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A Methodology for Preliminary Performance Estimation of a Hybrid-Electric Tilt-Wing Aircraft for Emergency Medical Services

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***Abstract*— This paper aims to provide a simple methodology to preliminary size a hybrid-electric propulsion system for large scale piloted, optionally piloted or unmanned tilt-wing aircraft. In this work, the author refers to three mission profile representative of an Emergency Medical Service (EMS) operation and estimate the performance of the aircraft along the mission. Thus, based on some assumptions on battery technology, architecture of the hybrid system and mission safety requirements, a methodology for preliminary performance estimation is described and results for a baseline architecture are presented. Based on present and near future battery technology (in terms of charge/discharge rates and energy density), the present study shows how safety requirements can strongly affect the overall size of the power-plant system and impact the feasibility of hybrid-electric technology in aeronautical applications.**

I. INTRODUCTION

A growing concern for the environmental impact of aviation has been driving research activities for the past two decades and is currently leading to the exploration of unconventional aircraft and propulsion systems concepts. Among a wide range of interesting innovative options, the tilt-wing concept draws particular interest for its Vertical Take Off and Landing (VTOL) capability and its potentially enhanced efficiency compared to conventional helicopters. A tilt-wing aircraft may look like a conventional multi-propeller aircraft, with its propellers mounted along the wing-span and may behave like an airplane during cruise flight, but its wing is also capable of rotating around its span-wise axis and reach a relative angle of 90 degrees with respect to the fuselage so that the thrust generated by the propellers can counteract the whole weight of the aircraft as in a multi-rotor helicopter. The ability of tilting its wing allows the tilt-wing aircraft to perform vertical take off, hover and low-speed manoeuvres as well as fly much more efficiently and at higher cruise speed and altitude like conventional propelled airplanes. As summarized by Anderson in [1] and [2], tilt-wing technology was first explored in North America by several aerospace companies, mostly under U.S. Army/Naval contracts, willing to develop the future means of transport for troops and military vehicles. Few are the attempts which led to a flyable prototype, among which the Canadair CL-84 is believed to be the most successful. Nevertheless, the concept was later put aside unlike other platforms such as tilt-rotors, who found instead their way into a military application like the V-22 Osprey. After years of silence, the tilt-wing is currently being brought to light once again as a possible configuration for air-taxi services (as unveiled by Rolls-Royce at the Farnborough International Airshow in 2018, [5]). Full scale unmanned applications are being investigated (among many examples, the NASA GL-10C, as reported in [4]).

Given its promising characteristics, a tilt-wing aircraft is potentially suitable for many applications requiring


Fig. 1. A rendering picture of the Dufour Aerospace aERo2 Tilt-Wing Aircraft in helicopter mode


Fig. 2. A rendering picture of the Dufour Aerospace aERo2 Tilt-Wing Aircraft in airplane mode

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hovering and VTOL capability as well as helicopter-like low speed maneuverability, such as Emergency Medical Services. Furthermore, tilt-wing technology may enable the combination of VTOL technology and greener aviation by means of an innovative hybrid electric powerplant: a serial, rechargeable hybrid-electric system may allow a fully electrical take off and landing, while in cruise a conventional gas-turbine provides enough power to sustain flight and recharge the battery. Unlike Electric Propulsion (EP), which makes no use of aviation fuel as energy source, the Hybrid-Electric Propulsion (HEP) combines the use of gas turbine and energy storage in either ”parallel” or ”series” configuration and better suits mid-range aircraft applications. For the sake of completeness, the definition of parallel and series, shall be recalled. As introduced in [23], in parallel HEP, power flow down to the propulsor originates in part from a gas turbine, in part from a motor/generator drawing energy from another source such as a battery; in series HEP, instead, power flow down to the propulsor originates exclusively from a motor/generator which is then drawing energy from a motor/battery setup, therefore no direct mechanical link is provided between a gas turbine and the propulsor (the rotor, for instance). While many possible configurations are currently being studied (many of them are discussed in [7], among which serial and parallel architectures with several peculiar variations), in the case at hand, a serial configuration is analysed in which the gas-turbine is exclusively used to generate electrical power to be supplied to the propulsion system, as shown in [8] for naval applications. If well optimised, the analysed architecture is supposed to increase the global efficiency of the powerplant while reducing emissions.

