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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Preliminary design of hybrid-electric VTOL air vehicle with multiple ducted fans

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

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1. Introduction

Hybrid-electric technology combined with distributed propulsion enables the investigation of new aircraft concepts to meet the ever-changing needs of modern aviation. In the near future, Urban Air Mobility (UAM) will be achieved with Vertical Take-Off and Landing (VTOL) solutions.

The scope of this work is to introduce a parametric model of such an aircraft. Existing procedures described in the literature do not include vertical take-off or hovering segments as sizing conditions for ducted fans, whose very low Mach numbers require special attention. Electrical power is provided by batteries and a turbogenerator, whose mathematical model is also proposed. A typical UAM mission is composed of vertical flight segments like take-off, landing and hovering, whose power estimation formula is studied. Such methodology is then applied on a customized version of Pacelab APD [2], a commercial preliminary design software for aircraft. The case study has as baseline design the model ANN2 by Manta Aircraft [1], a two-passengers hybrid-electric VTOL solution for regional and inter-regional air mobility with a full carbon fiber structure. Few specifications are available online and some assumptions have to be made, e.g. EIS at 2030.

2. Developed mathematical models

The focus of the preliminary design model is on the sizing of Electric Ducted Fan (EDF), turbogenerator and vertical flight segments. The targeted powertrain in fig. 1 is inspired from the case study. It is powered by eight EDFs, four of which are mounted on the fuselage fixed to provide vertical thrust and four more on the wing, which instead are tiltable to power both horizontal and vertical flight.

The mathematical model of EDFs is built from pure propulsion theory receiving flight condition as input and retrieving correspondent geometric and operational characteristics. It is modelled as a duct in which air is accelerated by an electrically driven fan (fig. 2) and it is based on a few assumptions, in detail: nozzle is neglected, fan is assumed as a 1-stage axial fan, the electric motor is sized through a power-volume-rotational speed historical relation and nozzle is adiabatic and adapted. For the sake of simplicity, items efficiencies are kept constant. Isentropic compressible theory for perfect gas and

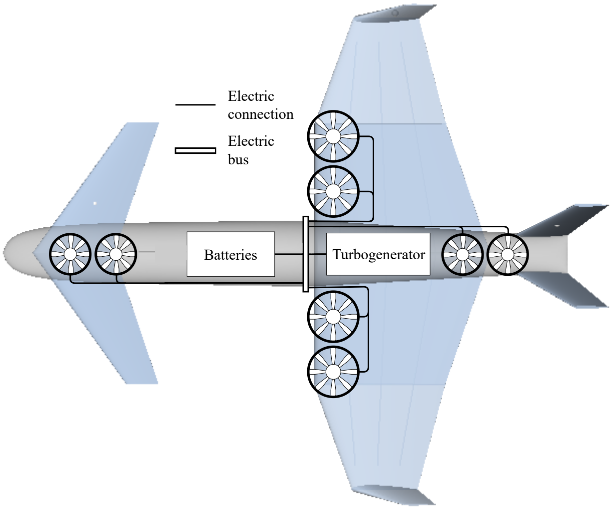


Figure 1: Hybrid-electric powertrain.

Euler equation for turbomachinery are combined into a closed set of equations.

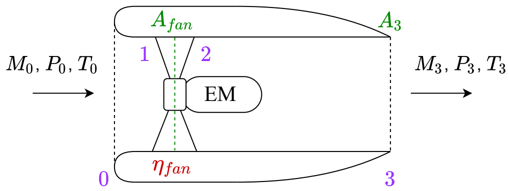


Figure 2: Electric ducted fan scheme.

This model is run twice, once for fuselage group and once for wing group, keeping vertical take-off at sea level as design condition. Moreover, a performance deck is searched, mapping thrust at different off-design flight conditions. A mixed approach is chosen: low Mach (0 - 0.1) operational points are studied with a reduced version of the same mathematical model but with fixed geometries, while higher Mach numbers (0.2 - 0.3) are simulated on Javaprop, an open source tool for propeller and ducted fan analysis. This decision is taken due to the impossibility to simulate static and quasi-static flight on Javaprop and, on the other hand, the increase of inaccuracy of the mathematical model the further from design condition.
Turbogenerator is a combination of turboshaft, modelled as a simple Joule Brayton cycle, and electric generator, assumed with constant efficiency. The idea is to set cruise point as design condition and let batteries cope with the defect of available power in other flight segments. A Specific Fuel Consumption (SFC) map is achieved, together with a mass estimation based on design power coming from literature data.
As already anticipated, the case study is intended for UAM operational scenario. In fig. 3 an example of design mission is proposed, combining both literature and market studies with aircraft specifications. Vertical rate of climb and descent is set at 500 fpm and cruise is performed at 3000 ft with 2 hours endurance at 300 km/h. Two hovers are flown, each of 3 minutes.

