

Article

Improving the Dynamic Behavior of a Hybrid Electric Rotorcraft for Urban Air Mobility

Teresa Donateo ^{1,*} , Ludovica Spada Chiodo ¹ , Antonio Ficarella ¹  and Andrea Lunaro ²¹ Department of Engineering for Innovation, University of Salento, Via per Monteroni, 73100 Lecce, Italy² Avio Aero, Via Giovanni Amendola 132, 70126 Bari, Italy

* Correspondence: teresa.donateo@unisalento.it; Tel.: +39-0832-297754

Abstract: A rising number of aerospace manufacturers are working on the development of new solutions in the field of Urban Air Mobility with increasing attention addressing electric and hybrid electric propulsive systems. Hybrid electric propulsive systems potentially offer performance improvements during transient maneuvers, as well as sustaining the engine during flight phases characterized by high power demands. Among the challenges of hybridization in rotorcraft, there is the necessity to predict the dynamic behavior and its effect on the control of rotor shaft speed. In the present study, the dynamic behavior of a parallel hybrid electric propulsive system for a coaxial-rotor air taxi is analyzed in response to a typical sequence of pilot commands that encompasses the range of operations from hover to forward flight. The system is modeled with a dynamic approach and includes sub-models for the coaxial rotors, the turboshaft engine, the electric machine, and the battery. The results of the investigation show a better performance during transients of the hybrid system than a conventional turboshaft configuration, especially if the electric contribution to the power request is coordinated to account for the lag due to slower engine dynamic response.

Keywords: hybrid electric propulsion systems; rotorcraft; urban air mobility



Citation: Donateo, T.; Spada Chiodo, L.; Ficarella, A.; Lunaro, A.

Improving the Dynamic Behavior of a Hybrid Electric Rotorcraft for Urban Air Mobility. *Energies* **2022**, *15*, 7598.

<https://doi.org/10.3390/en15207598>

Academic Editors: Jamie W.G. Turner, Hui Liu, Giovanni Vorraro and Toby Rockstroh

Received: 9 September 2022

Accepted: 13 October 2022

Published: 14 October 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Urban air mobility (UAM) and urban air delivery (UAD) are safe, sustainable, affordable, and accessible means of transportation of people and goods, respectively, that will transform local and intraregional missions [1]. This concept has gained ever-increasing interest and industry investments, with many aerospace manufacturers involved in the design, production, testing, and certification of new solutions for UAM and UAD. A comprehensive review of the literature sources related to urban air mobility can be found in [2]. Thanks to UAM, advanced technologies and new operational procedures are expected to enable practical, cost-effective air travel in metropolitan areas in the forthcoming years.

Driven by the need to overcome the problem of increasing ground traffic congestion in urban areas [3], UAM also focuses on the reduction in the carbon footprint. In fact, UAM transportation is generally realized in the form of electric and hybrid-electric vertical takeoff and landing vehicles (eVTOL/hVTOL), which are quieter and are associated with lower operating costs. The Vertical Flight Society has classified 600 different designs of eVTOL aircraft [4] that integrate existing and emerging technologies, including distributed electric and hybrid-electric propulsion systems [5]. Among the advantages associated with electric propulsion aviation [6], Moore [7] enumerates motor compactness, high efficiencies at both full and part load, no power lapse with altitude, insensitivity to air temperature, together with the already mentioned low noise, low operating costs, high reliability, and absence of local emissions. The current state of the art in terms of energy and power density of the battery, however, is not sufficient to sustain all-electric flight for UAM for long routes, as demonstrated in [7]. To solve this problem, hybrid electric propulsion systems (HEPSs) have been proposed for UAM. A HEPS exploits the presence of two energy sources, usually

a chemical storage unit (a fuel) and a battery and the corresponding energy converters. Note that this definition also includes hydrogen-powered vehicles where the chemical energy carrier is represented by the hydrogen vessel and a fuel cell is used as the energy converter instead of an internal combustion engine [8].

UAVs with HEPSs can sustain longer route lengths and flight duration with respect to the all-electric counterpart, as pointed out in several works in the literature (see, for example, [9,10]). As a further advantage, in a hybrid electric UAM vehicle, takeoff and landing can be performed in electric mode to reduce the noise and the emissions of pollutants in urban areas [11]. On the other hand, electrification calls for the need for improvement not only in batteries but also in motors, power converters, etc. [12].

Studies on hybrid electric aircraft are mainly devoted to sizing (see, for example, [13]) or to the energy management of HEPS (such as in [14]). The energy flows in a vehicle for UAM are usually analyzed with a steady-state model applied to each flight phase (vertical climb, climb, cruise, etc.), but the transition between a flight condition and the following one cannot be captured by this modeling approach, as pointed out in [15,16]. Bianco et al. [17] also emphasized how dynamic modeling is important in the development of electrified aircraft propulsion and advanced control techniques for unmanned vehicles for UAM, while conventionally, the dynamic behavior of a helicopter is linearized around some operating conditions [18].

The dynamic response of the power system is quite critical in the case of rotorcraft. During its basic flight regimes (hover, climb, descent, and forward flight), the helicopter is not able to maintain a steady flight in the case of external disturbance, such as the action of a wind gust, so the pilot has to act continuously on the helicopter's control [19]. The fundamental control inputs of rotorcraft are the main rotor collective pitch, the lateral cyclic pitch, the longitudinal cyclic pitch, and the second rotor collective pitch. The collective pitch control simultaneously changes the pitch angle of all the rotor blades and, therefore, the lift. To maintain a constant rotor rpm, a proportional alteration in power is required to compensate for the drag change caused by the variation of the pitch angle [19]. In fact, the engine speed for a helicopter must be held in a range $\pm 2.5\%$ of its nominal values for safety reasons [20]. To this scope, a correlator is used in piston engines while a governor is adopted in turbine helicopters, such as that considered in this investigation. The governor senses the shaft RPM and adjusts the throttle of the engine to regulate the rotor rpm. If these devices are not installed, the throttle must be moved manually, and, in this case, the failure of the pilot to hold the rotor-motor chain is the cause of crashes. The engine governor is implemented as a single-loop feedback control system that measures the engine regime. This topic was extensively addressed in the scientific literature in the 1980s [21] and is nowadays an established technology, even if the problem of rotorcraft stability has received new study in the last decade because of the development of remotely controlled rotorcraft (see [22,23]). However, the action of the governor depends on the dynamic response of the powertrain, which can be quite different in a hybrid electric power system with respect to a conventional turboshaft engine or a full electric configuration, so it is important to address this topic.

The role of hybridization in supporting the engine during transients has only been hinted at in the scientific literature. Wortmann et al. [24] pointed out that electric motors can produce their torque within a few milliseconds, while gas turbine engines produce their torque within a split of a second. Bianco et al. underlined that the slow response of the turboshaft engine is due to the operational and safety limits that must be satisfied by the engine controller in [14].

The dynamic of a turbine engine is addressed in some works in the literature [25,26] but, to the authors' knowledge, only a few of them analyze the dynamic behavior of the whole hybrid electric system, and only one considers a parallel HEPS with a turboshaft for rotorcraft application. Wortmann et al. [24], in fact, performed a comparison in terms of acceleration time from low thrust to full power by keeping the speed of the engine constant. In fact, the investigation by Wortmann et al. refers to turbojet engines where there is no

mechanical production of the thrust. In [17], a parallel configuration with two single-spool turboshaft engines and an electric machine is considered. The rotor's dynamics are not modeled in detail, and their revolutionary speed is considered constant. This is achieved by a torque-sharing controller that determines a speed setpoint bias applied to the turboshaft engine producing the lesser torque. This coordination action does not take advantage of the already cited better transient characteristics of the electric machine.

The dynamic of a hybrid-electric multi-copter is analyzed by Bouchard et al. [27] but for a series configuration where the rotors are mechanically connected to electric motors, and one of them is used as a master to regulate the angular velocity. The model was mainly developed to analyze the dynamic behavior of the system in the case of faults.

The investigation of Roumeliotis et al. [28] analyzes the performance of a recuperated gas turbine in a hybrid electric configuration and puts into evidence the possibility of using an electric drive to compensate for the delay of the turbine engine in providing the required torques thanks to the small time-constants of the electric system. However, this effect is addressed only qualitatively in the work by Roumeliotis et al., and this lack of detailed analysis gave the authors of the present investigation the idea of analyzing this aspect in a HEPS for a coaxial-rotors rotorcraft developed in the framework of the SMEA project of the Aerospace technology district. The SMEA project is aimed at developing health monitoring tools for conventional and hybrid electric power systems.

In the present study, the dynamic behavior of the parallel hybrid coaxial rotorcraft is evaluated with a forward modeling approach that takes a sequence of pilot commands and operating conditions as input and analyzes the transition between the typical flight regimes of the rotorcraft (from hover to high-speed forward flight). The entire propulsive system, together with the rotors, has been modeled with a dynamic approach paying particular attention to the turboshaft engine. Moreover, this investigation proposes and tests a coordination method that achieves torque-sharing control by exploiting the faster dynamic response of electric machines. Such coordination has been previously discussed by the authors in [29], with a simplified version of the model in response to an arbitrary power request discontinuity, while in the present investigation, complete system analysis is performed, including rotor dynamics. This aspect, together with more accurate implementation of powertrain controls and low pressure (LP) spool dynamics, represents the element of novelty of the proposed work with respect to the literature and past works of the authors.

The paper is organized as follows. Section 2 describes the specification of the hybrid electric UAM vehicle, including the energy management strategy. Section 3 explains the modeling approach, while Section 4 reports the results of the investigation that are discussed in Section 5.

2. The Hybrid Electric Air-Taxi

The configuration considered here for the UAM application is a coaxial-rotor helicopter that uses two main rotors mounted one above the other on coaxial rotor shafts. Such a configuration is making a comeback in recent years because of its higher flight speed capability, payload capacity, and maneuverability [30]. Though its performances are still unclear and debated amongst the research community, the advantage deriving from the elimination of the tail rotor and its transmission [31] is undisputed. In fact, the torque balance is achieved thanks to the adoption of the second counter-rotating rotor.