This paper presents a methodology for estimating the performance of tilt-wing aircraft (in manned as well as unmanned configurations) equipped with such a hybrid propulsion system and analyses how mission safety constraints can strongly impact the overall size of the powerplant. The paper aims to give the reader useful means to approach the preliminary design of a hybrid-electric tilt-wing aircraft, therefore the analysis is kept as general as possible in order to account for a broad range of similar tilt-wing design options: this approach differs from what, for instance, presented in [25], in which several specific concepts are taken into account and compared carrying more detailed aerodynamic analysis. In fact, the reader shall understand that tilt-wing aircraft, as well as other unconventional VTOL architectures, involve aerodynamic effects which are very peculiar and highly non-linear, mostly due to the combination of wing-rotor interaction effects and high local angles of attack experimented by the aircraft. Consequently, accurate mathematical models are generally complex and tailored for the specific architectures and flight conditions, so that a comprehensive comparison between architectures can be challenging. On the contrary, in this paper, the authors wish to address the early phases of a project, in which, based on business objectives and mission requirements, several educated high level design choices must be made and will strongly impact the project, but a detailed and definitive aircraft architecture has not necessarily been defined yet. Consequently, with due caution the presented methodology may be applied to other VTOL aircraft configuration since the tilt-rotor as well.

The paper is structured as follows: after an introduction, the reference mission profiles are described in section II. Section III introduces the mathematical model with the assumptions and simplifications made, while Section IV introduces the hybrid architecture considered for the study at hand and the assumptions made based on current technology. Subsequently, Section V describes the analysis performed and presents the results. Eventually, conclusions are reported.

II. MISSION PROFILES

The aircraft performance is estimated in terms of required power along the reference missions and for each single mission phase. For the task at hand 3 reference mission profiles are considered.

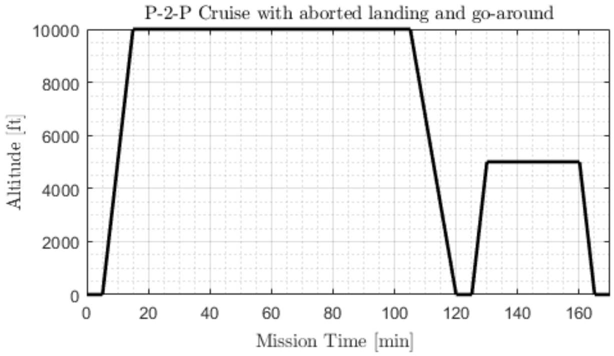

Fig. 3. Point-to-Point Mission

A. Point to Point Cruise Flight

The first mission profile account for a conventional cruise flight between two heliports, with vertical take off and landing in helicopter mode and climb, cruise and descend performed in the more efficient airplane mode. Furthermore, a possible aborted landing with go-around is considered.

B. EMS Transfer Flight

The second mission profile shall account for a generic Emergency Medical Transfer Flight, in which the aircraft is required to overcome a mountain, reach a medical facility, embark the patient, take off again and carry the patient to a second medical facility, disembark the patient and then return to base, with a possible go-around involved.

C. Advanced Rescue Mission

The third mission profile is a hypothetical Advanced Rescue Mission performed in a fairly mountainous area (Fig. 5). The tilt-wing aircraft shall take off from an operative base, climb beyond a mountain of average height, perform a hover task, reach a medical facility and eventually go back to the operative base, with a possible go-around involved.

