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

Tesi di Laurea Magistrale in
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*Ti auguro che la tua direzione non*
*rimanga soltanto un disegno sulla mappa.*

*(I wish you that your direction does not*
*remain just a drawing on the map.)*

# Abstract

Modern aviation has been focusing on hybrid-electric propulsion since few years, trying to decrease atmospheric and acoustic pollution hence increasing social acceptance. New technologies enable also the investigation of new aircraft concepts like Electric Vertical Take-Off and Landing (eVTOL) for urban air mobility.

The present work focuses on the preliminary design of a hybrid-electric Vertical Take-Off and Landing (VTOL) with multiple ducted fans, suggesting a theoretic sizing model and then implementing it on APD, a commercial preliminary design tool developed by PACE Aerospace Engineering and Information Technology GmbH. The mathematical model for electric ducted fans is developed from scratch starting from pure propulsion theory receiving flight condition and retrieving correspondent geometric and operational characteristics. In addition to the design condition, chosen to be vertical take-off, off-design thrust map is built and then used to simulate the mission. The targeted powertrain is completed with a turbogenerator, modelled as a simple turboshaft combined with an electric generator. After having designed it at cruise condition, a specific fuel consumption map is retrieved. A typical urban air mobility operational framework is considered when building the design mission, composed by vertical take-off, hover, cruise and vertical landing, as suggested by market analysis. Power requirement in vertical flight segments is also estimated.

An example of the developed model application is proposed on APD, taking inspiration from existing prototypes on the market. It presents a hybrid electric powertrain with eight ducted fans and a full composite airframe. The mathematical model is coded on a customized version of APD, having implemented the missing engineering objects. The design mission is then simulated and analysed, eventually suggesting a feasible aircraft solution.


**Keywords:** predesign, eVTOL, hybrid-electric, ducted fan, personal air vehicle, urban air mobility

# Abstract in lingua italiana

Negli ultimi anni, la propulsione ibrido-elettrica è stata al centro dell'aviazione mondiale: diminuendo l'impatto atmosferico e acustico, sarebbe possibile esplorare le sue applicazioni all'aviazione urbana e, in questo contesto, proporre nuovi concetti e configurazioni di velivoli elettrici come, ad esempio, i velivoli Vertical Take-Off and Landing (VTOL).

La presente tesi si concentra sul design preliminare di un aereo VTOL ibrido elettrico multi-fan, suggerendo un approccio teorico di dimensionamento e applicandolo ad un caso studio su APD, un software commerciale sviluppato da PACE Aerospace Engineering and Information Technology GmbH per il dimensionamento preliminare di velivoli. Grazie al modello matematico sviluppato è possibile definire la geometria dei fan, la velocità rotazionale e la spinta al punto di design: quest'ultima viene inoltre studiata in diverse condizioni di volo per simulare un'intera missione. Il sistema propulsivo è completato dalle batterie e dal turbogeneratore, quest'ultimo modellato come turboshaft combinato a un generatore. La crociera è scelta come condizione dimensionante per il turbogeneratore ma, come per i fan, si propone una mappa di consumo specifico anche in altri punti di funzionamento. Viene quindi simulata una missione composta da decollo verticale, atterraggio verticale, hover e crociera (come suggerito dall'analisi di mercato nell'ottica della mobilità aerea urbana). È proposta inoltre una stima della potenza richiesta nei segmenti verticali.

I modelli sviluppati sono successivamente applicati ad un caso studio su APD, traendo ispirazione da prototipi presenti attualmente sul mercato. Esso presenta otto fan distribuiti sulla fusoliera e sul bordo d'attacco dell'ala, alimentati da una catena propulsiva turboelettrica e una struttura totalmente in materiale composito. APD è stato customizzato a questo scopo: dopo aver implementato le componenti mancanti rappresentando il modello matematico precedentemente creato in modo da simulare la missione, viene infine suggerita una possibile soluzione di design preliminare.

**Parole chiave:** predesign, eVTOL, ibrido-elettrico, fan, personal air vehicle, urban air mobility

# Contents

# 1 | Introduction

Hybridization in the aerospace world has been investigated for quite a few years and, thanks to recent technology developments, new aircraft concepts are becoming feasible in the near future. Once noise and air pollution are reduced, Electric Vertical Take-Off and Landing (eVTOL) aircraft will be accepted also for Urban Air Mobility (UAM). Most of the time their powertrain presents distributed propulsive concepts enabling the management of propulsion engines in a more flexible and differential way. Power source can be hybrid-electric or, when battery technology development will be advanced enough, fully electric.

The present work fits this research framework, suggesting a preliminary design approach for eVTOL with multiple ducted fans. The proposed procedure starts from UAM mission requirements and aims at vertical take-off as design condition.

## 1.1. Motivation

Traditional aircraft configurations have consolidated preliminary sizing procedures adjusted over the years thanks to experience and tailored for different applications, e.g. military, commercial or general aviation. When it comes to new solutions, however, a great amount of uncertainty is still present due to the lack of empirical data on innovative concepts. To fill this gap, researches and experiments have been done and several approaches are proposed with different levels of accuracy and stability. The final aim is to arrive to a robust method as for traditional designs, even if it's a long road ahead.

The new eVTOL presents two, so to say, innovation items: electric propulsion and vertical flight. Nowadays different solutions exist on the market. One can cite Joby Aviation, Lilium and Manta Aircraft as examples of UAM concepts presenting multiple Electric Ducted Fans (EDFs) for vectored thrust in horizontal and vertical flight. In particular, model ANN2 by Manta Aircraft will be considered as a baseline design. Ducted fans present the following advantages [7, 11]:

- an increased flexibility of location and compactness: they can even be embedded in the aircraft structure, e.g. the wing trailing edge or the fuselage;

- high aerodynamic efficiency at low speed, optimal for vertical take-off and hovering, due to the absence of blade tip losses;
- low acoustic impact, thanks to the duct that shields the blade noise;
- better protection of blades from debris compared to open propellers.

Even if only low subsonic condition is discussed in the present work, EDF can be applied also in large commercial aircraft for high subsonic flight. Paper [24] presents an interesting study of the aerodynamic effects of distributed EDFs with respect to different possible configurations in high subsonic application and [21] applies a sizing procedure for a large passenger aircraft with distributed fans mounted on wing trailing edge.

## 1.2. Workflow and thesis organisation

The present thesis is a result of a six-month collaboration with Politecnico di Milano and PACE Aerospace Engineering and Information Technology GmbH which is based in Berlin. The workflow is reflected on the report organization.

1. First of all, a literature and market research is undertaken, exploring the state of the art of hybrid-electric ducted fan propulsion and vertical flight in order to define the contribution and the motivation of the thesis;
2. software Pacelab APD (section 1.2.1) is decided as workbench for model application, choosing model ANN2 by Manta Aircraft as case study guideline;
3. preliminary design models for electric ducted fans, turbogenerator and vertical flight segments are defined (see chapter 2);
4. the new propulsion and mission engineering objects are implemented on APD, customizing the software for the case study (section 3.2);
5. lastly, a final solution is found and design space is explored through a sensitivity study (section 3.3).

### 1.2.1. Pacelab APD

The theoretical model is validated on Pacelab Aircraft Preliminary Design (APD) tool [13]. It is a software provided by PACE which supports aircraft modeling, sizing, analysis and optimization in their conceptual and preliminary design phases. It supports a fast and multi-level evaluation of a wide range of possible aircraft configurations. A vast library of ready-to-use aircraft models and methods is extensible and available to customization in order to include new and innovative case studies.

Pacelab APD is composed by two main applications:

- *Pacelab APD Knowledge Designer*, fig. 1.1, where engineering knowledge components are built, combining knowledge methods and parameters and creating a local database of reusable items; a set of knowledge components are already implemented like the single segments of a mission (cruise, take-off, ...) or propulsive units;
- *Pacelab APD Engineering Workbench*, fig. 1.2, where the assembly of knowledge components is made for analysis and design space optimization; in practical terms, this is the application where the aircraft is built and its performances are studied.

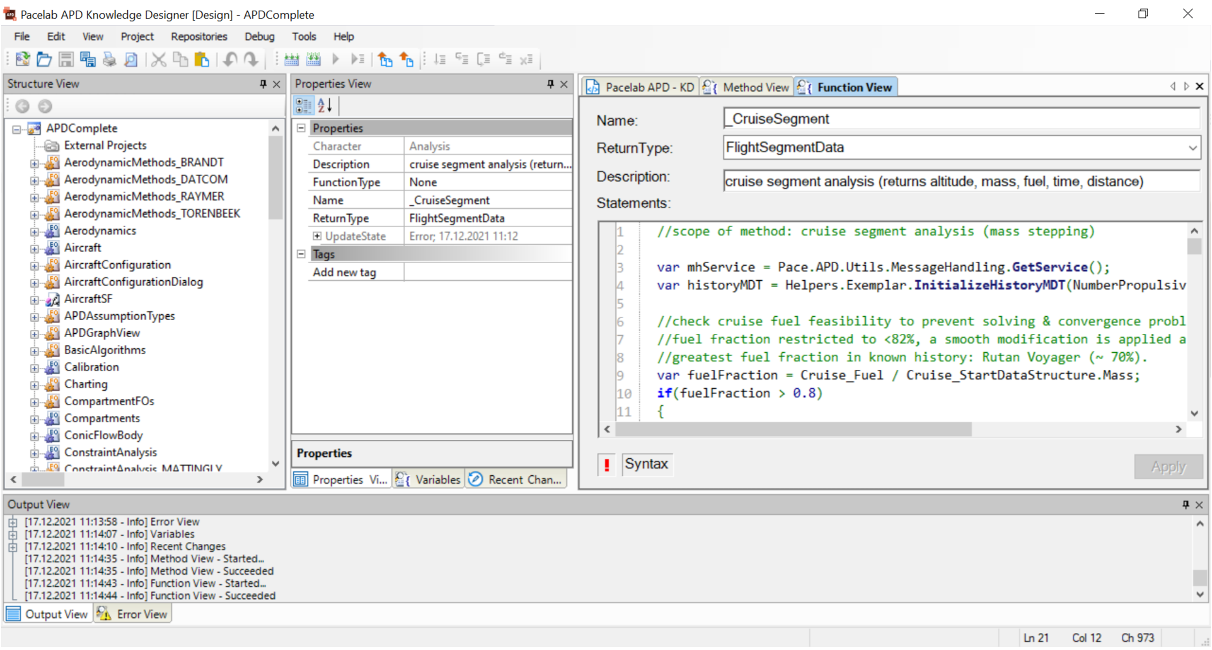



Figure 1.1: Pacelab APD Knowledge Designer.