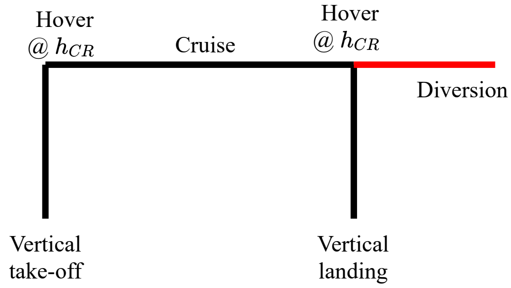


Figure 3: Urban air mobility mission.

Power requirement in vertical flight segments is estimated from [3]: applying momentum theory it is possible to find an expression dependent on weight (W), total rotor area (A), vertical rate of climb (V_{VROC}), fuselage downwash, approximated with a coefficient (f) and density (ρ).

$$P = \left[\frac{fW}{c_{FoM}} \sqrt{\frac{fW/A}{2\rho}} + \frac{WV_{VROC}}{2} \right] \frac{1}{\eta_{mech}}$$

c_{FoM} and η_{mech} are figure of merit and a mechanical efficiency respectively, as suggested by [3].

3. Application on APD

The first step in model implementation is the geometrical representation of the case study on APD, starting from few specifications inspired from the baseline design [1]; the result is shown in fig. 4. The software is subsequently customized: EDF, turbogenerator and vertical flight segments are coded and implemented in APD Knowledge Designer. In more detail, EDF engineering object is created taking inspiration from the electric propeller powerplant, already available, and adding the duct and whatever that implies, e.g. contribution to

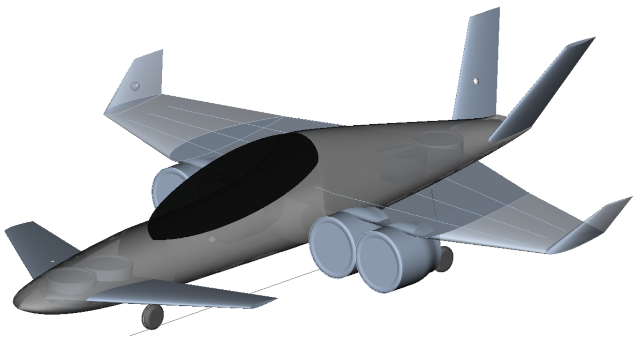


Figure 4: Case study on APD.

wet area computation. The previous mathematical model defines inputs parameters to APD like reference power, RPM, shape and thrust map. The turbogenerator is instead considered as fuel cell, already implemented in current APD version. Producing both electrical power out of fuel consumption, it is sufficient to insert reference power, SFC map and mass formula obtained earlier.

Vertical take-off (VTO), anding (VLND) and hover (HOV) are coded. The mathematical model is inserted to compute point performance in terms of power, thrust, fuel consumption, battery State Of Charge (SOC), etc. Eventually, the requirements are set up in APD and the mission is built like shown in fig. 5.

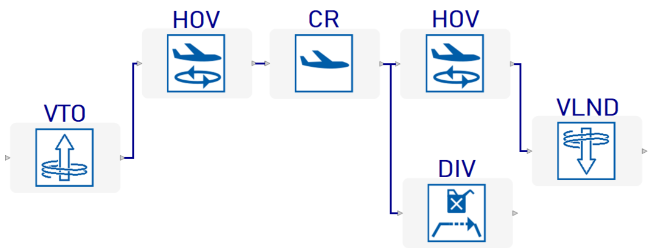
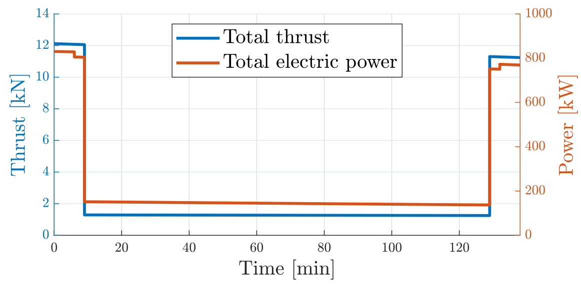


Figure 5: Design mission on APD.