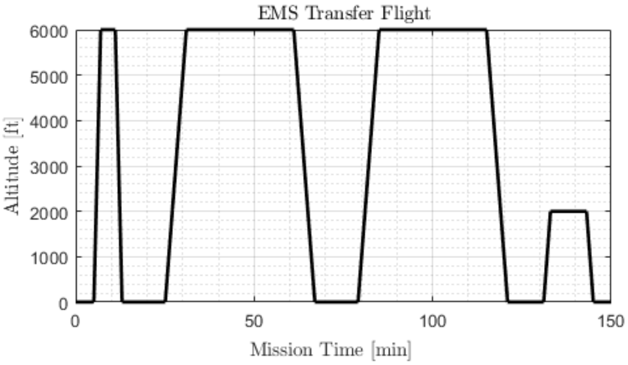

Fig. 4. Advanced Rescue Mission

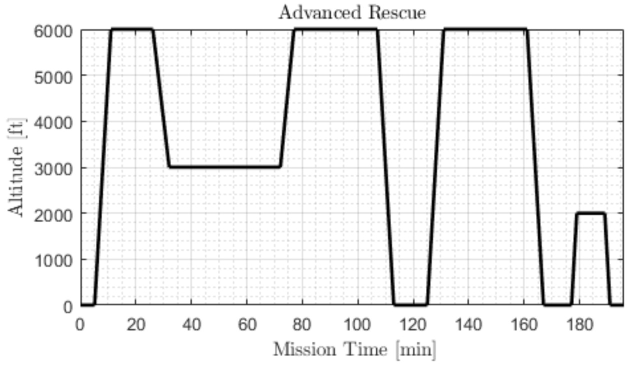

Fig. 5. Advanced Rescue Mission

III. MATHEMATICAL MODELLING

What presented below is a simplified mathematical model to compute the power required to sustain flight in each flight phase of the mission. For a better understanding, should be clear to the reader that the power computed here only accounts for the generation of the forces required by the aircraft to sustain flight and does not include what required by additional aircraft systems. A more detailed study could be performed for a specific aircraft and would be the subject of a forthcoming paper.

A. Hover, Take-Off, Landing and Transition

The required power in a hover phase can be estimated in a simple fashion as the power needed to generate enough thrust to counteract the aircraft weight and then corrected for the propulsion system efficiency η_P (for helicopter rotors the Figure of Merit FM is generally used, the airplane notation is here used instead since the tilt-wing aircraft are generally equipped with variable/fixed-pitch propellers). According to [17], the power required to hover P_h can be written as

$$P_h = \frac{1}{\eta_P} \frac{W^{3/2}}{\sqrt{2\rho A}} \tag{1}$$

where W is the gross weight of the aircraft, ρ is the air density and A the equivalent rotor disk area. Eq. (1) is a strong simplification to the overall power calculation for a rotorcraft, but the results can be corrected acting on η_P and matched with reference data for a preliminary estimation. In this case, η_P was estimated using a simulation code based on a modified blade element theory as described by Stahlhut in [21]. Eq. (1) is here exploited for the take-off, landing and transition phases as well. Nevertheless, when not strictly in hover conditions, the overall thrust and efficiency η_P shall be slightly modified according to the analysed case (during take-off the overall thrust will be slightly higher than what needed to counteract the sole weight of the rotorcraft to allow this to lift from the ground and eventually start transition to airplane mode. As highlighted in [18], [19], the power requirement of a tilt-wing aircraft is very sensitive to several design parameters, such as the type of flaps, control strategy, position of the proprotors along the wing and the wing geometry itself. All these aspects are essentially related to the different interaction between the proprotor slipstream and the freestream aerodynamics of the wing. Thus, with the intent of keeping the analysis as general as possible and account for the worst scenario, the power required during the transition will be considered as equal to that required to hover. In reality, the reader shall consider that the actual power budget during the transition shall in fact be reduced with a proper design of the aircraft [19], [22].

B. Climb

For a climb phase, a simplified form of the equations of motion can be expressed according to [15] as the summation of forces acting in the longitudinal plane of symmetry of the aircraft and referred as parallel and perpendicular to the flight path:

$$\begin{aligned} m\left(\frac{dV}{dT}\right) &= \quad T\cos\left(\phi_T+\alpha\right) - D - W\sin\gamma \\ m\left(\frac{V^2}{r}\right) &= \; -T\sin\left(\phi_T+\alpha\right) - L + W\cos\gamma \end{aligned} \tag{2}$$

where ϕ_T is the thrust line incidence, α is the angle of attack (AoA) of the aircraft and γ is the climb angle. Assuming a straight unaccelerated climb, small AoA and thrust line incidence, the following simplifications can be introduced

$$\begin{array}{lll} \alpha+\phi_T \approx 0 & \rightarrow \cos(\alpha+\phi_T) & \approx\ 1.0, \\ & \rightarrow \sin(\alpha+\phi_T) & \approx\ 0.0, \\ \gamma \leq 15^\circ & \rightarrow \cos\gamma & \approx\ 1.0. \end{array} \tag{3}$$