In the context of HEPS, several configurations are possible, including series hybrid, parallel hybrid, and turbo-electric, according to the electric or mechanical sum of the power derived from the two energy sources. These configurations are compared in detail in [32], where Finger et al. proved the higher performance of the parallel hybrid configuration with respect to the series configuration if no aerodynamic enhancement of the vehicle is assumed [33]. Further, the disadvantages related to the series-hybrid scheme are reported in [34], where different hybridization schemes have been compared using typical mission profiles for the analysis.

In this investigation, a parallel HEPS (Figure 1) with a hybridization degree of 0.45 (ratio of electric power to total installed power) is considered [35]. A turboshaft engine and two electric motors are mechanically connected to the rotor shaft through a gearbox. The electric machines are fed by a lithium-ion battery sized to ensure electric backup operation [34] with a specific electric-backup mission that differs from the operating conditions considered in this investigation. Therefore, the safety issue will not be considered in the present investigation. The details of the machines and of the battery are not reported for the sake of confidentiality.

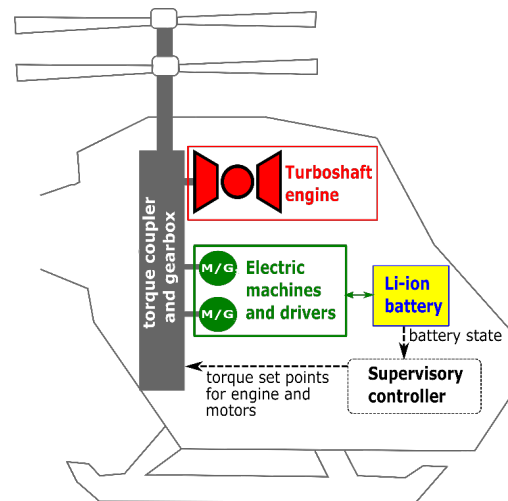


Figure 1. The hybrid electric power system.

With respect to a conventional power system, hybridization allows the engine working point to be controlled, thus reducing low-efficiency operating points. Moreover, the presence of the electric machine is also a beneficial aspect in terms of flight safety since the battery and the electric motors would also allow mission completion in the case of engine failure occurrence, whilst such an event could jeopardize the mission if it happened on a single-engine vehicle. Finally, hybridization avoids the presence of an additional starter engine, such as that used in a traditional turboshaft engine, to drive the engine shaft to the desired speed. Only after the engine reaches a predetermined speed, fuel is supplied to the engine, and the ignition starts.

Since the energy management strategy (EMS) of the multi-source operation is a critical feature in HEPS, this aspect has been investigated by some of the authors in previous works. In particular, the optimal curve for the discharge of the battery along the mission was found with the application of the Dynamic Programming Method [14]. For the same reference vehicle, a fuzzy logic energy management strategy was also defined in [14].

In this investigation, the torque split ratio will be arbitrarily defined, and a sensitivity study will be performed. The torque split ratio is defined as:

$$k = \frac{Q_{EMreq}}{Q_R} \quad (1)$$

where Q_{EMreq} is the torque to be delivered by the electric machines according to the energy management strategy, and Q_R is the torque required by the rotor.

In fact, while previously mentioned works from the same authors are aimed at developing and optimizing energy management strategies 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 an electronic device designed to act in the case of disturbing actions (pilot commands or wind gusts) that generate a difference between

the engine required power and the engine actual power output and to adjust the torque split consequently. Since such deviation is mainly due to response lag of the engine (as explained in [27]), electric motors are used here to reach the equilibrium at the desired speed in a faster way. The action of the coordination block can be expressed as follows:

$$\text{If } Q_{ICE} < Q_{ICE,req} \text{ then } Q_{EM} = Q_{EM,req} + (Q_{ICE,req} - Q_{ICE}) \quad (2)$$

where Q_{ICE} and Q_{EM} represent the actual torques of the engine and the electric motors, respectively, and the subscript req refers to the set points decided by the EMS.

Two cases are compared in this investigation, with and without the coordination block. In the first case, the torque split k defined by the EMS is kept unchanged while, in the second case, the value of k is dynamically adjusted according to Equation (2) with the goal of minimizing the deviations of the rotor's speed from the nominal value. Such a goal is achieved by setting a PID controller, as demonstrated later.

3. Modeling Approach and Controls

To compare the two cases, a dynamic model of the hybrid rotorcraft was developed and implemented in the Matlab/Simulink environment. It consists of several interconnected blocks (as shown in Figure 2) that solve a set of algebraic and differential equations with a fixed-step time (10 ms) Bogacki–Shampine method (ode3) [36].

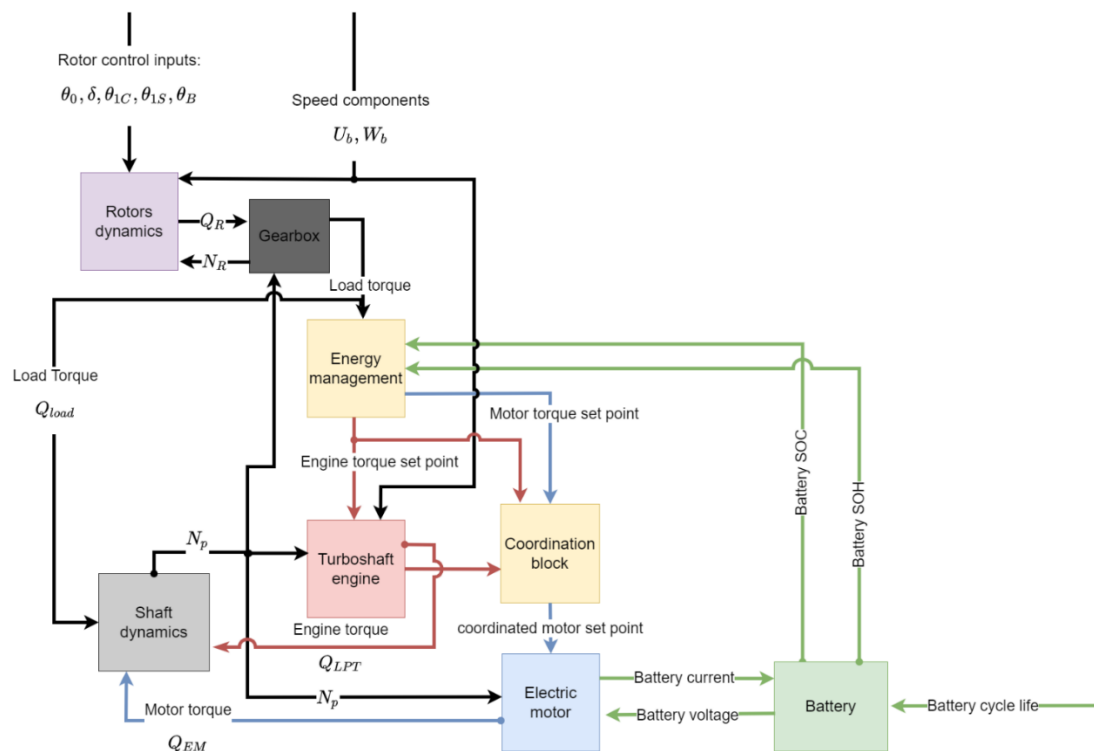


Figure 2. Flow chart of the whole model.

The model takes, as inputs, the rotor control signals ($\theta_0, \delta, \theta_{1c}, \theta_{1s}, \theta_B$) and the speed components of the rotorcraft (U_b, W_b) and calculates the rotor speed N_R and the main working parameters of each component of the powertrain, the fuel flow rate, and the battery state of charge. The engine and the motors are connected to the rotor shaft through a clutch to decouple them in the case of thermal only or all-electric behavior, respectively, or in the case of failure. Moreover, brakes are used to slow down the rotor during shutdowns [17]. These components are not modeled because they are not relevant to the present investigation. Moreover, their dynamic is much faster than the dynamic of the engine and the battery.

3.1. The Rotor Dynamics

The rotor dynamics block models a couple of coaxial counter-rotating rotors. Since the lower rotor partially works in the wake of the upper one, accordingly to their axial spacing, this requires adjusting the rotors to a different collective pitch angle if yaw trim must be achieved [30]. Thus, for each flight condition, the collective pitch angles $\theta_{0,UR}$ and $\theta_{0,LR}$ of the upper and lower rotors are obtained by subtracting and summing an amount δ to a common value of initial collective pitch θ_0 , respectively. Both rotors have the same characteristics, which are reported in Table 1, and the axial spacing is assumed to be equal to 1 m. Starting from the inputs of the overall model, the rotor torque calculation is carried out as proposed in the literature in [21,37], i.e., with the Blade Element Momentum Theory. The blade elemental forces are integrated along the useful radius (net of tip and root cut out losses) with the assumption of uniform inflow, which requires an iterative procedure to calculate rotor forces and moments as a function of inflow ratio and then update inflow estimation. Flapping dynamics are taken into account too, with the assumption of a rigid blade and uncoupled pitch and flap motion. Note that the details of the rotors model, which was developed by Avio Aero, cannot be reported because of confidentiality issues. The gearbox is simulated, in the present investigation, with a quasistatic approach, so the torque and speed of the rotors are simply corrected by the gear ratio to obtain the torque and speed at the main shaft. It should be noted that both thermal and electric power sources are considered as always connected to the rotor shaft in the simulations performed in this work.

Table 1. Rotor parameters.