Version 8.0.1 of Pacelab APD is used and it's documentation can be found in [14].

Pacelab APD is just one of the three solutions for predesign support developed by PACE. As pictured in fig. 1.3, Pacelab is composed by *Pacelab Suite* [16] and *Pacelab SysArc* [17]. The first provides basic functional ad procedural infrastructure for model-based multidisciplinary design, while the latter focuses on system architectures and failure modes.

## Customization

For the purpose of this work a few items are created or customized on Pacelab APD. First of all, the Vertical Take-Off and Landing (VTOL) and Hover (HOV) mission segments are

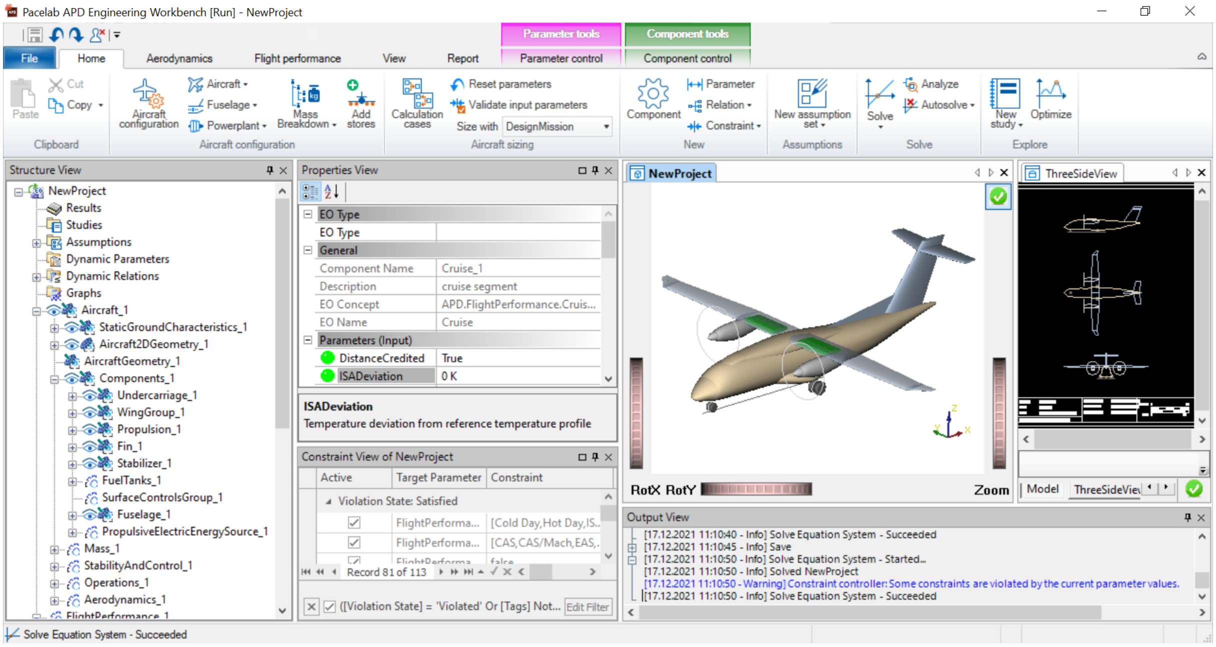



Figure 1.2: Pacelab APD Engineering Workbench.

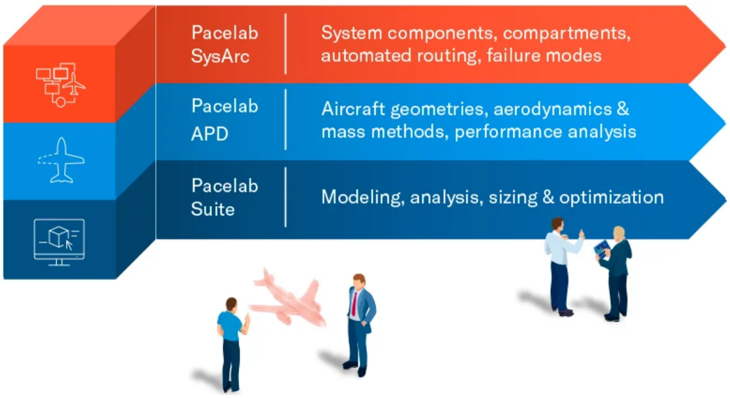



Figure 1.3: Structure of Pacelab solutions for predesign, taken from [15].

implemented to represent a typical targeted mission. Then the propulsion is customized: EDF engineering concept is created and turbogenerator (turboshaft coupled with electric generator) is modeled with a performance deck. More details on implementation and customization of the software can be found in the dedicated section 3.2.

# 2 | Developed mathematical models

In this chapter the preliminary sizing model for a Hybrid Electric Vertical Take-Off and Landing (HeVTOL) aircraft with multiple ducted fans is proposed. Starting from market requirements, a mission is defined and the propulsion system is sized for a preliminary study. The mathematical model aims at the definition of geometries, masses and power at design condition and, where possible, the exploration of off-design points that will be inserted in the APD in next chapter.

As previously anticipated, the case study takes inspiration from model ANN2 by Manta Aircraft, so it will be used as guideline in the creation of the mathematical model. It is powered by a distributed turbo-electric propulsive architecture shown in fig. 2.1. More details about the configuration are discussed in section 3.1.

The focus is on the following items:

- EDF;
- turbogenerator;
- vertical flight segments.

Entry In Service (EIS) is assumed to be 2030 and batteries are sized accordingly. No mathematical model will be discussed in the present work for those items, but whoever is interested could take a look into [2].

## 2.1. Electric Ducted Fan (EDF)

Electric Ducted Fan (EDF) is modeled as a duct in which air is accelerated by a fan, driven by an Electric Motor (EM). Just a few examples of EDF sizing exist in literature, such as the ones proposed by Jin et al. [7] and Sgueglia et al. [21]. The first study applies the actuator disk theory for the fan and an historical regression between power, volume and rotational speed for the Electric Motor (EM). Not only the power limitation but also the

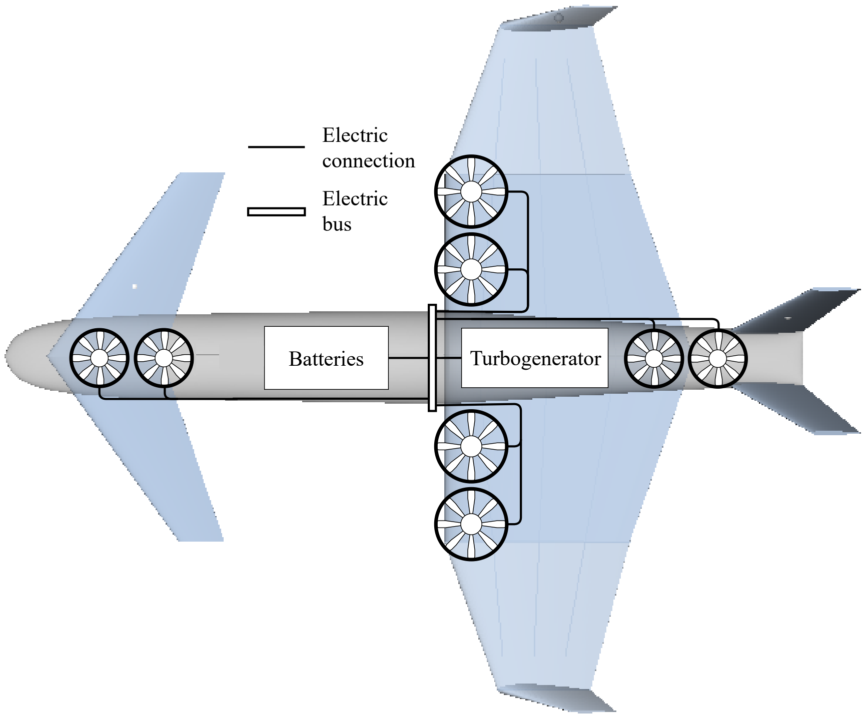



Figure 2.1: Hybrid-electric propulsion architecture of case study.

cooling problem is taken into consideration: it sets a limit in the actual achievable power density of the EDF. This approach is very interesting and straightforward, however the actuator disk theory lacks in modeling the contribution of the duct to the produced thrust. The second paper, written by ONERA and ISAE-SUPAERO, preliminary sizes a large passenger aircraft with distributed EDFs. The application is high subsonic flight (Mach 0.7), so the model is more detailed than a simple actuator disk, implying compressible theory.

The targeted case study presents a very simple mission composed by vertical take-off, hover, cruise and landing, as will be clear in section 2.3. Vertical take-off is the most requiring in terms of power requirement, so it is chosen as sizing condition. A reasonable value for vertical rate of climb, so flight speed, is 500 fpm (table 2.3), translating into a very low Mach number (0.0075) at sea level ISA condition. Setting this as the design one for EDF translates into the necessity of a new model applicable to almost zero inlet air velocity.

The following preliminary sizing model is developed for the special case of zero or almost zero inlet speed, hence for hover and vertical take-off applications. Starting from traditional propulsion theory, the general design idea is:

- inlet is not considered;

- ducted fan is modeled as a single stage axial fan, from [4];
- an historical regression is used as a relation between electric motor power, volume and rotational speed;
- nozzle is expected to be adapted and adiabatic, also from [4] theory.

Figure 2.2 is a schematic representation of a typical EDF.