Consequently, Eqs. (2) can be expressed as

$$\begin{aligned} T &= D + W\sin\gamma \\ L &= W \end{aligned} \tag{4}$$

Consequently, using Eqs. (4), recalling the definition of lift and drag, the equation of thrust can be easily expressed as

$$T_{cl} = W \cdot \left(\sin\gamma + \frac{C_D}{C_L}\right) \tag{5}$$

and the power required during climb P_{cl} as

$$P_{cl} = \frac{1}{\eta_P} T_{cl} V_{cl} = \frac{1}{\eta_P}\sqrt{\frac{2W^3}{\rho S C_L}} \cdot \left(\sin\gamma + \frac{C_D}{C_L}\right) \tag{6}$$

C. Cruise

For a cruise phase, Eqs. (4) can be simplified considering the climb angle equal to zero and straight unaccelerated flight, therefore

$$\begin{aligned} T &= D \\ L &= W \end{aligned} \tag{7}$$

The equation of thrust can than be expressed as

$$T_{cr} = \frac{1}{2}\rho V_{cr}^{2} S C_D \tag{8}$$

and the required power as

$$P_{cr} = \frac{1}{\eta_P} T_{cr} V_{cr} = \frac{1}{2\eta_P}\rho V_{cr}^{3} S C_D \tag{9}$$

IV. HYBRID-ELECTRIC SYSTEM ARCHITECTURE

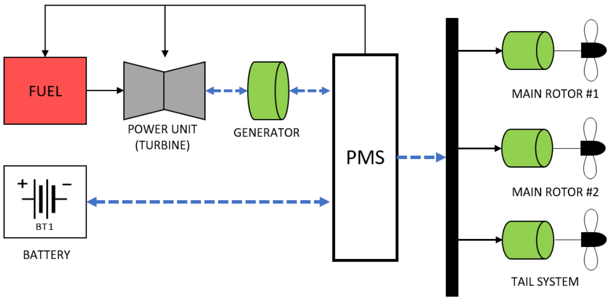

Fig. 6. A conceptual scheme of the hybrid system

A. The concept architecture

In this work the hybrid system shown in Fig. 6 is considered: the architecture shall resemble that of a tilt-wing aircraft with two main propellers-rotors and a tail blower/rotor which produces thrust to counteract the pitching moment generated by the aircraft's aerodynamics during hover and transition to forward flight. As briefly introduced in the previous section of this paper, the hybrid system consists of a turbine engine (for the sake of brevity this will be shortly called turbine from now on in the paper) that acts like a power unit providing mechanical power to drive a generator and produce electrical power. The turbine has no mechanical link to the propellers and the propulsion system is meant to be fully electrical. The mechanical power delivered by the turbine and converted into electrical power by the generator is instead managed by a Power Management System (PMS). The PMS manages the interaction between the generator and the battery depending on the battery's state of charge and the flight condition. The scope of this paper is not to describe in detail how such a PMS shall work, rather include this hybrid powerplant concept into the estimate of the flight performance of a tilt-wing aircraft, therefore an interested reader shall refer to [9] for examples of experimental aeronautical application of such a technology but also to [8], which is instead related to naval applications but provides useful insights into how similar hybrid-systems work.

B. Assumptions and Simplifications

For the sake of simplicity, in this paper the concept will be instead simplified as the following:

- to lower the carbon-emissions and the noise level in populated areas, take off, landing, hover and transition to airplane mode can be performed setting the turbine to a minimum and relying on the battery to supply most of the required power to the propulsion system;
- after transition to airplane mode, therefore generally during climb, cruise and descend, the turbine works at a constant maximum regime and generates enough power to sustain flight and fully recharge the battery;
- once the battery is fully charged ad the aircraft flies in airplane mode, the turbine adapts to supply enough energy to sustain flight.
- the hybrid system is sized based on the power required to generate the aerodynamic forces to sustain flight; the additional power needed by other aircraft systems is neglected and meant to be a fraction of the required power; a more detailed study will be the object of a forthcoming paper.