Number of Blades	N	3
Blade length (m)	R	4.2
Blade chord (m)	c	0.2
Flapping hinge offset (m)	e	0.24659
Flapping hinge elastic constant (N/rad)	k	0
Blade mass (kg)	m_b	12
Lift curve slope	a	5.9
Total blade twist angle (°)	θ_{tw}	4
Required rotational speed (rad/s)	Ω	47

The rotor speed is calculated by the balance implemented in the shaft dynamics block:

$$\frac{dN_p}{dt} = \frac{30}{\pi} \frac{Q_{LPT} - Q_{load} - Q_{EM}}{J} = \gamma \frac{dN_R}{dt} \quad (3)$$

where N_p is the shaft speed (proportional to the rotor speed N_R through the gear ratio γ), J is the overall moment of inertia of the components connected to the shaft, while Q_{LPT} , Q_{load} , and Q_{EM} are the torques of the engine, load, and electric machines, respectively. At this point, after the integration of Equation (3), the value of the shaft speed is updated at each iteration, and the deviation from the nominal value is calculated. Such speed error is given to a PID controller as input, which gives a torque correction as output so as to stabilize the shaft speed. The shaft balance block is depicted in Figure 3. The parameters of the PID controller were identified with a trial-and-error approach. A sensitivity analysis of the effect of the PID parameters on the dynamic response of the system is reported in Section 4.3.

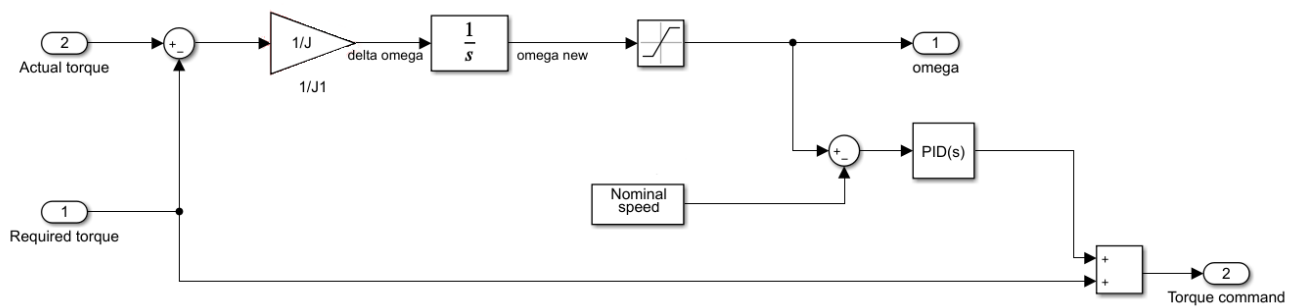


Figure 3. Shaft balance block.

As pointed out in [27], spool dynamics are critical for stationary and transient analysis because it captures the interactions among the power-consuming and producing gas turbine components on a spool. The typical value of the time constant for spool dynamics reported in the literature is about one second for turboshaft engines.

3.2. The Energy Management Block

The load torque is the main input of the energy management block that implements the logic explained below and calculated the setpoints for the engine and the motors. The setpoints are then corrected in the coordination block, which has the goal of correcting the electric motor's torque request to counterbalance the slow dynamics of the engine.

3.3. The Engine Model

The engine considered in this investigation is a two-spool turboshaft engine simulated with the sub-model reported in Figure 2 and detailed in Figure 3. The high-pressure turbine (HPT) is connected to the compressor and rotates at speed N_c , while the low-pressure turbine (LPT) is connected to the rotor shaft and rotates at N_p . A zero-dimensional approach is employed in modeling engine components, i.e., the flow properties are averaged at the inlet and exit sections of each sub-component [38], namely the inlet, the compressor, the burner, and the two turbines. As explained in detail later, the three most important dynamics of a turboshaft engine are included in the model:

- The balance of work between the components on the compressor shaft.
- The volume dynamics, i.e., the accumulation of gas mass inside the cavities between adjacent components.
- The delay in the fuel flow rate provided by the fuel control system.

Heat transfer between a component's material and the flow going through the component during operation and tip clearance effects are neglected in this work, as also in [27].

The thermodynamic processes throughout the engine are represented with the station numbers 1–6 in Figure 4.

The inlet (stations 1–2) is modeled as a ram-air element with a constant efficiency ($\eta_r = 0.9$) so that the actual pressure rise realized in the inlet is:

$$\Delta p = \eta_r \frac{1}{2} \rho V_0^2 \quad (4)$$

However, due to the low airspeeds of the air-taxi rotorcraft, this effect is quite negligible.

The compressor (stations 2–3) and the two turbines (stations 4–5 and 5–6 for HPT and LPT, respectively) 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. The efficiency maps of the compressor and the two turbines were obtained with the procedure explained in [39].

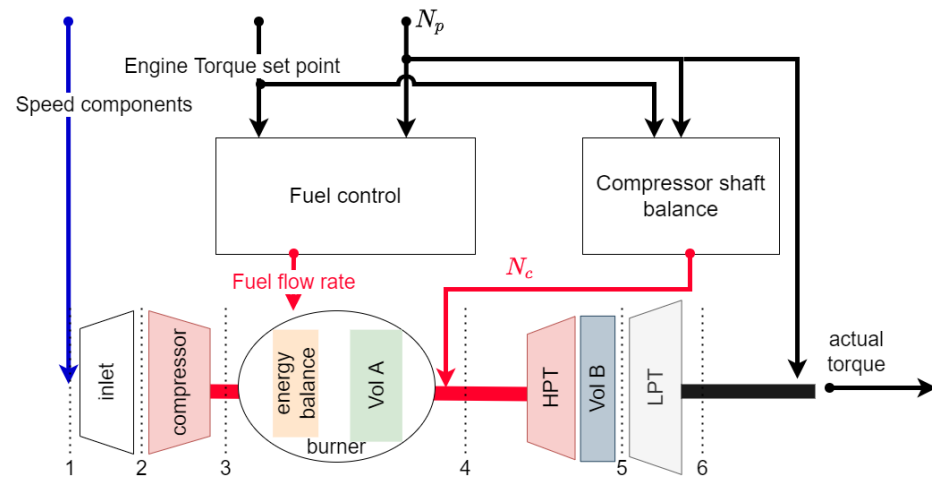


Figure 4. Details of the turboshaft dynamic model.

In particular, the compressor map is used to obtain the corrected mass flow rate and isentropic efficiency η_c as a function of the corrected rotational speed and the pressure ratio β_c . The core speed is mapped as a function of power request. Once obtained η_c from the map, compressor exit temperature T_3 is calculated as:

$$T_3 = T_2 \left[1 + \frac{1}{\eta_c} (\beta_c^{\frac{\gamma-1}{\gamma}} - 1) \right] \quad (5)$$

In turn, β_c is calculated iteratively from the burner exit pressure.

The burner's (stations 3–4) dynamics are represented by its temperature, which is calculated with an energy balance using the fuel flow rate (FFR) as input:

$$T_4 = T_3 + \frac{\eta_b H_i}{c_p \alpha} \quad (6)$$

where η_b is the combustion efficiency, H_i is the lower heating value, and α the air-fuel ratio. c_p is averaged among air and burned gas values of constant pressure specific heat, which, in turn, are polynomial functions of the temperature. The pressure drop across the combustion chamber is assumed to be 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 [40]. The dynamics of the fluid pressure in the ICV volumes A and B of Figure 4 can be written as:

$$\frac{dp}{dt} = \frac{RT}{V} \frac{dm}{dt} = \frac{RT}{V} (\dot{m}_{in}(t) - \dot{m}_{out}(t)) \quad (7)$$

where the variation in 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 (7), p and T are the pressure and temperature in the ICV at each time step, V is the volume, and R the elastic constant of the gas (universal gas constant divided by the molecular mass of the gas).

The same procedure is applied to HPT, with an inter-component volume between the two turbine modules, which gives HPT exit pressure and thus allows the flow rate and efficiency η_t to be obtained from the corresponding maps given $\beta_t = p_4/p_5$ and, consequently,

$$T_5 = T_4 \left[1 - \eta_t (1 - \beta_t^{\frac{1-\gamma}{\gamma}}) \right] \quad (8)$$

Instead, LPT exit pressure is calculated as a function of fuel flow rate, with a correction to account for altitude effects.

The balance of the work between the components on the compressor shaft can be written as:

$$\frac{dN_c}{dt} = \left(\frac{30}{\pi}\right)^2 \frac{1}{J_2} \frac{P_{HPT} - P_C}{N_c} \quad (9)$$

where J_2 is the moment of inertia of the compressor shaft, and P_{HPT} and P_C are the instantaneous power of the high-pressure turbine and the compressor.

The fuel system dynamics are modeled through a first-order system, with a time constant $\tau = 0.03$ s, as in the GSP reference turboshaft model [41]. In fact, the whole stand-alone turboshaft engine developed in Simulink had been previously validated by the authors in comparison with the analogous GSP reference model [42].

3.4. The Electric Motor

The electric motor block distributes the electric torque request equally among the available electric machines. Each motor is modeled with the Simulink “Mapped Motor block” that implements mapped motor and drive electronics operating in torque control mode.

The output torque tracks the torque reference demand and includes a motor-response and drive-response time constant. The block assumes that the speed fluctuations due to mechanical load do not affect the motor torque tracking. The efficiency of the machine/drive block is mapped as a function of the required torque only (being the shaft speed almost constant in all cases), as reported in Table 2.

Table 2. Part load efficiency of the electric machine (inclusive of the driver).

Torque (Nm)	64	127	191
Efficiency	92.7%	94.3%	94.8%

3.5. The Battery Block

As for the battery block, the model has been developed in-house and consists of three sub-models, as clarified in Figure 5.

