C.

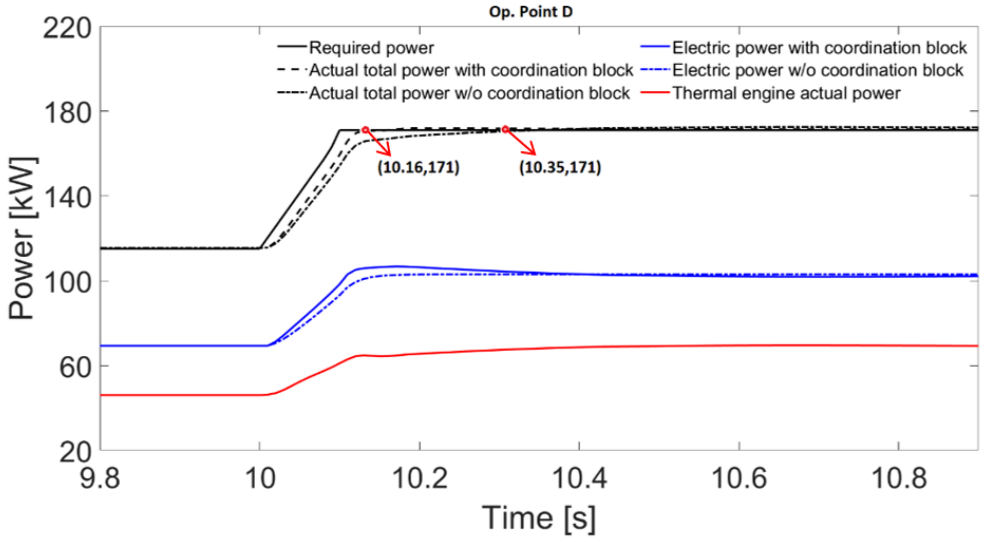

Fig. 6d. Effect of coordination on transient response, Op. Point D.

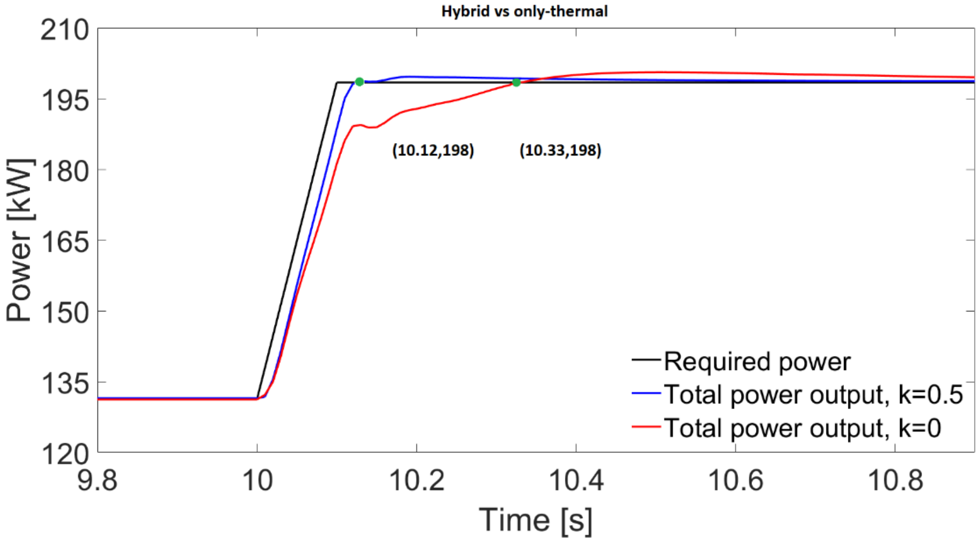

Fig. 7. Performance improvement attained with system hybridization.

4. Conclusions

This paper investigated the capability of a Hybrid Electric Propulsion System designed for Urban Air Mobility applications to rapidly match power demand variations in the form of a transient PLA command given in input to the tested Simulink model.

In particular, the paper focuses on the difference in transient response determined by the activation of a coordination block following the supervisory controller, which previously defined energy management strategy in terms of load split between thermal and electric modules. The role of the coordination block is that of adjusting electric power demand during transient phases to compensate for thermal engine response delay and thus allow the whole system to adapt faster to the new power request. This is made possible by the different typical inertias of the two power sources since it is known that electric machine's response times are generally lower than that of turbine engines, whose performance is even worse at part load use.