C. Battery

Some assumption shall be made on the overall characteristics of the battery system. For the task at hand, specific considerations on the internal chemistry are neglected, but a generic Lithium Polymer (Li-Po) battery is considered, with the following specifics:

- maximum charge rate of 5-C
- maximum discharge rate of 12-C
- energy density of 0.24 kWh/kg

The characteristics listed above shall be considered optimistic based on current state-of-the-art, but may well be in line with the forecasts for the advancement of the battery technology during the new decade, as reported by Thalin in [23] and Kuhn in [12] and [13].

D. Turbine Engine

Hybrid-electric powerplants are bound to make use of highly customized gas turbine engines, several companies are currently putting a considerable effort in developing solutions for such a specific application and very little performance data is currently available on public domain. For the sake of this paper and with the mere intent to analyse the hybrid-powerplant as a concept, a generic aeronautical gas-turbine engine was considered and according to [16], a general law was derived based on the engine size (max available power) and as a function of the delivered power. Given the engine size, the generic equation of the fuel mass flow $\dot{m}_f$ can be expressed as a function of the required power P_{req}:

$$\dot{m}_f = a_5 P_{req}^5 + a_4 P_{req}^4 + a_3 P_{req}^3 + a_2 P_{req}^2 + a_1 P_{req} + a_0 \tag{10}$$

Eq. (10) allows to enter a Required Power value in SHP and get the fuel flow in kg/s. As reported in [16], the equation coefficients a_0, a_1, a_2, a_3, a_4, a_5 depend on the size of the engine and are based on the fitting on the swiss Federal Office of Civil Aviation (FOCA) own engine test data and on confidential engine manufacturer data (which are therefore not published together with corresponding engine names, only the final fitting parameters are available). Furthermore, the gas turbine installed power is generally referred to as the Mean Sea Level value P_{MSL} and shall be corrected with altitude to account for the change in air density. According to [26], the available power can be modelled as

$$P_{av} = P_{MSL} \cdot \left(\frac{\rho}{\rho_0} \right) \tag{11}$$

where ρ is the air density at the given altitude and ρ_0 that at sea level.

V. HYBRID SYSTEM ANALYSIS

In this study the hybrid system concept is analysed with a focus on the impact of specific emergency constraints on the overall sizing of the system. As previously introduced, the system is supposed to allow the discharge of the battery to provide additional power to the propulsion system when the required power exceeds what provided by the turbine engine, and the recharge of the battery up to its maximum capacity when in flight an excess of power becomes available. According to this logic the State of Charge (*SoC*) of the battery can be computed for each flight phase and mission profile. Furthermore, the resulting *SoC* can be compared to an Emergency Minimum State of Charge (SoC_{EM}) of the battery, which can be used to define a safety constraint for the sizing of the battery and the turbine engine.

A. Definition of the Emergency Requirement

At this step, an extensive discussion should be carried on how the SoC_{EM} should be defined: evident is the need for a systematic safety analysis to identify the proper drivers in the definition of the emergency requirements. For the sake of this paper, given the focus on the hybrid system and the interesting correlation between the SoC_{EM} and the overall system size, the specific case of the turbine engine failure is considered: in a tilt-wing hybrid electric aircraft, an engine failure shall at least allow the aircraft to be landed safely in both helicopter and airplane mode. When an engine failure occurs, no excess of power is available anymore and the battery becomes the sole power source to sustain flight until landing. Depending on the flight mode (helicopter or airplane), the emergency requirement will differ in terms of time span and amount of required power. For the task at hand, in the event of failure of the gas turbine, the following shall be granted:

- in helicopter mode, the battery *SoC* shall be sufficient to allow the descent from the ceiling altitude ($h_{max,h} = 2500\,m$) to the ground in $t_{EM,h} = 8\,min$;
- in airplane mode, the *SoC* shall be sufficient to allow the descent from the maximum altitude ($h_{max,a} = 3048\,m$) to the ground in $t_{EM,a} = 6\,min$;

B. Description of the study

The performed study is rather simple but the authors believe it serves the useful purpose of highlighting the correlation between the SoC_{EM} and the sizing of a hybrid system. The study is performed according to the following procedure:

- according to what described in the previous section of this paper, the required power P_{req} is computed along the mission profile;
- consequently, the required power is compared with the available power at each instant of the mission and the difference ΔP is computed as

$$\Delta P = P_{av} - P_{req} \tag{12}$$

- when $\Delta P < 0$, the *SoC* decreases at a rate which cannot exceed the maximum discharge rate (12-C); $\Delta P > 0$, the *SoC* increases up to the maximum capacity Q_{batt} at a rate which cannot exceed the maximum charge rate (5-C). The *SoC* is computed for each time step as

$$SoC_i = SoC_{i-1} + \frac{\Delta P}{Q_{batt}} \cdot \Delta t_i \tag{13}$$

- at each time step along the mission, the SoC_{EM} is computed according to the required power, the altitude and the flight mode, therefore

$$SoC_{EM} = \frac{P_{req}}{Q_{batt}} \cdot \frac{h}{h_{max}} \cdot t_{EM} \tag{14}$$

- based on the chosen configuration (gas turbine power size and setting, and battery size), *SoC* and SoC_{EM} are compared to assess whether the system satisfies the design constraint ($SoC > SoC_{EM}$ along the whole mission) or not ($SoC < SoC_{EM}$) at least in one point along the mission);

The procedure was applied to obtain the initial baseline configuration of the hybrid system, together with the additional constraints on the battery capacity described above in this paper. The baseline configuration is the following;

- the turbine-engine is sized for a maximum available power equal to half the estimated required power in helicopter mode at the ceiling altitude;
- the battery is sized for an energy capacity which allows to provide all the power required by the rotors to sustain a hover condition at ceiling altitude for 5 minutes to full discharge.

At this point an additional analysis is performed to assess to what extent the use of the turbine can be reduced in specific flight missions. Two examples alternative configurations are here reported in which the power setting is varied when operating in helicopter mode:

1) in the first case, the power setting is kept constant and the gas turbine is assumed to always provide the

power at maximum efficiency, unless the battery is fully charged and the power request decreases (fig. 7);

2) in the second configuration the turbine power setting is limited to 55% when the aircraft is operating close to the ground in helicopter mode (fig. 8);

Both configurations are tested for all of the 3 mission profiles. The scope of the analysis is to evaluate the degree of hybridization that can be achieved by the system based on the power required by the aircraft and the imposed emergency constraints.

C. *Results*

The study is carried using a set of routines that allow to compute the power budget for each flight phase and mission profile, given the overall hybrid-system parameters and emergency constraints. The level of complexity of the analysis can be increased and transient behaviours might be included, but only a simplified analysis is shown here. The results are shown in Fig. 7 and 8. Based on the assumptions made and the system parameters used, the following results can be highlighted:

- Fig. 7 shows that a relevant amount of energy shall be always stored in the battery for emergency scenarios, meaning that since the battery's weight remains constant along flight from take off to landing, the emergency constraint imposes a relevant limit on the aircraft overall mass breakdown and can limit the payload capability, compared to conventional fuel powered aircraft; in this sense, the most demanding mission is the point to point cruise.
- Fig. 7 also shows that a system sized as described above meets the imposed emergency constraints as long as the the gas turbine is kept at the maximum power setting;
- As shown in Fig. 8, however, by lowering the turbine power setting to 55% during close-to-ground operations, the limit to the system set by the emergency constraint is reached.
- Fig. 8 also shows that the limit is not posed by the mission profile requiring the higher average SoC_{EM} (Point-to-Point Cruise), rather by those involving a higher number of phases performed in helicopter mode (EMS Transfer Flight, Advanced Rescue).
- Fig. 8 shows that the system cannot perform fully electrical take off and landings in helicopter mode during more demanding missions such as EMS Transfer Flight and Advanced Rescue.

VI. CONCLUSIONS

A. *Limits to VTOL Aircraft Electrification*

The presented work offers a practical, preliminary methodology to evaluate the performance of a conceptual hybrid electric powerplant for tilt-wing aircraft applications. Although more detailed analysis can be performed at a later time, several additional requirements included and a more detailed modelling used to properly design the real system, this study explains the strong impact of the emergency requirements on the size of a hybrid system and highlights how a fully electric propulsion is, at the current state of technology well described by Hepperle in [6] and to the best knowledge of the authors, very unlikely to be implemented