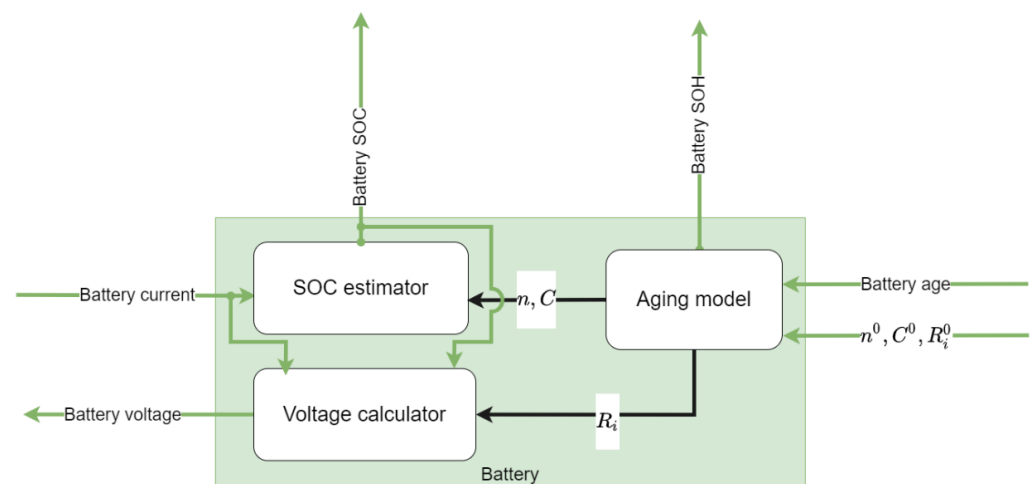


Figure 5. Details of the battery block.

The voltage calculator determines the voltage of the battery V_{batt} as:

$$V_{batt} = VOC - R_i I_{batt} \quad (10)$$

where I_{batt} is the battery current and VOC is the open-circuit voltage mapped as a function of the battery state of charge SOC. The internal resistance R_i can be upgraded in the aging sub-block according to the battery cycle number (i.e., the number of complete

discharge/charge cycles performed on the battery) using a model previously developed in [43] and obtained by fitting the experimental data reported in [44].

The SOC estimator implements a modified version of the coulomb counting method that includes the Peukert effect. The model calculates the corrected current I_{corr} as in Equation (11), where I_{nom} is the current at which the nominal capacity of the battery is referred to (usually 1C) [45].

$$I_{corr} = I \cdot \left(\frac{I}{I_{nom}} \right)^{n-1} \quad (11)$$

The battery dynamic is expressed by the rate of variation of the State of Charge

$$\frac{dSOC}{dt} = \frac{I_{corr}(t)}{C} \quad (12)$$

Note that in Equations (11) and (12), both the battery capacity C and the Peukert coefficient n are dependent on the battery age (Figure 5) and can be updated in the aging sub-block. For the validation of the battery model with experimental data, please refer to [43].

3.6. Validation Issues

The lack of experimental data in the literature about hybrid electric power systems for rotorcraft makes it impossible to perform a full validation. Nevertheless, the proposed model can be considered valid because the stand-alone models of the engine and the battery were validated in previous works. In particular, ref. [42] compares the dynamic behavior of the stand-alone turboshaft engine with the results of the same engine modeled in GSP, while investigation [43] details the validation of the battery model. A sensitivity study will be proposed for the parameters that were arbitrarily chosen by the authors in the range suggested by the GSP simulation package [38] since it is quite impossible to find experimental data for the validation.

4. Results

The modeling approach described in the previous section was applied to a sequence of the following flight phases: hover, low-speed climb, high-speed climb, low-speed forward flight, medium-speed forward flight, and high-speed forward flight of arbitrary duration.

Each of them was simulated at sea-level conditions. The torque split ratio k was varied between 0 (thermal mode) and 1 (all electric). However, the entire mission cannot be performed with a $k \geq 0.8$, unless on-board battery charging is provided since, in these cases, the battery gets fully discharged and the simulation is aborted. Though not complete, these simulations have been included in the plot for a comparison of the dynamic behavior of the hybrid electric power system. The transition from one phase to the following one is supposed to take place in a time interval of three seconds. The resulting collective pitch command is depicted in Figure 6, as well as the entire sequences of all input commands.

Each flight phase is characterized by the torque demand depicted in Figure 7, which is split into the thermal engine torque request and electric motors torque request accordingly to the value of k defined by the EMS.

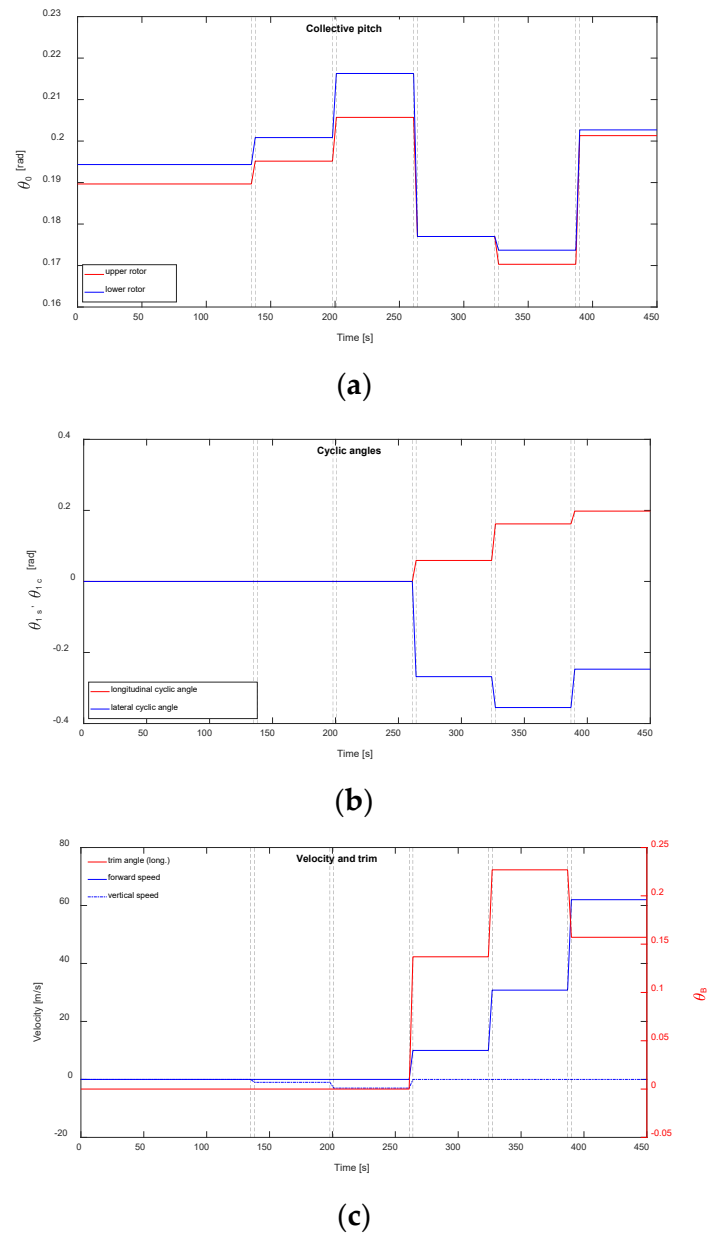


Figure 6. Sequence of input commands: (a) Collective pitch angle; (b) Cyclic pitch angles; (c) Euler pitch angle and velocity components in the body reference system.

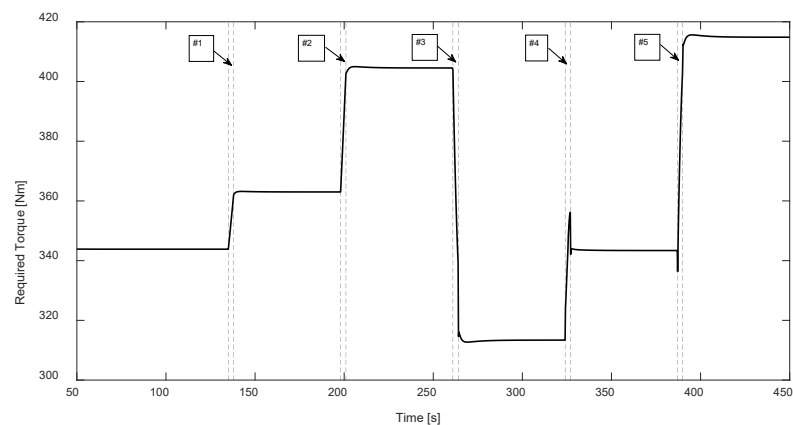


Figure 7. Torque required by rotor shaft (vertical dashed lines correspond to transient start and end).

Figure 8 shows the LP spool speed with different values of k , with both the coordination block activated and deactivated, around each transient phase (labeled #1, #2 etc., in Figure 7). Transient #1 has been neglected because its effect resulted in being quite negligible on the system. From the plots of Figure 8, it can be noted that, without coordination, shaft speed stability increases with increasing involvement of the electric machines: the highest oscillations during transients are associated with the pure thermal configuration, while the lowest deviations from nominal speed are obtained in electric mode. The activation of the coordination block alters this trend: lower values of k correspond to a higher load on the turboshaft engine, and the electric torque correction determined by the coordination block is slightly higher in such cases.