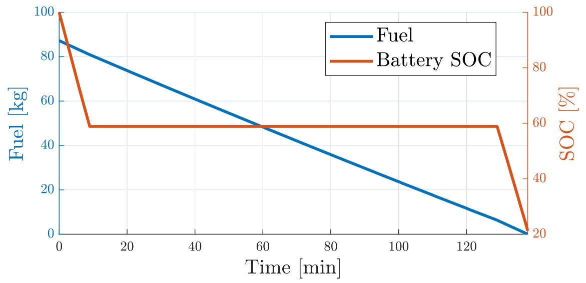
For mass estimation, structure and subsystems follow traditional methods for commercial aircraft, due to the absence of a tailored method for UAM applications. Since the case study has a full composite structure, factors are used to calibrate mass estimation [3].

3.1. Results

A solution is found on APD accounting of 1204.5 kg of Maximum Take-Off Weight (MTOW), with 90 kg fuel and almost 600 kg batteries. This huge amount of battery pack is needed because the turbogenerator is sized at cruise and the difference between power requirement in cruise and vertical flight is great, as visible in fig. 6a. In fig. 6b it is visible how batteries are not consumed during cruise and fuel instead has an almost constant consumption rate, since turbogenerator operates at fixed continuous power and SFC is only slightly effected by the small altitude range explored (0 - 3000 ft). End SOC respects the minimum of 20% imposed for optimal battery life.



(a) Total thrust and power.



(b) SOC and fuel consumption.

Figure 6: Design mission point history; cruise from minute 9 to 129.

The proposed solution does not claim to be the optimal one with respect to requirements. With APD tool it is possible to explore the design space achieving sensitivity studies and finding eventually new possible solutions. As example, a sensitivity study on battery nominal energy and turbogenerator power is run and the resultant MTOW graph is shown in fig. 7.

4. Conclusions and future outlook

The present work has achieved a preliminary design model for hybrid-electric VTOL aircraft with multiple ducted fans for a typical UAM design mission. Sizing procedures of EDFs and turbogenerator are applied on a case study, tak-

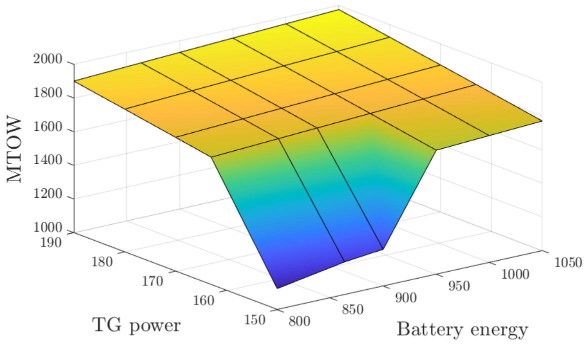


Figure 7: Sensitivity study on APD.

ing inspiration from model ANN2 by Manta Aircraft, based on power requirement in vertical flight. The model is reproduced on Pacelab APD, a tool for aircraft preliminary design, which is customised adding EDF, turbogenerator and vertical flight segments engineering objects. Finally a feasible design is found with 1204.5 kg of MTOW.
However, it is important to notice the main approximations and assumptions that have been done throughout the study, in order to inspire future developments:

- the performance deck for EDF thrust could be simulated more properly on one software capable of computing performance also at static conditions and, maybe, expanding the range of explored flight conditions;
- there is the need of a tailored mass method for UAM category, which is difficult now to create due to its infancy of Technology Readiness Level (TRL);
- the peculiarity of case study configuration would require a proper aerodynamic simulation, also for a better estimation of the fuselage downwash effect;
- finally, it would be interesting to explore different power management solutions, for example opening to the possibility of recharging battery in flight and see its effect in mass breakdown.

5. Acknowledgements

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