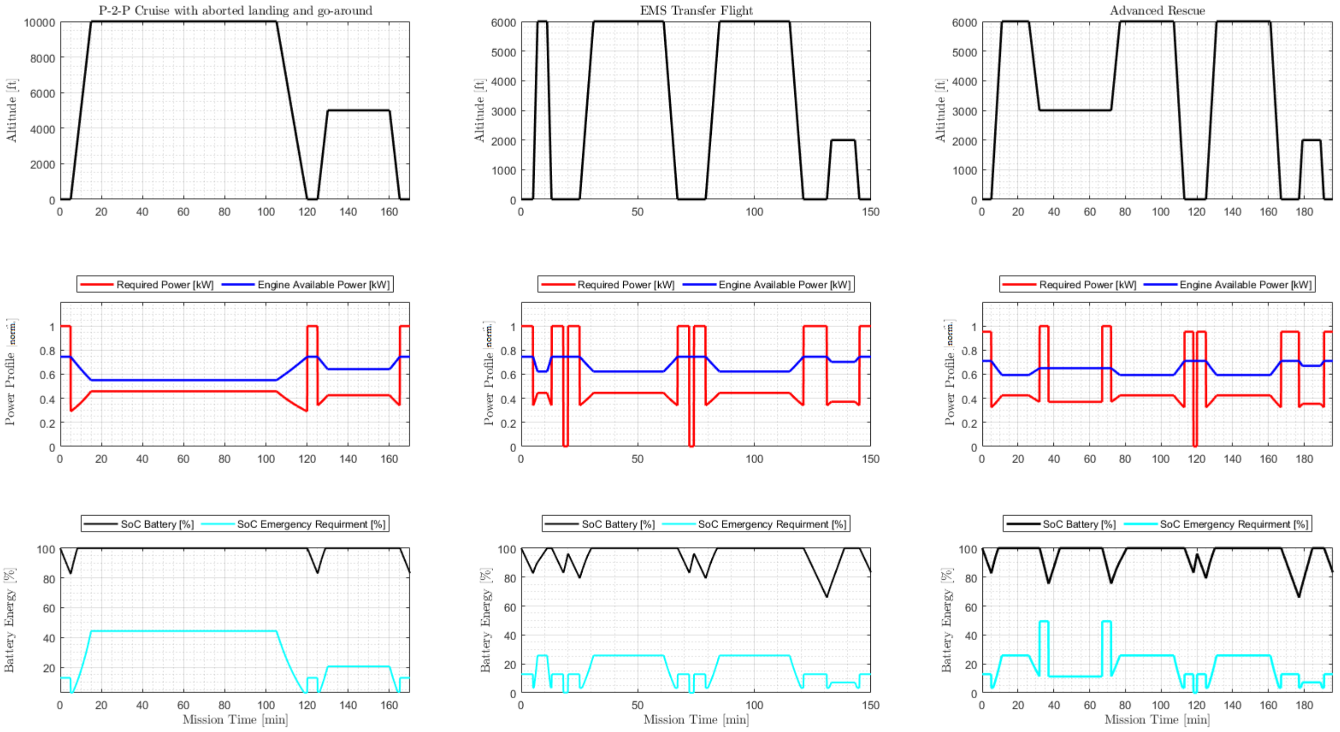

Fig. 7. Power Management Analysis with Constant Max Power Setting of the Gas Turbine when operating close to the ground