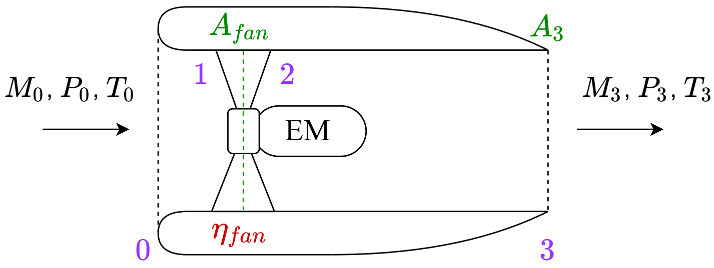



Figure 2.2: Electric ducted fan scheme.

### 2.1.1. Model inputs and assumptions

The following sizing process is based on simple and reasonable assumptions. First of all air is considered as perfect gas. Altitude, speed and power requirement are defined by the design point, which is vertical take-off at sea level in this specific case.

For the sake of simplicity at this early state of design, fan efficiency ($\eta_{fan}$) is assumed as constant. Moreover, the nozzle is considered adiabatic ($T_{t,3} = T_{t,2}$) with a total pressure loss of $\pi_{nozz}$.

$$p_{t,3} = p_{t,2} \left(1 - \pi_{nozz}\right) \tag{2.1}$$

The hub-to-tip ratio ($\sigma$) of the fan is a design parameter, hence it can be varied to explore the solution space. A typical value for this ratio is 0.3, but it can change in a range between 0.2 and 0.5 [7].

$$\sigma = r_{hub}/r_{fan} \tag{2.2}$$

Another important geometrical parameter is the ratio between the area of the fan and the nozzle.

$$A_3 = \delta A_{fan} \tag{2.3}$$

Typical value ranges for those parameters are reported in table 2.1.

Finally, the electric motor is directly connected to the fan, since no gearbox is considered, and it is installed behind the hub so that their diameters will coincide.

| Parameter | Symbol | Range |
|---|---|---|
| Fan | $\eta_{fan}$ | 70% - 90% |
| Hub-to-tip ratio | $\sigma$ | 0.2 - 0.5 |
| Nozzle-fan section ratio | $\delta$ | 0.7 - 1 |
| Nozzle total pressure loss | $\pi_{nozz}$ | 1% - 3% |

Table 2.1: Typical values for EDF parameters [4].

The outputs of main interest are of both geometrical and operative nature. In particular dimensions of nozzle, fan and electric motor are obtained, along with shaft rotational speed and thrust.

### 2.1.2. Method

As previously enunciated, inlet is considered as negligible since it is expected to be very short with respect to the whole duct. Consequently static and total quantities at station 1 coincide with station 0. After applying ISA atmosphere model to get static pressure, temperature and Mach number, total quantities are found:

$$T_{t,1} = T_{t,0} = T_{s,0}\left(1 + \frac{\gamma - 1}{2}M_0^2\right) \tag{2.4}$$

$$p_{t,1} = p_{t,0} = p_{s,0}\left(1 + \frac{\gamma - 1}{2}M_0^2\right)^{\frac{\gamma}{\gamma - 1}} \tag{2.5}$$

Fan Pressure Ratio (FPR) defines the total pressure increment produced by the fan

$$\pi_p = p_{t,2}/p_{t,1} \tag{2.6}$$

so it is strictly related to the power that must be provided.

From compressible theory it is possible to define the pressure and temperature conditions after the fan (2) as function of $\pi_p$.

$$\frac{T_{t,2}}{T_{t,1}} = \pi_p^{\frac{\gamma - 1}{\gamma\eta_{fan}}} \tag{2.7}$$

$$p_{t,2} = \pi_p \, p_{t,1} \tag{2.8}$$

Fan power, mass flow and total enthalpy variation are related as follows:

$$P = \dot{m} \, \Delta H = \dot{m} \, c_p \, (T_{t,2} - T_{t,1}) \tag{2.9}$$

Starting from axial compressor theory [4], ducted fan is modeled as single stage axial fan; fig. 2.3 presents its velocity triangle. Angles $\alpha_i$ and $\beta_i$ are respectively the deviation of absolute ($\vec{V}$) and relative ($\vec{W}$) air speed with respect to compressor axis. In particular $\alpha_1$ could be determined by the possible presence of guidance inlet vanes, but will be zero in this case thanks to the hypothesis of clean inlet flow. Angle $\beta_2$ instead is fixed by the geometry of rotor blades. At station 2, relative airspeed is the vectorial sum of inlet and rotor speed ($\vec{U}$):

$$\vec{W}_2 = \vec{V}_2 - \vec{U} \tag{2.10}$$

from which these useful scalar relations can be obtained

$$V_{\theta,2} = V_{z,2} \tan(\alpha_2) \tag{2.11}$$

$$W_{\theta,2} = V_{z,2} \tan(\beta_2) \tag{2.12}$$

$$V_{\theta,2} = U - W_{\theta,2} \tag{2.13}$$

being $z$ the axial coordinate and $\theta$ the azimuth in cylindrical reference frame. Absolute value of rotor speed is

$$U = \Omega r \tag{2.14}$$

and it is usually evaluated at middle radius in the space between rotor hub and tip ($r_m = (r_{fan} + r_{hub})/2$) as representative of the whole flow. Rotor speed evaluated at $r_m$ will be referred as $U_m$.

Euler turbine equation describes the fluid interacting with a compressor, relating specific power to flow velocity as follows:

$$\frac{P}{\dot{m}} = \Omega \, (r_2 V_{\theta,2} - r_1 V_{\theta,1}) \tag{2.15}$$

Fan radius is constant and is set to $r_m$. Substituting also the definitions of azimuth speeds

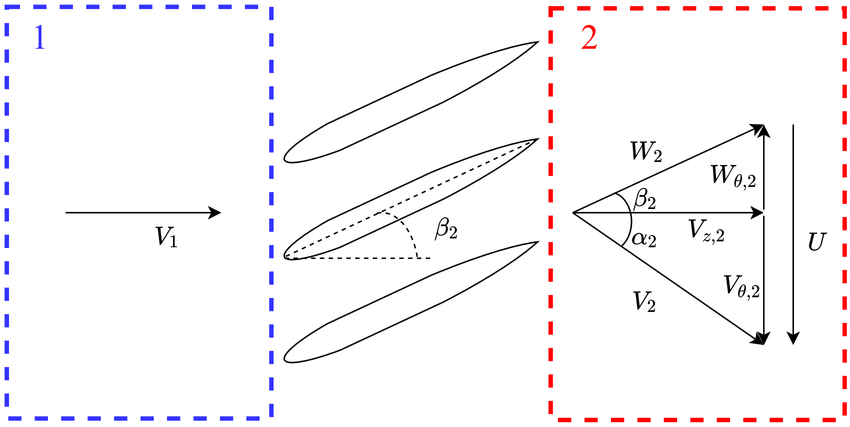



Figure 2.3: Geometry and velocities at axial rotor.

one obtains:

$$\frac{P}{\dot{m}} = U_m(U_m - V_{z,2} \tan \beta_2) \tag{2.16}$$

The available power from an electric motor is proportional to its rotational speed and volume through an historical regression

$$P_{EM} = -2.60 \, (\mathcal{V} \, \Omega)^2 + 2.92\text{e}3 \, \mathcal{V} \, \Omega - 1.53\text{e}4 \tag{2.17}$$

graphed in fig. 2.4. As can be clearly seen, the present historical regression is a little scattered; this needs to be taken into consideration later. Please note that rotational speed is expressed in rpm and volume is approximated as a cylinder of length $l_{EM}$ and radius equal to hub's:

$$\mathcal{V} = \pi \, r_{hub} \, l_{EM} \tag{2.18}$$

Length and radius of the EM can be related through a ratio which was observed empirically from the state of the art of electric motors:

$$l_{EM}/r_{hub} = 0.97 \tag{2.19}$$

Electric motor rotational speed is equal to fan's since no gearbox is considered.

Nozzle is assumed as adapted ($p_{s,0} = p_{s,3}$) and thanks to this hypothesis Mach number at exit can be found from de Saint Venant relations.

$$p_{s,0} = p_{s,3} = p_{t,3} \left(1 + \frac{\gamma - 1}{2} M_3^2\right)^{-\dfrac{\gamma}{\gamma - 1}} \tag{2.20}$$

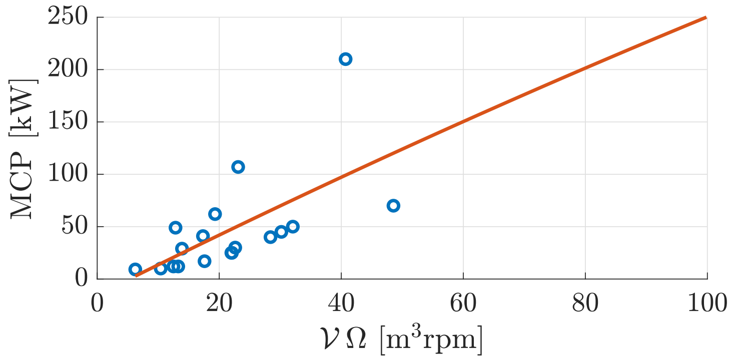



Figure 2.4: Historical regression of electric motors.

where exit total pressure $p_{t,3}$ is defined from total pressure loss parameter:

$$p_{t,3} = p_{t,2}(1 - \pi_{nozz}) \tag{2.21}$$

Assumption of adiabatic nozzle leads to the conservation of total temperature ($T_{t,3} = T_{t,2}$). Nozzle section sizes mass flow in the EDF.

$$\dot{m} = A_3 \rho_{s,3} V_3 \tag{2.22}$$

with $A_3$ exit section, $V_3$ exit speed - assuming uniform flow - and static density $\rho_{s,3}$

$$\rho_{s,3} = \frac{p_{s,3}}{RT_{t,3}} \left(1 + \frac{\gamma - 1}{2} M_3^2\right) \tag{2.23}$$