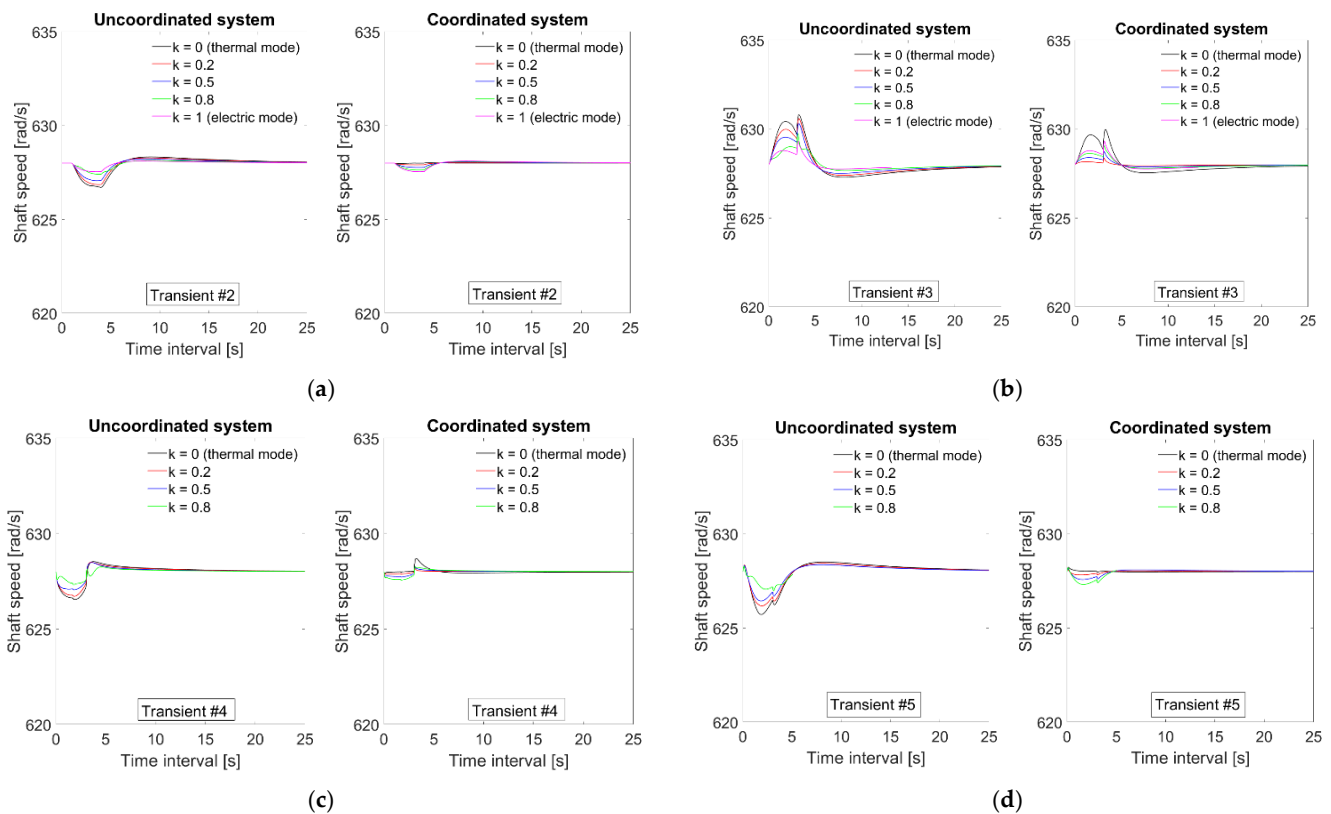


Figure 8. Effect of power split k on LP spool speed, with and without the coordination block: (a) Transient #2, (b) Transient #3, (c) Transient #4, and (d) Transient #5.

Figure 9 underlines the effect of coordination on each transition previously defined. Generally speaking, the system with coordination appears to be more stable than the uncoordinated one in all cases, and the differences due to the hybridization degree are negligible. On average, the role of coordination fades away in about 6 s.

From the plots above, it is evident that the most critical transient is #3. For this reason, transient #3 has been chosen for quantitative analysis by calculating the overshoot and settling time of the shaft speed (see Table 3). Note that the settling time has been calculated as the time required for the shaft speed error to fall in a range $\pm 0.1\%$ since the oscillations of the speed are quite limited in all cases.

The values reported in Table 3 shows how the increasing recourse to electric motors in power generation is generally beneficial in stabilizing the system behavior. In fact, both overshoot and settling time decreases with increasing k . For the coordinated system, the overshoots and the settling times are quite low for all values of electric contribution, proving the effectiveness of the coordination action.

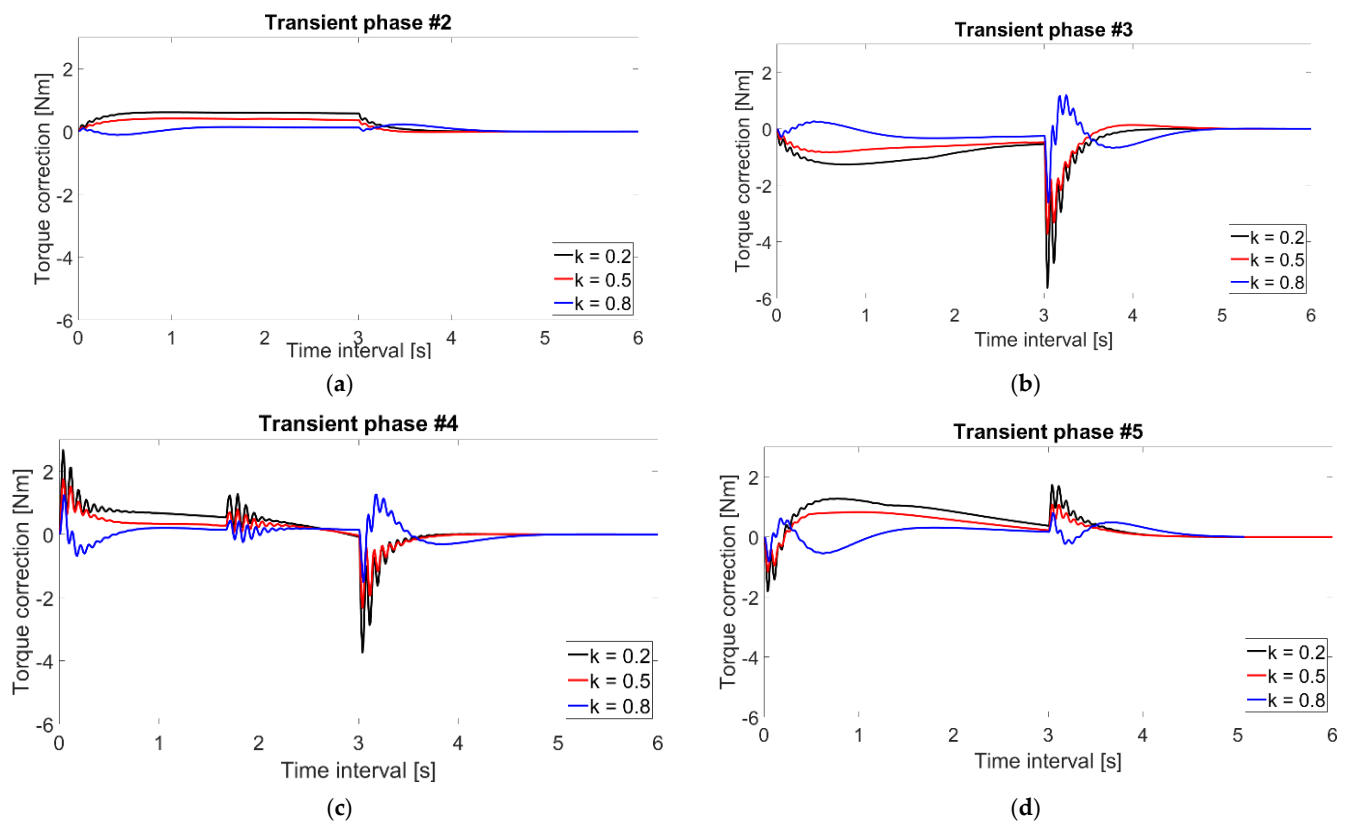


Figure 9. Details of coordination during transients: (a) Transient #2, (b) Transient #3, (c) Transient #4, and (d) Transient #5.

Table 3. Overshoot and settling time of Transient #3 vs. electric contribution (k).

Electric Contribution	Uncoordinated System		Coordinated System	
	Overshoot	Settling time	Overshoot	Settling time
k				
0	0.45%	10.16 s	0.32%	4.20 s
0.2	0.41%	4.49 s	0.06%	0 s
0.5	0.37%	4.28 s	0.12%	3.25 s
0.8	0.28%	4.57 s	0.17%	3.59 s
1	0.21%	3.75 s	0.21%	3.75 s

4.1. Effect on the Battery Current and State of Charge

The effect of additional torque request on electric motors due to coordination is visible on battery current draw during transients, as depicted in Figure 10. Note that in the case of $k = 0$, the EMS selects a thermal operation mode where the battery is not used while the coordination block makes use of the battery only to stabilize the rotor shaft speed.

The coordination effect determines a peak current in each transient, which is more evident when the electric contribution is low ($k < 0.5$) but never exceeds the maximum c-rate of the battery. The overall effect on the state of charge is negligible; the maximum difference between the final state of charge with and without coordination is 0.3% and is obtained in the case of $k = 0$ (thermal mode).