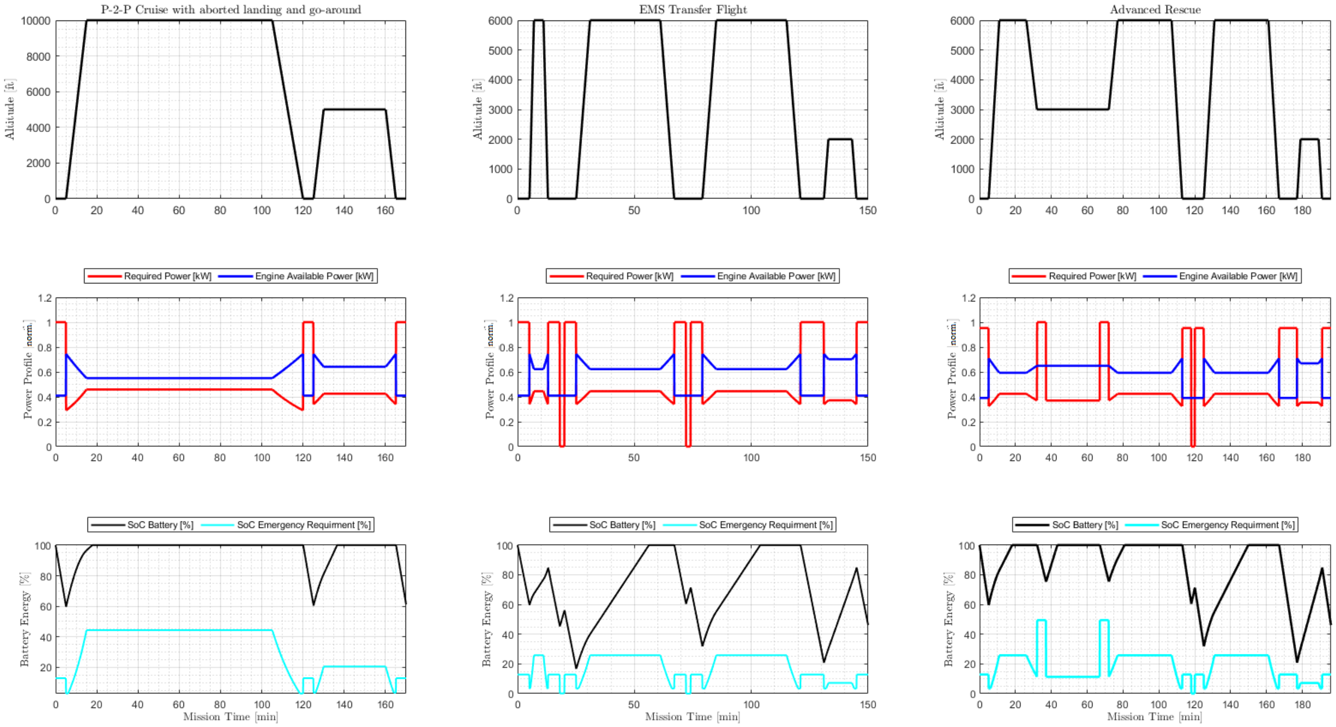

Fig. 8. Power management analysis with reduced power setting of the turbine when operating close to the ground

on VTOL platforms that require mid-range capabilities and enhanced low speed manoeuvrability. On the other hand, hybrid-electric technology, if properly designed and implemented, may well be the right path to follow towards improved electrification of general aviation. Furthermore, as shown by the results of the study, hybrid technology applied to tilt-wing can allow a significant reduction of the size of the conventional gas turbine compared to what currently implemented on conventional helicopters and therefore turn convertiplanes into appealing solutions which can challenge the helicopter concept in several regional-mobility applications among which Emergency Medical Services, in spite of their unquestionable complexity and their possibly worse low-speed maneuverability [1], [19].

B. *Impact of the aircraft architecture on the hybrid system*

According to the Required Power profile for each analyzed mission, the most demanding flight phases are those performed in helicopter mode, therefore those in which the positive effect of the aircraft aerodynamics can be poorly exploited. In this perspective, the authors believe that a tilt-wing architecture such as the one presented in this paper better suits the hybrid-electric technology since the helicopter envelope is limited to the take-off, hover and landing phases, while the much more aerodynamically efficient airplane mode can be exploited for the rest of the mission. This particular aspect, from an overall efficiency point of you, make the tilt-wing aircraft more convenient than alternative multicopter or conventional helicopter-like options. On the other hand, the use of multiple rotors, with smaller radius and higher disk-loading is likely to reduce the efficiency of the aircraft during hover if compared to conventional helicopters [24]. For this reason, the authors believe that the use of more and smaller rotors might affect the overall required power and therefore the hybrid electric configuration, yielding to an over sizing of the system, compared to the two-rotors configuration presented in this paper.

C. *Limits of of the study and future developments*

The analysis involves relevant simplifications and a limited consideration of the actual efficiency of the whole powerplant. Furthermore, as also reported in [25], several are the design implications and the safety critical aspects which would make difficult to derive a general guideline for all tilt-wing aircraft. Nevertheless, studies involving more detailed simulation models are being performed by the authors and will be used to extend and improve this analysis.

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