Recalling that fan and nozzle section are related through a ratio $\delta$, radii can be easily found as function of $A_3$:

$$r_3 = \sqrt{\frac{A_3}{\pi}} \tag{2.24}$$

$$r_{fan} = \sqrt{\frac{\delta A_3}{\pi(1 - \sigma^2)}} \tag{2.25}$$

Assuming mass flow conservation, axial velocity at station 2 can be found

$$V_{z,2} = \frac{\dot{m}}{A_{fan} \rho_{s,2}} \tag{2.26}$$

where static density is computed from isentropic flow equations

$$\left(\frac{\rho_{s,2}}{\rho_{s,1}}\right)^{\gamma} = \frac{p_{s,2}}{p_{s,1}} \tag{2.27}$$

$$p_{s,2} = p_{t,2}\left(1 + \frac{\gamma - 1}{2}M_2^2\right)^{-\dfrac{\gamma}{\gamma - 1}} \tag{2.28}$$

$$T_{s,2} = T_{t,2}\left(1 + \frac{\gamma - 1}{2}M_2^2\right)^{-1} \tag{2.29}$$

$$p_{s,2} = \rho_{s,2}\, R T_{s,2} \tag{2.30}$$

The model just described is composed by a set of closed but nonlinear equations, which can be solved numerically with the help of a calculus software like Matlab. The design is considered successful if thrust is greater or equal than the requirement

$$\mathcal{T} = \dot{m}(V_3 - V_0) \geq \mathcal{T}_{req} \tag{2.31}$$

As previously stated, the historical regression for EM can't be considered completely reliable, since different technologies lead to a very scattered set of data. If no better relation can be found, one can consider to set a weight in the optimization tool, to give less "importance" with respect to other equations. Another option is to set an acceptable range of offsets from that relation - for example, solution needs to stand ±10% from the line.

If the geometry is known, the designer can decide to make variable $A_3$ as an input, adjusting the ratio between nozzle and fan section as necessary. This is actually a preferred approach in engine predesign, leading to a numerically simpler problem. In this operational framework, required power is divided among eight EDFs whose dimensions are estimated by engineering judgement, representing the baseline design as reliable as possible (fig. 2.1). Having fixed the dimensions, parameters are varied inside their range (table 2.1) in order to produce a reasonable solution. The results of the design process applied to the case study are presented in section 3.1.

### 2.1.3. Model validation and performance deck

After defining the design condition of EDF, it is necessary to explore the off-design behaviour and produce a performance map, which will be implemented on APD software for the case study.

Usually, simulation software can help to validate engineering models about propulsion. Several options are available off-the-shelf, e.g. JavaProp and GasTurb, each one specializing in a different design aspect and producing more or less accurate predictions. In particular, JavaProp [6] is an open source software for the design and analysis of propellers and wind turbines, both in aeronautical and marine applications, implementing blade element theory. Ducted fan can be also preliminary sized, adding the shroud option which will suppress blade tip loss. Among the necessary inputs (design power, rotational speed, fan dimensions, ...) JavaProp requires inclination and length of the shroud. However, like GasTurb, it is not specialized in ducted fan design in static or quasi-static condition and, as a consequence, the design point could not be simulated for validation.

The performance deck is then created with the same mathematical model as presented earlier, fixing geometrical properties and varying flight condition and power input, in order to extract the correspondent thrust. In particular, the mesh of data varies in order to match an UAM mission (section 2.3.1):

- flight Mach number $M \in [0,\ 0.3]$;
- altitude $h \in [0,\ 3000]$ ft;
- input shaft power $P \in [0.5,\ 1]\, P_{ref}$.

For the purpose of APD, the searched output is thrust normalized by reference power for at least two power setting for flight condition, in order to interpolate and extrapolate data for the required thrust. Usually the inter-extrapolation is linear, but this can be changed if necessary.

JavaProp is then used to validate the mathematical model in subsonic conditions - i.e. Mach 0.2 and 0.3. A good thrust correspondence is found at 100% reference input power, matching the order of magnitude and value of normalized thrust, while greater discordance is found at lower values, when the distance from the design condition is greater. The mathematical model, in fact, underestimates the obtained thrust by one order of magnitude. The error could be caused by the several limiting assumptions of the model with respect to the simulation software; the most relevant are:

- JavaProp does a 2D estimation while the model is 1D, i.e. the EDF is modeled as a set of consequent operational and non-dimensional points while the simulation takes into account duct length and its effect;
- efficiency of the fan is constant but, in a more realistic simulation, it varies with operational condition.

Despite that, the results seem promising at design condition, so the following hybrid approach is chosen:

- at static and low speeds (Mach 0 and 0.1), where JavaProp fails to converge, the mathematical model is used;

- at higher speed (Mach 0.2 and 0.3), JavaProp data is preferred.

In this way, a preliminary performance study can be obtained in the neighbourhood of requested flight conditions. The implementation and use of EDFs and, in particular, their performance deck on APD is showed in section 3.2.1.

## 2.2. Turbogenerator

To complete the hybrid-electric powertrain the model of a Turbogenerator (TG) is proposed. As shown in fig. 2.5, it is created as the coupling of a turboshaft with an electric generator. In the preliminary sizing phase of an aircraft, the definition of the Specific Fuel Consumption (SFC) is of main interest hence it will be the focus of this model.

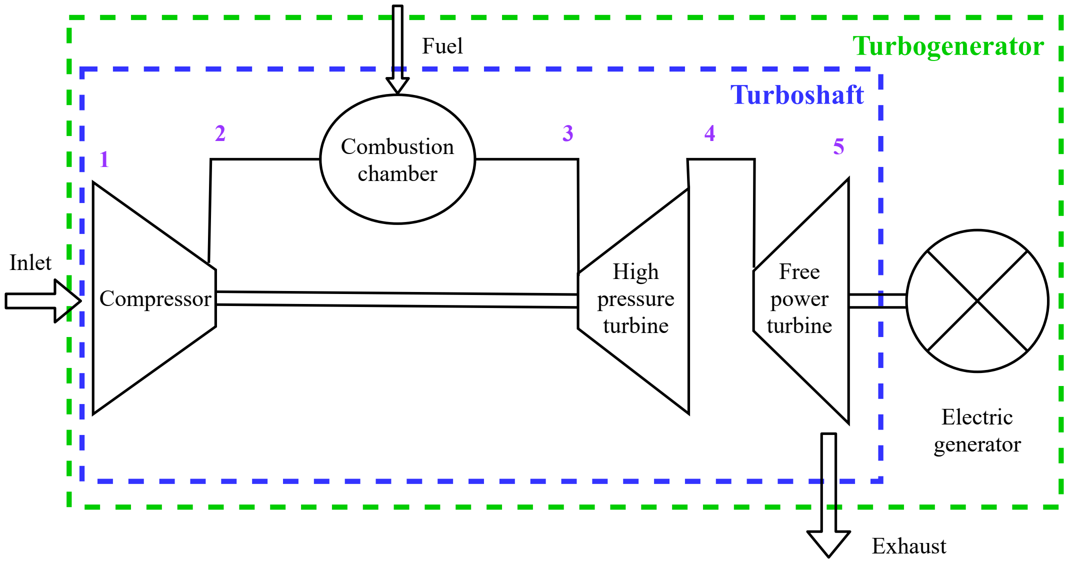



Figure 2.5: Turbogenerator, scheme.

The most simple turboshaft is composed by one compression stage, a combustion chamber, one high pressure turbine and one free power turbine. The cycle can be modeled as a Joule-Brayton cycle in order to estimate the fuel consumption in the design point, requiring a certain output power ($P_{req}$) at a specific flight condition ($T_1$, $p_1$). For the sake of simplicity, efficiencies of EDF and electric generator are considered constant, leading to the definition of design power of the turboshaft:

$$P_{TS} = \frac{P_{req}}{\eta_{EDF}\eta_{EG}} \tag{2.32}$$

Combustion chamber, compressor and nozzle efficiencies are also fixed to reasonable values. Table 2.2 collects some suggested numbers.

| **Parameter** | **Symbol** | **Value** |
|---|---|---|
| Compressor | $\eta_C$ | 90% |
| Combustion chamber | $\eta_{cc}$ | 98% |
| Turbine | $\eta_T$ | 95% |
| Nozzle | $\eta_{nozz}$ | 97% |
| Electric generator | $\eta_{EG}$ | 90% |
| Electric ducted fan | $\eta_{EDF}$ | 85% |

Table 2.2: Typical values for powertrain efficiencies; note that $\eta_{EDF}$ is found by multiplying $\eta_{fan} \cdot \eta_{EM}$, by consistency with EDF design.

Compressor ratio ($\beta$) and turbine entry temperature ($T_3$) are decided upon engineering judgement and experience, and may be varied in different design cycles. Air is assumed as perfect gas. The ratio between air mass flow and fuel is defined as

$$\chi = \dot{m}/\dot{m}_f \tag{2.33}$$

and typically assumes value of 2%.