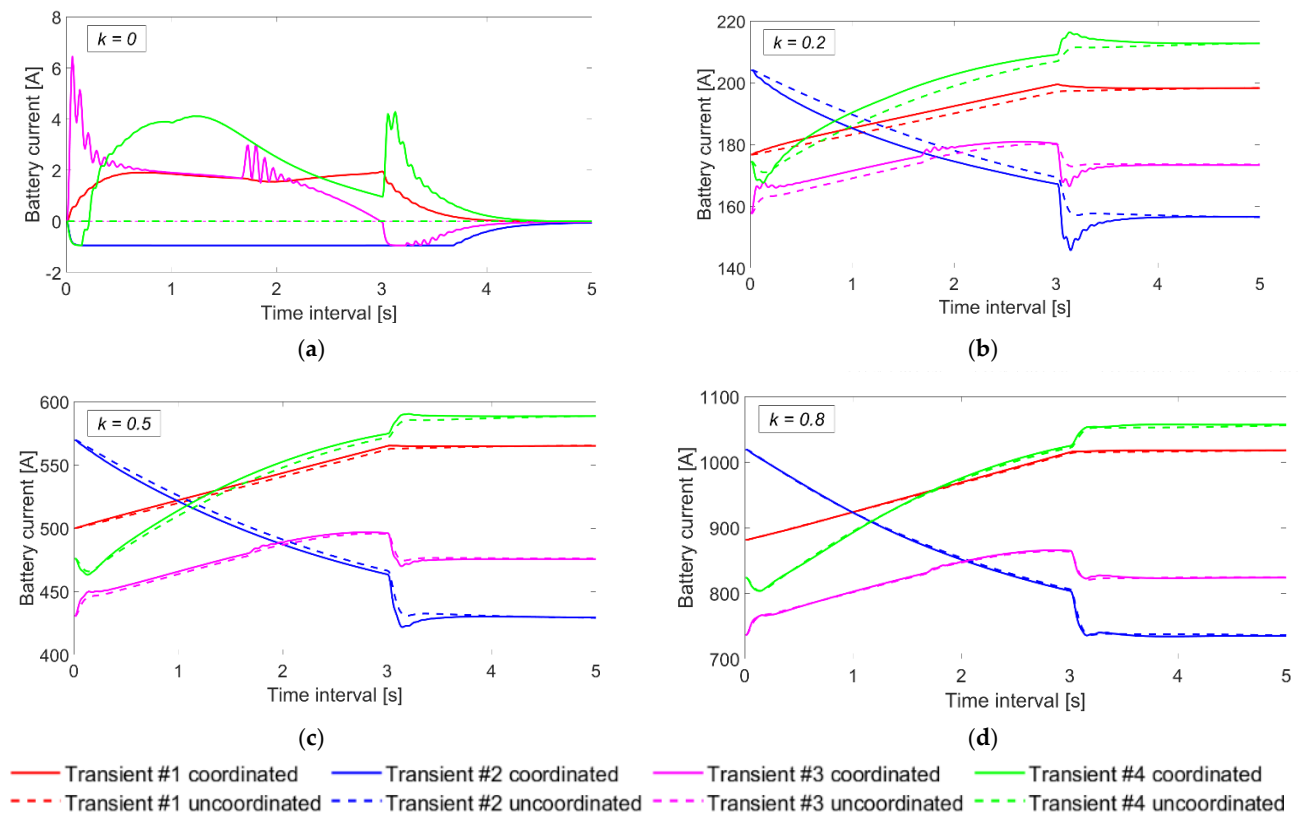


Figure 10. Effect of coordination on battery current with different values of electric contribution: (a) $k = 0$, (b) $k = 0.2$, (c) $k = 0.5$, and (d) $k = 0.8$.

Figure 11 shows the impact of the selected power split and coordination on battery SOC along the simulated sequence. As is obvious, battery discharge is strongly related to the selected value of k to the extent that power splits higher than 0.8 cause the battery to fully discharge before the end of the simulation. The effect of coordination is not discernible since battery SoC for the coordinated and uncoordinated systems appear overlapped. In fact, as can be seen in Figure 11, the difference in battery current during transient phases is too small and of short duration to determine a more tangible difference in overall battery discharge.

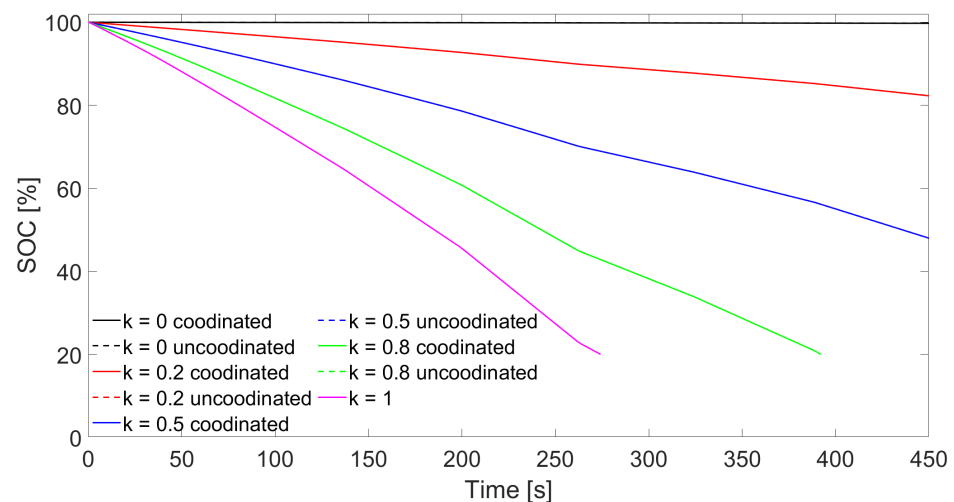


Figure 11. Effect of k and coordination on battery discharge.

4.2. Effect on Fuel Flow Rate and Compressor Speed

Figure 12 shows the compressor speed related to each power split level: apart from the different operating regimes associated with each load condition, being the gas generator speed mapped as a function of engine torque request and actual LP shaft speed, in this case, a slight difference between the coordinated system and the uncoordinated one is recognizable. Though, also in this case, the difference between the two cases for a fixed value of k is negligible and vanishes during steady-state operation; the same trend characterizes fuel flow rate, as shown in Figure 13.

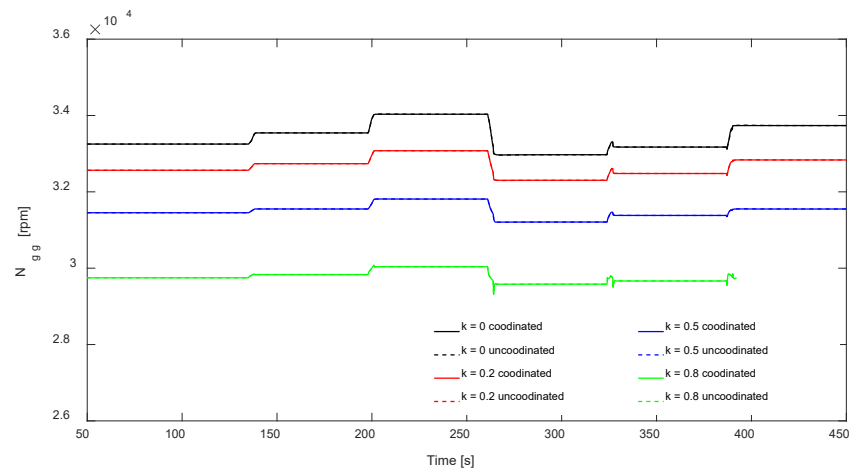


Figure 12. Effect of k and coordination on gas generator speed.

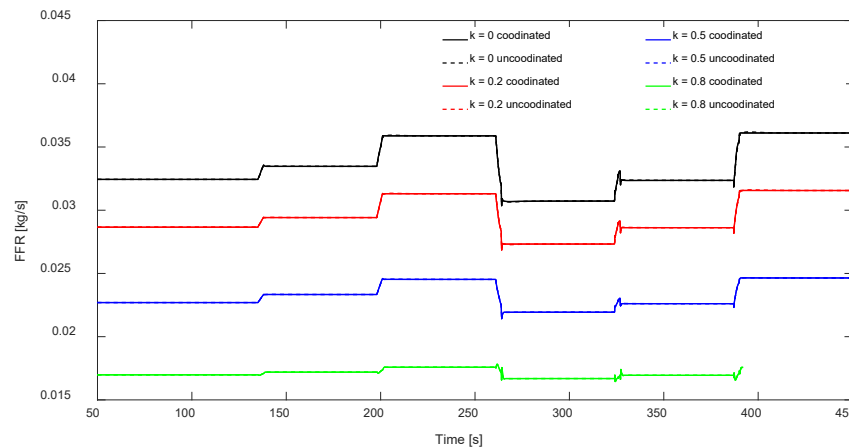


Figure 13. Effect of k and coordination on fuel flow rate.

We can conclude that the major effect of coordination activation is on the electric machines only and, most importantly, on the rotor speed stabilization, which is the purpose it was designed for.

4.3. Sensitivity Analysis

In the present investigation, the shaft inertia of the LP spool shaft has been arbitrarily assumed, starting from a value of inertia taken from the reference GSP turboshaft model. A plausible value of inertia for the electric drive was assumed on the basis of the data in [46], where an electric motor with the same rated power is described. As previously mentioned, however, such value only has an approximate significance, which should be investigated deeper with a proper design of the coupling devices if a more accurate estimation is needed.

To address this issue, a sensitivity analysis of the influence of shaft inertia has been performed in this investigation by increasing the overall inertia J up to a factor of 10. The results are shown in Figure 14.

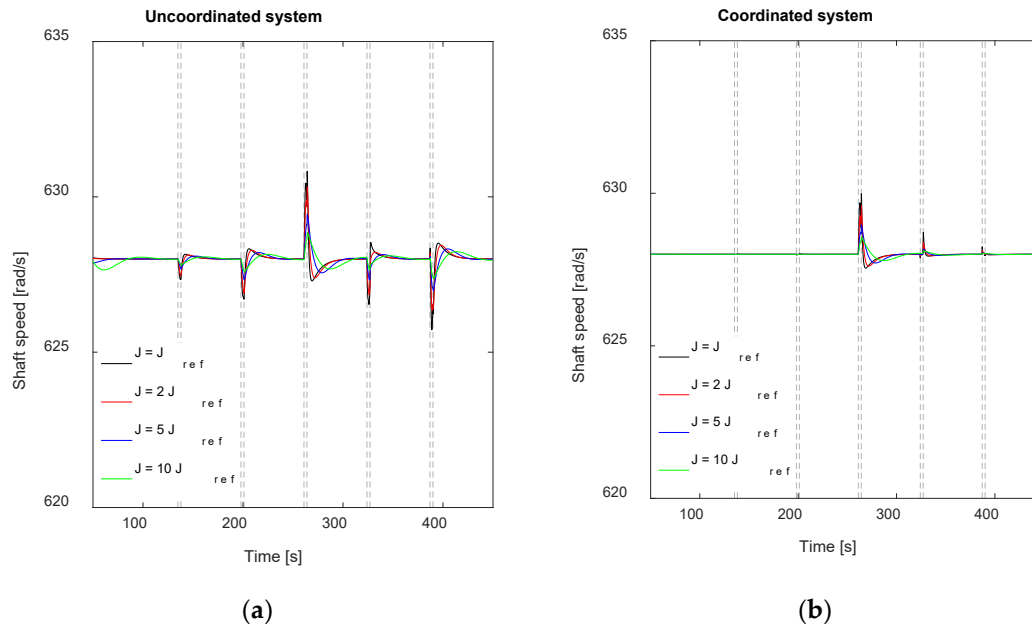


Figure 14. Influence of shaft inertia for a given power split ratio: (a) uncoordinated system, (b) coordinated system.