The coordination block has been revealed to be effective over all four typical mission profiles analyzed in the paper.

As a further development, a dynamic model of the rotor will be included to characterize LP spool dynamics more in-depth and thus investigate system behavior in a more realistic fashion.

Abbreviations

HEPS	:	Hybrid Electric Propulsion System
HPT	:	High Pressure Turbine
ICV	:	Inter Component Volume
LPT	:	Low Pressure Turbine
N_c	:	Core speed
N_p	:	Low pressure spool speed
PLA	:	Power Lever Angle
RSOC	:	Reference State of Charge
SOC	:	State of Charge
SOH	:	State of Health
UAM	:	Urban Air Mobility
VTOL	:	Vertical Take-Off and Landing

CRediT Author Statement

Ludovica Spada Chiodo: Investigation, Software, Writing-Original Draft. **Teresa Donateo:** Conceptualization, Methodology, Writing-Review & Editing Supervision. **Antonio Ficarella:** Conceptualization, Writing-Review & Editing Supervision, Funds acquisition.

Acknowledgements

This study has been funded by the Italian Ministry for Education, University and Research and developed in collaboration with Aerospace Technological District (DTA) and AvioAero within project SMEA - *Diagnostic and Prognostic Methods and Sensors Development for the Health Monitoring in Aeronautic and Transport Applications*.

References

Airbus. (2021). *Micro-hybridisation: the next frontier to electrify flight?* (Retrieved on January 2022) https://www.airbus.com/en/newsroom/news/2021-09-micro-hybridisation-the-next-frontier-to-electrify-flight

Airbus. (2022). *Urban Air Mobility*. (Retrieved on February 2022) https://www.airbus.com/en/innovation/zero-emission/urban-air-mobility

Donateo, T., De Pascalis, C., Strafella, L., & Ficarella, A. (2021). Off-line and On-line Optimization of the Energy Management Strategy in a Hybrid Electric Helicopter for Urban Air-Mobility. *Aerospace Science and Technology*, 113.

Donateo, T., Terragno, A., & Ficarella, A. (2021). An optimized fuzzy logic for the energy management of a hybrid electric air-taxi. *76th ATI National Congress*. Rome, Italy.

Dubarry, M., & Liaw, B. (2009). Identify capacity fading mechanism in a commercial LiFePO4 cell. *Journal of Power Sources*, 194, 541–549.

EASA. (2022). *Urban Air Mobility* (UAM). (Retrieved on February 2022) https://www.easa.europa.eu/domains/urban-air-mobility-uam

FEV. (2022). *Urban Air Mobility - A game changer for smart cities*. (Retrieved on February 2022) https://uam.fev.com/

Guzzella, L., & Sciarretta, A. (2007). *Vehicle Propulsion Systems: Introduction to Modeling and Optimization*. Berlin, Germany: Springer.

Rendón, M. A., Sánchez R., C. D., Gallo M., J., & Anzai, A. H. (2021). Aircraft Hybrid-Electric Propulsion: Development Trends, Challenges and Opportunities. *Journal of Control, Automation and Electrical Systems*, 32(5), 1244-1268. https://doi.org/10.1007/s40313-021-00740-x

Roumeliotis, I., Mourouzidis, C., Zaffaretti, M., Pachidis, V., Broca, O., & Unlu, D. (2019). Assessmnet of Thermo-electric Power Plants for Rotorcraft Application. *Proceedings of ASME Turbo-Expo 2019: Turbomachinery Technical Conference and Exposition*. Phoenix, Arizona, USA.

Uber Elevate. (2016). *Fast-Forwarding to a Future of On-Demand Urban Air Transporation*. (Retrieved on September 2021) https://uberpubpolicy.medium.com/fast-forwarding-to-a-future-of-on-demand-urban-air-transportation-f6ad36950ffa

Wang, C., Li, Y., & Yang, B. (2017). Transient performance simulation of aircraft engine integrated with fuel and control systems. *Applied Thermal Engineering*, 114, 1029-1037.

Wortmann, G., Schmitz, O., & Hornung, M. (2014). Comparative assessment of transient characteristics of conventional and hybrid gas turbine engine. CEAS *Aeronautical Journal*, 5, 209-223.