The Joule-Brayton cycle is characterized by a simple set of equations. First of all the condition at compressor exit (station 2) can be defined:

$$p_2 = \beta p_1 \tag{2.34}$$

$$T_2 = \beta^{\frac{\gamma - 1}{\gamma \eta_p}} \tag{2.35}$$

Moreover, since compressor is driven by high-pressure turbine

$$P_{1,2} = P_{3,4} \tag{2.36}$$

and since useful power is given by low-pressure turbine

$$P_{TS} = P_{4,5} \tag{2.37}$$

The following formulas complete the model, creating a set of 11 equations with 11 unknowns ($\dot{m}$, $P_{1,2}$, $P_{2,3}$, $p_3$, $p_4$, $T_4$, $p_5$, $T_5$, $T_{4,is}$, $T_{5,is}$, $\eta_{TS}$).

$$\begin{cases} P_{1,2} = \dot{m}c_p(T_2 - T_1) \\ P_{2,3} = \dot{m}c_p((1+\chi)T_3 - T_2) \\ P_{3,4} = \dot{m}(1+\chi)c_p(T_3 - T_4) \\ P_{4,5} = \dot{m}(1+\chi)c_p(T_4 - T_5) \\ (T_3 - T_4) = \eta_T(T_3 - T_{4,is}) \\ (T_4 - T_5) = \eta_T(T_4 - T_{5,is}) \\ p_3 = p_2\eta_C \\ p_5 = p_1/\eta_{nozz} \\ \dfrac{T_3}{T_{4,is}} = \left(\dfrac{p_3}{p_4}\right)^{\dfrac{\gamma-1}{\gamma}} \\ \dfrac{T_4}{T_{5,is}} = \left(\dfrac{p_4}{p_5}\right)^{\dfrac{\gamma-1}{\gamma}} \\ \eta_{TS} = P_{TS}/P_{2,3} \end{cases} \tag{2.38}$$

Once the system is solved, fuel flow can be easily found by

$$\dot{m}_f = \chi\dot{m} \tag{2.39}$$

and, eventually, SFC of the turbogenerator can be computed

$$c_{SFC} = \dot{m}_f/P_{TG} \tag{2.40}$$

note that is defined with respect to the electric power, not the shaft power, since it must be referred to the entire turbogenerator and not only the turboshaft.

$$P_{TG} = P_{TS}\,\eta_{EG} \tag{2.41}$$

### 2.2.1. Mass

The mass of a turbogenerator can be preliminary estimated by historical regression. Paper [1] presents a study on 130 turboshaft engines, retrieving a relation from shaft power (expressed in kW) and mass:

$$m_{TS} = 0.625(P_{TS} + 200)^{0.8} \tag{2.42}$$

Paper [9] studies the trend of electrical power generation on aircraft, setting 20 kW/kg as power density goal for electric generators by year 2035. Summing turboshaft and generator, the mass of turbogenerator can be estimated as function of its power, expressed in kW:

$$m_{TG} = 0.625\left(\frac{P_{TG}}{\eta_{EG}} + 200\right)^{0.8} + \frac{P_{TG}}{20} \tag{2.43}$$

## 2.3. VTOL and mission definition

Power requirement in vertical flight segments can be found by applying momentum theory. Here the final formulas are reported for the sake of conciseness, but the whole procedure can be found in [19]. One defines the total propulsive area $A$ as the sum of the single rotor areas ($A_i$) engaged in vertical flight:

$$A = \sum_{i=1}^{N} A_i = \pi \sum_{i=1}^{N} r_i^2(1 - \sigma^2) \tag{2.44}$$

with $N$ the total number of propulsive units, $r_i$ the radius of each rotor and $\sigma$ the respective hub-to-tip ratio. The main assumption is that thrust disk loading ($\mathcal{T}/A$) is equal to the weight loading ($W/A$) increased by small percentage - typically 3% - to account for the force of the downwash blowing on the fuselage.

$$\frac{\mathcal{T}}{A} = \frac{W}{A} f \qquad \text{with} \qquad f = 1.03 \tag{2.45}$$

Hover is a steady state segment and also vertical climb is performed as stationary, hence in both segments the required thrust is usually estimated as the total aircraft weight increased by the fuselage downwash factor $f$.

$$\mathcal{T} = W f \tag{2.46}$$

The required power to lift and vertical climb is expressed below:

$$P_{VTO} = \left[\frac{fW}{c_{FoM}}\sqrt{\frac{fW/A}{2\rho}} + \frac{WV_{VROC}}{2}\right]\frac{1}{\eta_{mech}} \tag{2.47}$$

Power is dependent on aircraft weight ($W$), vertical rate of climb ($V_{VROC}$), fuselage down-wash coefficient ($f$), a figure of merit ($c_{FoM}$) and the total propulsive area ($A$). The figure of merit of a rotor is used to correct the momentum theory estimation of required power, in the same fashion as propeller thrust should be adjusted by an efficiency parameter. Its typical value is between 0.6 and 0.8; it is almost constant with rotational speed as demonstrated by experimental studies in [20]. Mechanical efficiency assumes characteristic value of 97% [19].

In the case of hover, the requirement of power is similar, setting null vertical rate of climb in eq. (2.47):

$$P_H = \frac{fW}{c_{FoM}}\sqrt{\frac{f\,W/A}{2\rho}}\frac{1}{\eta_{mech}} \tag{2.48}$$

### 2.3.1. Mission requirements

The typical mission profile adopted for the design process is presented in fig. 2.6. Transition phases are not considered in the preliminary design step for the sake of simplicity, leading however to an overall good estimation of power requirement [8]. For the same reason, no distance is credited for the ascent and descent phases.

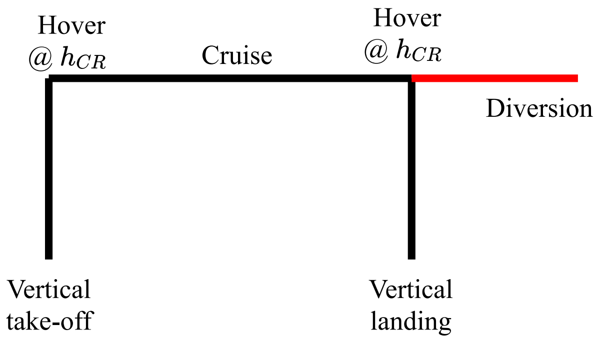



Figure 2.6: Urban Air Mobility mission.

Several studies [3, 5, 8, 10] have been done in recent years in order to establish typical requirements that will drive urban air mobility. The simple design mission is composed by vertical take-off, hover, cruise, a second hover and vertical landing. For conservativeness, the possibility of a diversion needs to be considered. Properties of each segment are reported in table 2.3, derived from different market investigations. The presented requirements for diversion segment, which are intended as mutually exclusive, are very different in terms of generated conservativeness. At the moment, no certification framework is present for eVTOL nor HeVTOL aircraft, that's why the reserve endurance requirement is taken from FAA for aircraft (30 min) or for helicopter (20 min) VFR operation rules. However, a proper regulatory class for eVTOL aircraft is expected in the future, for which a 2 mi distance diversion could be considered, as taken into account by Uber Elevate [8, 23]. This evident decrease in diversion requirement is probably related to the ability of eVTOL to land in small spaces, increasing versatility and security with respect to traditional aircraft. Hover and diversion are intended to be performed at the same altitude as cruise. Some studies [8] presented a design mission considering VTO and hover together, with a total duration of 120-180 s, however here the two segments will be analysed separately. Firstly a VTO at 500 fpm from 0 to hover altitude is completed, and then an hover of 120-180 s is performed. In literature, no particular requirements are defined for vertical landing. For the purpose of this work, it will be performed with a vertical rate of descent of 500 fpm.

| | **VTO** | **Hover** | **Cruise** | **Diversion** | **VLND** |
|---|---|---|---|---|---|
| **Distance** | - | - | - | 2 mi | - |
| **Endurance** | - | 120-180 s | up to 2 h | 20-30 min | - |
| **Velocity** | - | - | 80-300 km/h | - | - |
| **VROC** | 500 fpm | - | - | - | - |
| **Altitude** | - | $h_{CR}$ | 1500-3000 ft | $h_{CR}$ | - |

Table 2.3: Typical mission requirements.

The feasibility of the mission coming from these requirements is strictly dependant on the state of the art of propulsion technology, most of all batteries. As already presented, the preliminary design object of this master thesis aims at an hybrid-electric solution and this permits the possibility to have more demanding requirements with respect to an equivalent pure electric solution. To validate the theoretical model, the mission presented in table 2.4 will be used.

| | VTO | Hover | Cruise | Diversion | VLND |
|---|---|---|---|---|---|
| **Distance** | - | - | - | 2 mi | - |
| **Endurance** | - | 180 s | 2 h | - | - |
| **Velocity** | - | - | 300 km/h | 300 km/h | - |
| **VROC** | 500 fpm | - | - | - | -500 fpm |
| **Altitude** | - | 3000 ft | 3000 ft | 3000 ft | - |

Table 2.4: Final mission requirements of HeVTOL solution.

As regards the payload, UAM is intended for passengers transportation. At the moment on the market there are several solutions with up to 4 passengers. For the purpose of this study only 2 passengers are considered, in order to keep up with high performance requirements and taking inspiration from model ANN2 by Manta Aircraft.

# 3 | Models application

The mathematical model is applied to a case study on Pacelab APD.

ANN2 is considered as a reference design, which is a new hybrid-electric V/STOL aircraft by the Italian company Manta Aircraft [10]. At the moment, it is still in a preliminary conceptual design phase and only a scaled prototype has been built. With its 2 passengers and high performance requirements (cruise at 300 km/h speed, 2h endurance), it proposes a solution for regional and inter-regional air mobility. It has a fully composite structure and a fly-by-wire fully computerized control system. The powertrain is an innovative turbo-electric architecture, composed by a turbogenerator, a battery pack and eight EDFs, four of which are tiltable for horizontal and vertical flight.

EDF, turbogenerator and batteries are sized with the mathematical model from chapter 2 and are inputs in the application process, along with mission requirements. The implementation is described in details in the present chapter, focusing on the customization of Pacelab APD for the creation of fans, turbogenerator and vertical flight segments.

## 3.1. Input data

### Geometry and configuration

The first step in the implementation on APD is the geometrical representation of the aircraft. As already explained, model ANN2 is considered as baseline design, whose main dimensions can be found on the website [10] and are reported in table 3.1.

| Length | Wingspan | Height |
|---|---|---|
| 8.7 m | 6.8 m | 1.7 m |

Table 3.1: Overall model dimensions [10].

Starting from these poor data and a few images, the model is represented on APD. The result is presented in fig. 3.1.