Note that lower inertia cases are characterized by a higher amplitude of speed oscillation, but they achieve a steady condition faster than those with a high value of shaft inertia, which, in turn, display smaller deviations but in a longer time interval. When the coordination is enabled, differences in dynamic behavior due to system inertia are canceled by the beneficial effect of the coordination block so that shaft speed follows its nominal value tightly during each transition from one flight phase to another.

Table 4 gives the values of shaft speed overshoot and settling time corresponding to the third transient phase of Figure 14, for the system working in thermal mode ($k = 0$). The stabilizing effect of the coordination is evident. In fact, the speed oscillation amplitude is restricted by the activation of the coordination block, which, in turn, determines a shorter settling time.

Table 4. Overshoot and settling time at Transient #3 vs. shaft inertia of the LP spool.

Shaft Inertia	Uncoordinated System		Coordinated System	
	Overshoot	Settling time	Overshoot	Settling time
J_{ref}	0.45%	10.16 s	0.32%	4.20 s
$2J_{ref}$	0.37%	5.35 s	0.25%	4.74 s
$5J_{ref}$	0.23%	6.54 s	0.15%	5.10 s
$10J_{ref}$	0.13%	5.98 s	0.09%	0 s

As mentioned earlier, the parameters of the PID controller that determines the torque coordination were found with a trial-and-error approach. A sensitivity analysis was performed by varying the P, I, and D parameters according to the values reported in Table 5. The results are reported in Table 6 and show how the overshoot and the settling time in the case of $k = 0$ are only slightly affected by small variations of the PID parameters.

Table 5. Sensitivity analysis on the parameters of the PID controller.

	1 (ref)	2	3
P	−0.5	1.1 P_{ref}	0.9 P_{ref}
I	−0.05	1.1 I_{ref}	0.9 I_{ref}
D	0	0.1	−0.1

Table 6. Results of the sensitivity analysis on the parameters of the PID controller.

PID Configuration	Uncoordinated System		Coordinated System	
	Overshoot	Settling time	Overshoot	Settling time
P1, I1, D1	0.45%	10.16 s	0.32%	4.20 s
P2, I2, D2	0.43%	8.54 s	0.30%	4.00 s
P3, I3, D3	0.47%	11.99 s	0.34%	4.49 s

5. Discussion and Future Work

The results of this investigation show that hybridization can be useful to stabilize the shaft speed in rotorcraft and to smooth down the engine transients. It was also possible to quantify the improvement in the dynamic response of the powertrain with the additional electric path. The model will be extended to simulate the start-up process where the same electric machines will be used as a starter for the turboshaft engine [47], which is another advantage of the electrified powertrains.

The dynamic model presented in this work was developed with the goal of generating data for data-driven health monitoring systems [48] in the framework of the SMEA project (Diagnostic and Prognostic Methods and Sensors Development for Health Monitoring in Aeronautic and Transport Applications). Therefore, simulations with a degradation of the components will be performed as a further investigation, and the results of the simulation will be used as virtual sensors to predict the performance of the power system. Therefore, even if only the model of the single components was validated with experimental data, the reasonability of the assumptions makes the whole model suitable for this scope. Of course, it would be preferable to validate the whole model, but unfortunately, experimental data on hybrid electric power systems are very difficult to obtain.

Finally, the feasibility of the proposed control systems in real-time applications will be checked with hardware-in-the-loop tests.

6. Conclusions

The present investigation analyzes the dynamic behavior of a parallel hybrid electric propulsion system for a coaxial rotor air-taxi for typical UAM applications in response to a sequence of pilot commands, which simulate different flight regimes ranging from hover to forward flight.

The torque required by the rotors was calculated as a function of flight speed, rotor speed, and input commands and was divided among turboshaft engines and electric machines based on the nominal value of the power split ratio. A significant performance improvement was found with the usage of a coordination unit, which, besides a PID controller acting on shaft speed error to compensate for total torque requests, adjusts torque requests to compensate for engine delay in responding to varying power requests. This is accomplished by determining an additional torque demand for the electric motors any time the engine is not able to meet the input demand and is justified by the consideration of faster inherent electric machine dynamics. The result is an enhancement of the whole system performance during transients, which allows rotor speed to remain close to its nominal value throughout all mission phases. Such improvement has been verified by increasing the electric contribution from zero (in this case electric power source is involved

only during transients) to values close to one (thermal engine turned off). Overshoots and settling times were used as performance indices to quantify the dynamic behavior of the system with and without the proposed coordination action. Finally, a sensitivity analysis has been carried out to evaluate the influence of shaft inertia and PID parameters on the dynamic response. The activation of the coordination stabilized the rotor speed strictly at its nominal value regardless of shaft inertia.

Author Contributions: Funding acquisition, A.F.; Investigation, L.S.C., T.D. and A.L.; Methodology, T.D. and A.L.; Project administration, A.F.; Supervision, T.D.; Validation, T.D.; Writing—original draft, L.S.C.; Writing—review & editing, T.D. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Italian Ministry for Education, University and Research and developed in collaboration with Aerospace Technological District (DTA) and Avio Aero within project SMEA—Diagnostic and Prognostic Methods and Sensors Development for the Health Monitoring in Aeronautic and Transport Applications (PON SMEA 03PE_00067_5).

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

c_p	constant pressure specific heat
H_i	lower heating value
J	moment of inertia
k	hybridization degree
N_c	gas generator speed
N_p	power turbine speed
N_R	rotor speed
Q_{EM}	electric motors torque
Q_{ICE}	engine torque
Q_R	required torque
U_b	forward speed (body axes)
W_b	vertical speed (body axes)
α	air-fuel ratio
β_c	compressor pressure ratio
β_t	turbine pressure ratio
δ	collective pitch correction
γ	specific heat ratio
η_b	combustion efficiency
η_c	compressor isentropic efficiency
η_r	inlet efficiency
η_t	turbine isentropic efficiency
θ_0	collective pitch angle
θ_{1C}	cyclic pitch angle (lateral)
θ_{1S}	cyclic pitch angle (longitudinal)
θ_B	vehicle pitch angle
τ	fuel system time constant

References

1. Patterson, M.; Isaacson, D.; Mendonca, N.; Neogi, N.; Goodrich, K.; Metcalfe, M.; Bastedo, B.; Metts, C.; Hill, B.; DeCarme, D.; et al. An Initial Concept for Intermediate-State, Passenger-Carrying Urban Air Mobility Operations. In *AIAA Scitech 2021 Forum, Virtual Event, 11–15 & 19–21 January 2021*; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2021. [CrossRef]
2. Garrow, L.A.; German, B.J.; Leonard, C.E. Urban air mobility: A comprehensive review and comparative analysis with autonomous and electric ground transportation for informing future research. *Transp. Res. Part C Emerg. Technol.* **2021**, *132*, 103377, ISSN 0968-090X. [CrossRef]
3. Available online: <https://uam.fev.com/#start> (accessed on 10 March 2022).