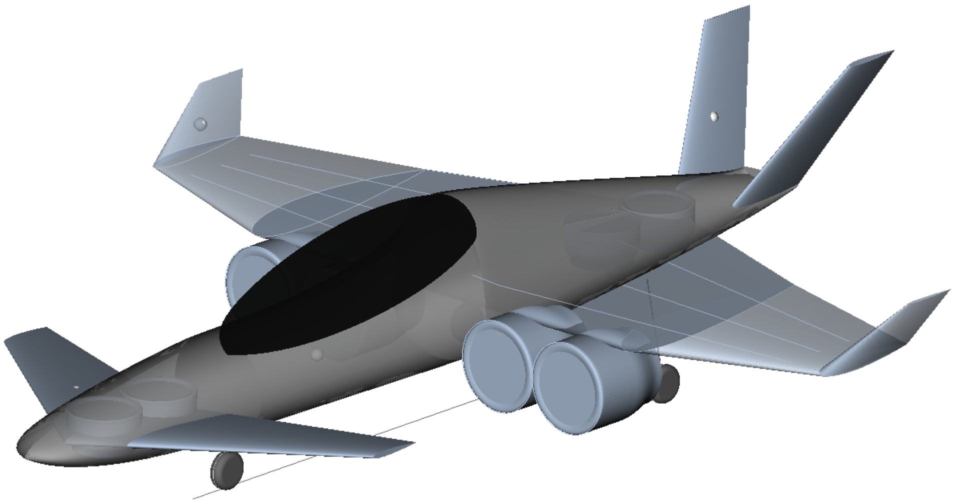


Figure 3.1: Case study on APD.

The case study has a peculiar configuration with canard and twin tail. The wing is mounted at middle height of the fuselage and has winglets at its tips. Undercarriage has a classical tricycle configuration and the cabin presents two seats in tandem. The most important and innovative subsystem is the propulsion one. It is composed by four EDFs mounted on the wing which can be tilted powering both horizontal and vertical flight, and four more mounted inside the fuselage, fixed vertically and closed with sliders during cruise. The power plant is parallel hybrid-electric: EDFs are driven by batteries and/or a turbogenerator, depending on the flight phase. The turbogenerator is placed in the rear of the cabin while batteries are under its floor.

More details about the propulsion implementation will be presented in section 3.2.1, whereas the procedure about the creation and assembly of the model in APD Engineering Workbench is described in appendix A.1.

## Mission

The typical design mission was already investigated in section 2.3. Just for the sake of completeness it is here resumed:

1. Vertical Take-Off (VTO) at a vertical rate of climb of 500 fpm from 0 ft to an altitude of 3000 ft;
2. Hover (HOV) for 3 minutes at 3000 ft;
3. Cruise (CR) for 2 h at 300 km/h at 3000 ft;
4. Hover (HOV) for 3 minutes at 3000 ft;

5. Vertical Landing (VLND) at a vertical rate of descent of 500 fpm from 3000 ft to 0 ft;

6. Diversion of 2 mi at 3000 ft.

The payload accounts for 2 passengers with luggage, using a reasonable and conservative value of 100 kg/person, since no certification framework is available nowadays for this type of aircraft.

## Propulsion

The hybrid-electric power train, shown in fig. 2.1, is composed by a turbogenerator, a battery pack and eight EDFs.

The turbogenerator is studied with the mathematical model already discussed in section 2.2. It is sized in cruise condition, so that two mission strategies can be achieved:

- pure electric vertical take-off, hover and vertical landing, to reduce noise and atmospheric pollution at low altitudes, a major concern in urban air mobility;
- full hybrid-electric mission, with turbogenerator always at MCP and batteries providing extra power whenever requested.

Aerodynamic estimation in cruise is retrieved from APD, obtaining the requirement in power and using it to determine design SFC. Results are reported in table 3.2. The mass formula is coded on APD receiving as input the reference power.

| Parameter | Symbol | Value |
|---|---|---|
| Power | $P_{TG}$ | 163 kW |
| SFC | $c_{SFC}$ | 0.2586 kg/kW/h |

Table 3.2: Turbogenerator results; sizing condition is cruise at 3000 ft at MTOW.

Case study runs of typical aircraft fuel (jet-A1, 43 MJ/kg, 0.803 kg/l).

Batteries are sized to perform pure electric vertical take-off, hover and vertical landing. Due to technological reasons, State Of Charge (SOC) must not reach values under 20% during the whole flight. Setting EIS to 2035, specific energy ($\overline{e}_{batt}$) and specific power ($\overline{p}_{batt}$) are estimated at 400 Wh/kg and 3000 W/kg respectively (Lithium-metal batteries, [18]).

Lastly, EDFs are designed. Sizing condition is set at VTO at sea level ISA and power is expected to be divided among the eight different fans proportionally to their area. In order to reproduce as reliable as possible the case study, it is assumed that, calling $A$ the total propulsive area, 60% of $A$ is placed on the wing propulsion group and the remaining 40% is on the fuselage one. Accounting that each propulsion group is composed by four identical EDFs, power requirement is defined as follows:

$$P_{EDF,wing} = \frac{0.6\,P_{VTO}}{4} = 120.5\,\text{kW} \tag{3.1}$$

$$P_{EDF,fus} = \frac{0.4\,P_{VTO}}{4} = 80.3\,\text{kW} \tag{3.2}$$

This is the input to the model proposed in section 2.1, which is run twice: once for wing and another more for fuselage propulsion group. The most relevant results are proposed in table 3.3.

| **Parameter** | **Symbol** | **Value** | |
|---|---|---|---|
| | | Fuselage | Wing |
| Nozzle-fan area ratio | $\delta$ | 0.8 | |
| Hub-to-tip ratio | $\sigma$ | 0.35 | |
| Nozzle pressure loss | $\pi_{nozz}$ | 2% | |
| Fan efficiency | $\eta_{fan}$ | 90% | |
| Mass flow | $\dot{m}$ | 16.24 kg/s | 25.01 kg/s |
| FPR | $\pi_p$ | 1.055 | 1.053 |
| Blade angle | $\beta$ | 70 deg | 71 deg |
| Exhaust Mach | $M_3$ | 0.22 | 0.21 |
| Thrust | $\mathcal{T}$ | 1210.6 N | 1825.1 N |
| Shaft rpm | $\Omega$ | 11177 rpm | 8152 rpm |

Table 3.3: EDFs results; sizing condition is VTO at 0 ft.

In particular, this condition is the reference one to be set in APD. For the flight performance evaluation on APD, a thrust map is created as explained in section 2.1.3. See section 3.2.1 for more details about its implementation.

## 3.2. Pacelab APD implementation

Neither EDF, turbogenerator nor vertical flight segments are available in the APD software and hence their creation is needed. An overview of the implementation strategy is hereafter presented, before going into deeper details in the following sections.

A tailored Engineering Object (EO) for EDF is implemented on APD Knowledge Designer, taking inspiration from the already existing electric propeller power plant and adding the duct. Once the set-up is done, the mathematical model (section 2.1) is used to create a performance deck. This look-up table provides a map of thrust at different flight conditions and power setting; it is used by APD Engineering Workbench to compute aircraft performance throughout the mission. Dimensions and reference condition come from the mathematical model as well (table 3.3). The turbogenerator is modelled as a turboshaft connected to an electric generator, therefore it consumes fuel in order to produce electrical power. In APD framework there is not such a solution, however fuel cells are implemented which, from an outside point of view, also produce electrical power out of fuel. For this reason it is sufficient to create a performance deck mapping the turbogenerator SFC and inserting it in the fuel cell EO.

Vertical flight segments are modelled in APD Knowledge Designer, taking inspiration from climb and cruise segments. In a *vertical flight* interface, three EOs are created in total: Vertical Take-Off (VTO), Vertical Landing (VLND) and HOV, implementing the formulas already presented in section 2.3.

### 3.2.1. Powertrain

The following paragraphs focus on the implementation of the powertrain components: EDF and turbogenerator.

#### Electric ducted fan

The creation of electric ducted fans on APD takes inspiration from the already implemented electric propeller power plant, composed by a propeller, an electric motor and its nacelle. A new engineering object that would take into account the effect of the duct is needed, therefore EDF is composed by the following items:

- fan, similar to the propeller, creating thrust from shaft power through a tailored performance deck;
- duct, purely geometric component modelling a cylindrical duct which contains fan

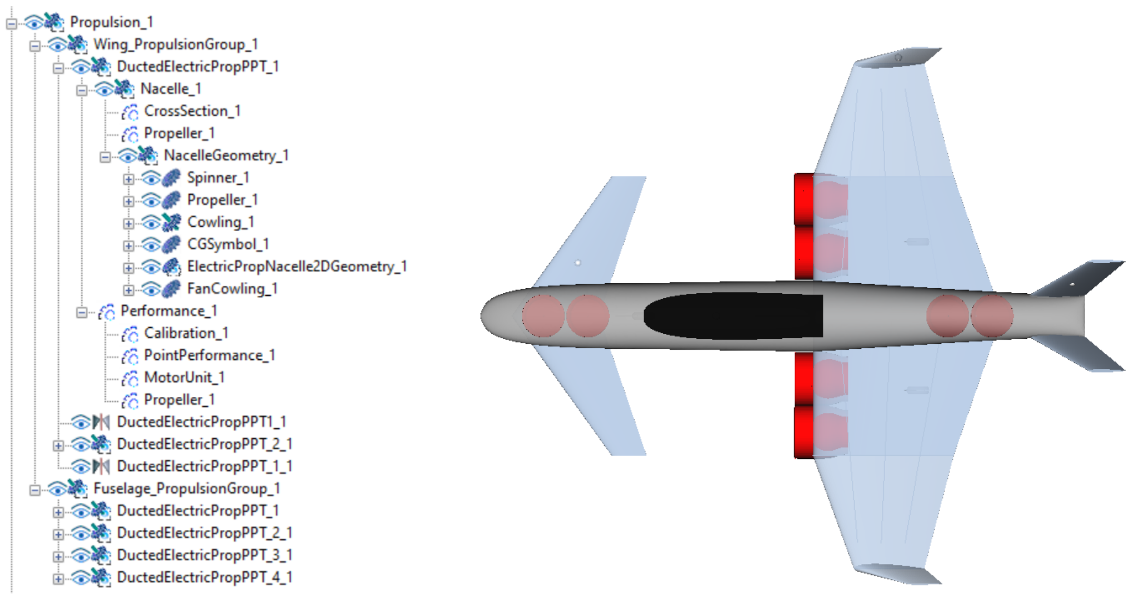
and electric motor nacelle;

- electric motor and its nacelle, as for the previous implementation.

The single components are created and assembled in APD Knowledge Designer. More details about the implementation can be found in appendix A.2.

Then, EDFs can be installed on the case study in APD Engineering Workbench, as in fig. 3.2. As can be clearly seen in fig. 3.2a, two propulsion groups are created:

- wing propulsion group, consisting of four tilting EDFs on the wing leading edge;
- fuselage propulsion group, consisting of two EDFs in the forward part of the fuselage and two more in the rear.

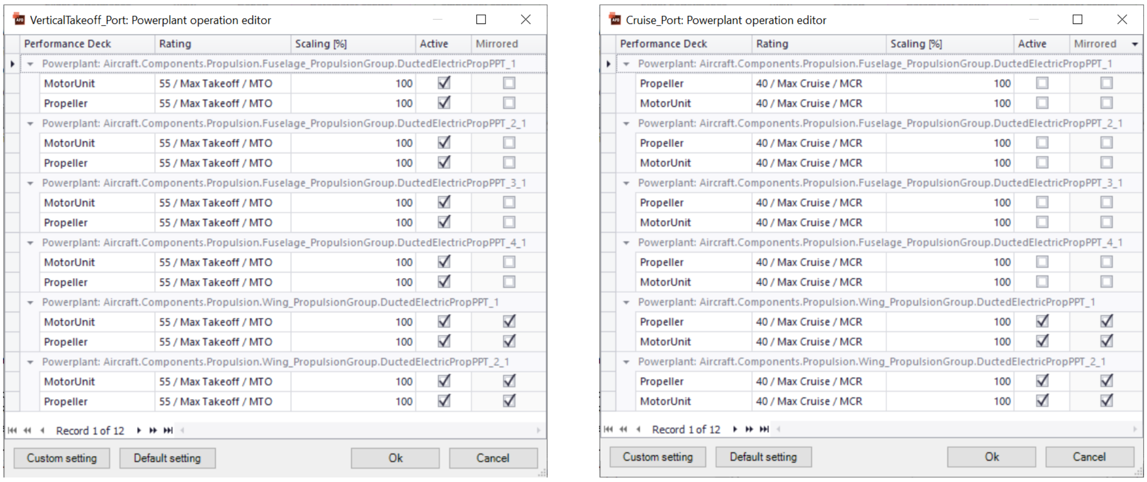



(a) Structure view. (b) Highlight on EDFs, top view.

Figure 3.2: Implementation of EDFs on APD Engineering Workbench.

At the moment there is not any degree of freedom for engine tilting, so wing propulsion group is mounted as fixed horizontal and fuselage propulsion group is fixed to provide thrust vertically instead. In the performance computation, there is the possibility to assign which propulsion group is available for each flight segment, being able to actually represent the mission of a typical eVTOL of this type: both propulsion groups power vertical flight segment while only the wing one drives cruise, as visible in the powerplant operation window in fig. 3.3.

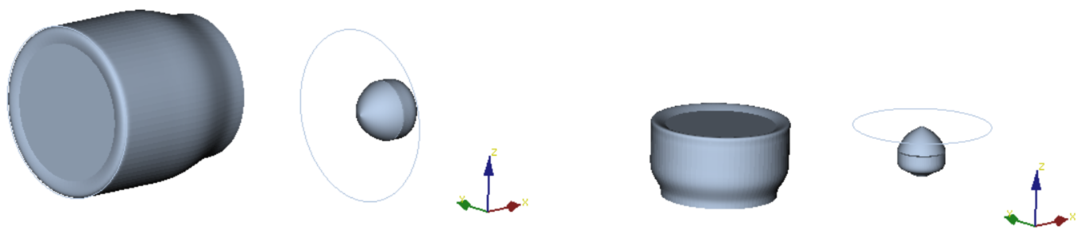
EDF shape must be defined, playing an important role in volume and wet area computation. A very simple cylindrical shape is chosen for the duct and the hub, consisting




(a) In vertical flight. (b) In horizontal flight.

Figure 3.3: Powerplant operation editor from APD; for the sake of conciseness, wing propulsion group is composed by two independent EDFs on one half wing then mirrored.

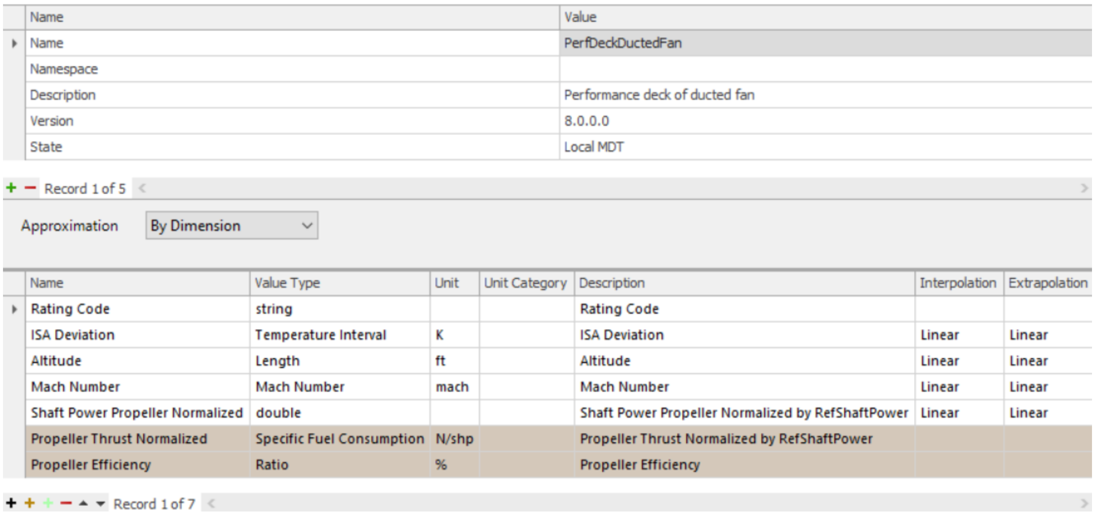
in the spinner and the electric motor nacelle. Diameters and lengths of each component presented in table 3.3 come from the result of the designing process. Figure 3.4 presents a single motor per propulsion group on APD.



(a) Wing propulsion group. (b) Fuselage propulsion group.

Figure 3.4: Resulting EDFs on APD Engineering Workbench: with and without duct.

The performance deck is equal to each EDF, which is scaled with the single reference power. Following the same fashion of Manta Aircraft, the wing ducted fans are slightly bigger in terms of fan area with respect to fuselage ones, translating greater fan area to greater available power. The latter will be an input to the performance deck, along with the present flight condition, in order to extract thrust and fan efficiency. This deck is classified as a Multidata table (MDT) and fig. 3.5a presents its set up, so name, data type and interpolation settings. The list of data is presented below, in two different colors representing inputs (white) and outputs (brown) in the computation process. Input data define the actual flight condition: altitude, ISA deviation, Mach number, normalized shaft power provided by the electric motor and mission segment, indicated by the rating code. As will be clearer in section 3.2.2, each flight segment is designated with a code, the rating code, increasing the flexibility of performance computation and mission execution. In this particular case, the word propeller is improperly used for ducted fan because of the inheritance of the old electric propeller power plant. As it is visible from the extract of the table in fig. 3.5b, each flight condition is described by two points, namely shaft power normalized 0.5 and 1, starting from which extrapolation and interpolation can be done, linear in this specific case (fig. 3.5a, last two columns). Propeller efficiency is set to 100% because normalized thrust was already computed taking into account fan efficiency. Please refer to section 2.1.3 for the complete procedure.



| Name | Value |
|---|---|
| Name | PerfDeckDuctedFan |
| Namespace | |
| Description | Performance deck of ducted fan |
| Version | 8.0.0.0 |
| State | Local MDT |

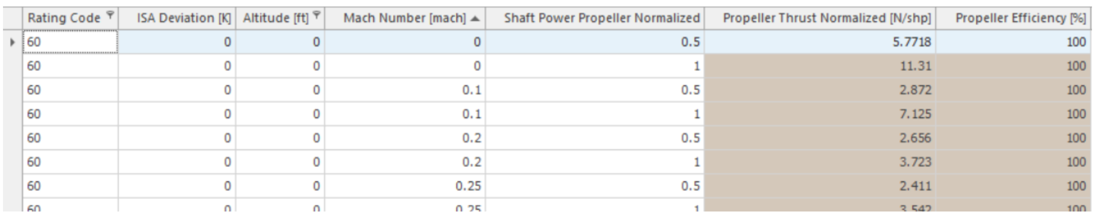
+ − Record 1 of 5

Approximation: By Dimension

| Name | Value Type | Unit | Unit Category | Description | Interpolation | Extrapolation |
|---|---|---|---|---|---|---|
| Rating Code | string | | | Rating Code | | |
| ISA Deviation | Temperature Interval | K | | ISA Deviation | Linear | Linear |
| Altitude | Length | ft | | Altitude | Linear | Linear |
| Mach Number | Mach Number | mach | | Mach Number | Linear | Linear |
| Shaft Power Propeller Normalized | double | | | Shaft Power Propeller Normalized by RefShaftPower | Linear | Linear |
| Propeller Thrust Normalized | Specific Fuel Consumption | N/shp | | Propeller Thrust Normalized by RefShaftPower | | |
| Propeller Efficiency | Ratio | % | | Propeller Efficiency | | |

Record 1 of 7

(a) Settings.