4. Sheehan, V. Press Release: Vertical Flight Society Electric VTOL Directory Hits 600 Concepts. Available online: <https://evtol.news/news/vertical-flight-society-electric-vtol-directory-hits-600-concepts> (accessed on 10 March 2022).
5. Hill, B.P.; DeCarme, D.; Metcalfe, M.; Griffin, C.; Wiggins, S.; Metts, C.; Bastedo, B.; Patterson, M.; Mendonca, N. *UAM Vision Concept of Operations (ConOps) UAM Maturity Level (UML) 4. UAM UML-4*; Document ID 20210010443; NASA Headquarters: Washington, DC, USA, 2020.
6. Epstein, A.H.; O'Flarity, S.M. Considerations for Reducing Aviation's CO₂ with Aircraft Electric Propulsion. *J. Propuls. Power* **2019**, *35*, 572–582. [\[CrossRef\]](#)
7. Moore, M.D.; Goodrich, K.H.; Viken, J.K.; Smith, J.C.; Fredericks, B.; Trani, T.; Barraclough, J.; German, B.J.; Patterson, M.D. High Speed Mobility Through On-Demand Aviation. In Proceedings of the AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Los Angeles, CA, USA, 2–14 August 2013.
8. Ploetner, K.O.; Al Haddad, C.; Antoniou, C.; Frank, F.; Fu, M.; Kabel, S.; Llorca, C.; Moeckel, R.; Moreno, A.T.; Pukhova, A.; et al. Long-term application potential of urban air mobility complementing public transport: An upper Bavaria example. *CEAS Aeronaut. J.* **2020**, *11*, 991–1007. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Cirigliano, D.; Frisch, A.M.; Liu, F.; Sirignano, W.A. Diesel, Spark-Ignition, and Turboprop Engines for Long-Duration Unmanned Air Flights. *J. Propuls. Power* **2018**, *34*, 878–892. [\[CrossRef\]](#)
10. Benbrook, J.A.; Hagen, C. Hybrid Powertrain Improvements for Increased Flight Duration in Multirotor Unmanned Aerial Systems. In *AIAA Propulsion and Energy 2019 Forum*; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2019. [\[CrossRef\]](#)
11. Donato, T.; Ficarella, A. A Methodology for the Comparative Analysis of Hybrid Electric and All-Electric Power Systems for Urban Air Mobility. *Energies* **2022**, *15*, 638. [\[CrossRef\]](#)
12. Coday, S.; Ellis, N.; Liao, Z.; Pilawa-Podgurski, R.C.N. A Lightweight Multilevel Power Converter for Electric Aircraft Drivetrain. In Proceedings of the 2021 IEEE Energy Conversion Congress and Exposition (ECCE), Singapore, 24–27 May 2021; pp. 1507–1513. [\[CrossRef\]](#)
13. An, J.H.; Kwon, D.Y.; Jeon, K.S.; Tyan, M.; Lee, J.W. Advanced Sizing Methodology for a Multi-Mode eVTOL UAV Powered by a Hydrogen Fuel Cell and Battery. *Aerospace* **2022**, *9*, 71. [\[CrossRef\]](#)
14. Donato, T.; De Pascalis, C.; Strafella, L.; Ficarella, A. Off-line and On-line Optimization of the Energy Management Strategy in a Hybrid Electric Helicopter for Urban Air-Mobility. *Aerosp. Sci. Technol.* **2021**, *113*, 106677. [\[CrossRef\]](#)
15. Dehesa, D.; Menon, S.; Brown, S.; Hagen, C. Dynamic Analysis of a Series Hybrid–Electric Powertrain for an Unmanned Aerial Vehicle. *J. Propuls. Power* **2022**, *38*, 84–96. [\[CrossRef\]](#)
16. Wall, T.J.; Meyer, R.T. Hybrid Electric Aircraft Switched Model Optimal Control. *J. Propuls. Power* **2020**, *36*, 488–497. [\[CrossRef\]](#)
17. Bianco, S.J.; Chevalier, C.T.; Litt, J.S.; Smith, K.; Chapman, W.; Kratz, J.L. *Revolutionary Vertical Lift Technology (RVLT) Side-by-Side Hybrid Concept Vehicle Powertrain Dynamic Model*; NASA/TM-20210014065; American Society of Mechanical Engineers: New York, NY, USA, 2021.
18. Wu, J.; Li, P.; Fang, Z.; Han, B. A Hybrid Control Method for an Unmanned Scale Helicopter Attitude. In Proceedings of the 6th World Congress on Intelligent Control and Automation, Dalian, China, 21–23 June 2006; pp. 9119–9123. [\[CrossRef\]](#)
19. Rotaru, C.; Todorov, M. Helicopter Flight Physics. In *Flight Physics: Models, Techniques and Technologies*; IntechOpen: London, UK, 2017. [\[CrossRef\]](#)
20. Zumarraga, A.J.; Garaventa, G.N. Cicarè CH7-B Engine Governor. In *II Congreso de Microelectrónica Aplicada*; Facultad de Ingeniería (UNLP): La Plata, Argentina, 2011.
21. Talbot, P.D.; Tinling, B.E.; Decker, W.A.; Chen, R.T.N. *A Mathematical Model of a Single Main Rotor Helicopter for Piloted Simulation*; NASA-TM-84281; National Aeronautics and Space Administration: Moffett Field, CA, USA, 1982.
22. Khalesi, M.H.; Salarieh, H.; Foumani, M.S. Dynamic Modeling, Control System Design and MIL–HIL Tests of an Unmanned Rotorcraft Using Novel Low-Cost Flight Control System. *Iran. J. Sci. Technol. Trans. Mech. Eng.* **2020**, *44*, 707–726. [\[CrossRef\]](#)
23. Yin, X.; Zhang, D.; Fang, Q.; Shen, L. Research on modeling and stability control of micro unmanned helicopter. In Proceedings of the 29th Chinese Control And Decision Conference (CCDC), Chongqing, China, 28–30 May 2017; pp. 6618–6622. [\[CrossRef\]](#)
24. Wortmann, G.; Schmitz, O.; Hornung, M. Comparative assessment of transient characteristics of conventional and hybrid gas turbine engine. *CEAS Aeronaut. J.* **2014**, *5*, 209–223. [\[CrossRef\]](#)
25. Chappell, M.A.; McLaughlin, P.W. Approach of modeling continuous turbine engine operation from startup to shutdown. *J. Propuls. Power* **1993**, *9*, 466–471. [\[CrossRef\]](#)
26. Pakmehr, M.; Fitzgerald, N.; Feron, E.; Paduano, J.; Behbahani, A. Physics-Based Dynamic Modeling of a Turboshaft Engine Driving a Variable Pitch Propeller. *J. Propuls. Power* **2016**, *32*, 646–658. [\[CrossRef\]](#)
27. Bouchard, E.D.; Verberne, J.; D'Arpino, M.; Ozcan, M.; Porpora, F.; Gladin, J.; Patel, S.; Justin, C.; Mavris, D. Modeling and Simulation of Novel Electric/Hybrid Electric Multicopter Architectures for Urban Air Mobility. In *2021 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*; IEEE: New York, NY, USA, 2021; pp. 1–24. [\[CrossRef\]](#)
28. Roumeliotis, I.; Mourouzidis, C.; Zaffaretti, M.; Pachidis, V.; Broca, O.; Unlu, D. Assessment of Thermo-electric Power Plants for Rotorcraft Application. In Proceedings of the ASME Turbo-Expo 2019: Turbomachinery Technical Conference and Exposition Volume 3: Coal, Biomass, Hydrogen, and Alternative Fuels; Cycle Innovations; Electric Power; Industrial and Cogeneration; Organic Rankine Cycle Power Systems, Phoenix, AZ, USA, 17–21 June 2019. [\[CrossRef\]](#)

29. Donato, T.; Spada Chiodo, L.; Ficarella, A. Effect of Coordination on Transient Response of a Hybrid Electric Propulsion System. *Int. J. Aviat. Sci. Technol.* **2022**, *3*, 4–12.
30. Kim, H.W.; Brown, R.E. A comparison of coaxial and conventional rotor performance. *J. Am. Helicopter Soc.* **2010**, *55*, 12004. [\[CrossRef\]](#)
31. Prior, S.D. Reviewing and Investigating the Use of Co-Axial Rotor Systems in Small UAVs. *Int. J. Micro Air Veh.* **2010**, *2*, 1–16. [\[CrossRef\]](#)
32. Rendón, M.A.; Sánchez, R.C.D.; Gallo, M.J.; Anzai, A.H. Aircraft Hybrid-Electric Propulsion: Development Trends, Challenges and Opportunities. *J. Control Autom. Electr. Syst.* **2021**, *32*, 1244–1268. [\[CrossRef\]](#)
33. Finger, D.F.; Goetten, F.; Braun, C.; Bil, C. On Aircraft Design Under the Consideration of Hybrid-Electric Propulsion Systems. In *Proceedings of the 2018 Asia-Pacific International Symposium on Aerospace Technology (APISAT 2018)*; Springer: Singapore, 2018; pp. 1365–1381.
34. Avanzini, G.; Carlà, A.; Donato, T. Parametric analysis of a hybrid power system for rotorcraft emergency landing sequence. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.* **2017**, *231*, 2282–2294. [\[CrossRef\]](#)
35. Guzzella, L.; Sciarretta, A. *Vehicle Propulsion Systems: Introduction to Modeling and Optimization*; Springer: Berlin, Germany, 2007.
36. *Simulink® User's Guide*; The MathWorks, Inc.: Natick, MA, USA, 2020.
37. Chen, R. *Effects of Primary Rotor Parameters on Flapping Dynamics*; NASA-TP-1431; National Aeronautics and Space Administration: Moffett Field, CA, USA, 1980.
38. *GSP 11 User Manual*; Version 11.4.6.0; National Aerospace Laboratory NLR: Amsterdam, The Netherlands, 2016.
39. De Pascalis, C.L.; Donato, T.; Ficarella, A. A scalable model for design and control of turboprop engines for advanced propulsion systems. *AIP Conf. Proc.* **2019**, *2191*, 020061. [\[CrossRef\]](#)
40. Wang, C.; Li, Y.G.; Yang, B.Y. Transient performance simulation of aircraft engine integrated with fuel and control systems. *Appl. Therm. Eng.* **2017**, *114*, 1029–1037. [\[CrossRef\]](#)
41. Panov, V. GasTurboLib: Simulink Library for Gas Turbine Engine Modelling. In *Proceedings of the ASME Turbo Expo 2009: Power for Land, Sea and Air*, Orlando, FL, USA, 8–12 June 2009; Volume 1, pp. 555–565.
42. Donato, T.; Cucciniello, L.; Strafella, L.; Ficarella, A. Control Oriented Modelling of a Turboshift Engine for Hybrid Electric Urban Air-Mobility. In *Proceedings of the 75th National ATI Congress, E3S Web of Conferences*, Rome, Italy, 15–16 September 2020; Volume 197.
43. Donato, T.; Ficarella, A. A Modeling Approach for the Effect of Battery Aging on the Performance of a Hybrid Electric Rotorcraft for Urban Air-Mobility. *Aerospace* **2020**, *7*, 56. [\[CrossRef\]](#)
44. Ning, G.; Haran, B.; Popov, B.N. Capacity fade study of lithium-ion batteries cycled at high discharge rates. *J. Power Sources* **2003**, *117*, 160–169. [\[CrossRef\]](#)
45. Hausmann, A.; Depcik, C. Expanding the Peukert equation for battery capacity modeling through inclusion of a temperature dependency. *J. Power Sources* **2013**, *235*, 148–158. [\[CrossRef\]](#)
46. Fadli, M.R.; Mushthofa Musyasy, M.; Furqani, J.; Purwadi, A. Modelling of Field Orientation Control (FOC) Method in 120 kW Brushless DC Motor (BLDC). In *Proceedings of the 2019 6th International Conference on Electric Vehicular Technology (ICEVT)*, Bali, Indonesia, 18–21 November 2019; pp. 383–389. [\[CrossRef\]](#)
47. Sheng, H.; Chen, Q.; Li, J.; Jiang, W.; Wang, Z.; Liu, Z.; Zhang, T.; Liu, Y. Research on dynamic modeling and performance analysis of helicopter turboshaft engine's start-up process. *Aerosp. Sci. Technol.* **2020**, *106*, 106097. [\[CrossRef\]](#)
48. De Giorgi, M.G.; Strafella, L.; Menga, N.; Ficarella, A. Intelligent Combined Neural Network and Kernel Principal Component Analysis Tool for Engine Health Monitoring Purposes. *Aerospace* **2022**, *9*, 118. [\[CrossRef\]](#)