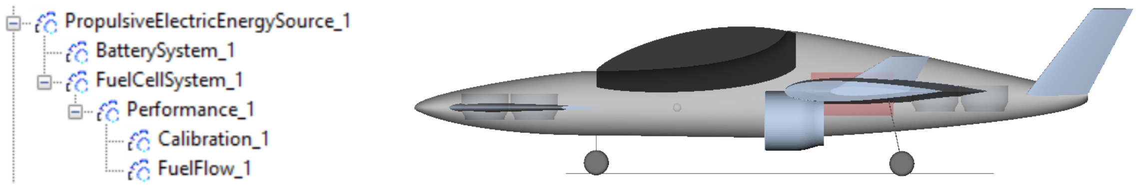
| Rating Code | ISA Deviation [K] | Altitude [ft] | Mach Number [mach] | Shaft Power Propeller Normalized | Propeller Thrust Normalized [N/shp] | Propeller Efficiency [%] |
|---|---|---|---|---|---|---|
| 60 | 0 | 0 | 0 | 0.5 | 5.7718 | 100 |
| 60 | 0 | 0 | 0 | 1 | 11.31 | 100 |
| 60 | 0 | 0 | 0.1 | 0.5 | 2.872 | 100 |
| 60 | 0 | 0 | 0.1 | 1 | 7.125 | 100 |
| 60 | 0 | 0 | 0.2 | 0.5 | 2.656 | 100 |
| 60 | 0 | 0 | 0.2 | 1 | 3.723 | 100 |
| 60 | 0 | 0 | 0.25 | 0.5 | 2.411 | 100 |
| 60 | 0 | 0 | 0.25 | 1 | 3.542 | 100 |

(b) Table.

Figure 3.5: EDF performance deck overview.

## Turbogenerator

The turbogenerator is implemented on APD through fuel cells. This simplification is possible since turbogenerator consists of a turboshaft connected to the electric generator, as theoretically presented in section 2.2. For the purpose of preliminary aircraft sizing, it can be described simply through its mass, essential for Maximum Take-off Weight (MTOW) computation, and SFC, needed for performance computations and fuel requirement with respect to electric power output. From an outside perspective, turbogenerator is equal to fuel cells, both burning fuel to produce electric power. Since the latter engineering object is already present in APD, there is no need for a new specific implementation, as long as tailored performance deck and mass method are inserted for turbogenerator. On the Engineering Workbench, turbogenerator results as shown in fig. 3.6.




(a) Structure view. (b) Highlight on turbogenerator, side view.

Figure 3.6: Implementation of turbogenerator on APD Engineering Workbench.

As already discussed in section 3.1, cruise is chosen as design condition. Thanks to the theoretical model in section 2.2, fuel consumption can be mapped in different flight conditions in order to build the required performance deck, shown in fig. 3.7. The reasoning is the same as for EDF: input parameters are rating code for mission segment and normalized electric power and the sole output parameter is SFC.

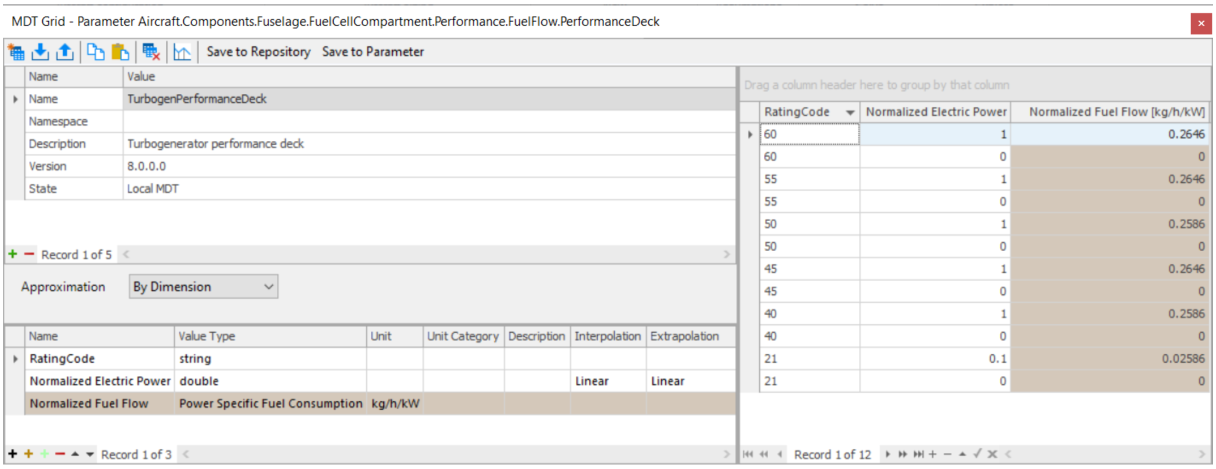



Figure 3.7: Turbogenerator performance deck overview. In order to perform PE VTOL and hover, it is necessary to force to zero the corresponding SFC (rating 55 and 60, rows 1 and 3), but here the complete hybrid-electric version is reported for the sake of completeness.

The limitation in using fuel cell implementation comes now clear: unlike turbogenerator, it does not depend on altitude. However some considerations can be done:

- in the present case study, it could be acceptable to consider SFC constant with altitude since the proposed mission has a limited range (0 - 3000 ft) not changing substantially the consumption rate;
- however, if greater precision is sought, dependency on altitude can be masked in the rating code, since each flight segment is associated to a flight regime.

The second approach is preferred: turbogenerator is studied throughout the different flight conditions. Even if design was completed with pure electric vertical flight segments, the presence of a complete performance deck permit a later investigation of design space and sensitivity studies.

The mass of the turbogenerator is strictly linked to its power. The historical regression proposed in section 2.2.1 is inserted as a formula receiving as input the nominal power and providing as output the mass of turbogenerator compartment.

### 3.2.2. Vertical flight segments

The implementation of vertical flight on APD follows the same approach as other mission segments. On the software, the users build the mission assembling different ports, engineering objects representing single segments (cruise, take-off, etc). Each port comes with a set of parameters, needed for the performance calculation. In order to build an history multidata table, collecting the evolution in time of important data throughout the mission, a performance method is needed computing point performance. One performance method is associated to a single segment type, and this association is created through a *smart formula*. The latter is capable of collecting all the engineering objects in a single interface, and dealing with them all at once before calling the performance methods. More details on smart formulas can be found in the documentation [12].

For the sake of clarity, this approach is schematized in fig. 3.8 for the specific case of vertical flight. Three mission ports are created on APD Knowledge designer: vertical take-off, vertical landing and hover. The user will be able to insert input parameters (i.e. duration, altitude, ...) and to connect them to the mission on APD Engineering Workbench. The ports are connected to an interface which is created to collect vertical flight segments. A vertical flight smart formula is written, interfacing with those ports and collecting useful data. Its last task is to call the correct method for point performance computation. The mathematical model for each segment type (section 2.3) is implemented in a different performance method, computing history of thrust and power, leading to battery discharge and fuel consumption. History data can be visualized in the segment port on the Workbench.

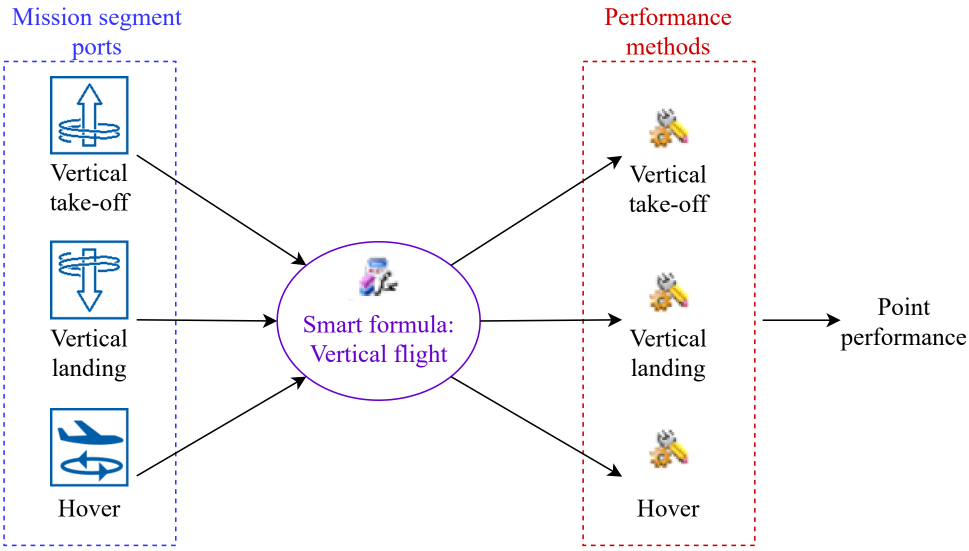



Figure 3.8: Vertical flight segments implementation approach.

Each performance method collects the available power and thrust from propulsion groups. As already explained, single power units can be enabled or disabled through the powerplant operation editor (fig. 3.3). For each available powerplant, the performance method reads the performance deck in correspondence of the correct flight condition. Each mission segment is associated to an universal rating code, as shown in fig. 3.9. A new code (60) is created just for hover whereas vertical take-off and landing are associated to take-off.

| Index ... | Rating Code | Rating Name | Rating Abbreviation | Applicable Flight Segments |
|---|---|---|---|---|
| 1 | 55 | Max Takeoff | MTO | Takeoff, TakeoffOEI, MissedApproach, VerticalTakeoff, VerticalLanding |
| 2 | 45 | Max Climb | MCL | Climb, OEIClimb |
| 3 | 40 | Max Cruise | MCR | Cruise, Hold, PickUpDropOff, Refuel, Turn, Loiter, Acceleration |
| 4 | 21 | Flight Idle | FID | Descent, Landing, Taxi |
| 5 | 60 | Hover | HOV | Hover |

Figure 3.9: Rating code table.

A more detailed insight in each mission segment will follow.

## Vertical Take-Off (VTO)

Vertical take-off power requirement is presented in eq. (2.47). The list of input parameters is the following:

- vertical rate of climb;
- target altitude;
- downwash coefficient;

- figure of merit;
- mechanical efficiency.

In order to complete the formula, propulsive area is computed by the performance method collecting and summing fan areas from each propulsive unit and aircraft weight is updated from mission development. In the event of insufficient thrust, no vertical climb will be computed and a warning message is produced.

#### Vertical Landing (VLND)

Vertical landing is implemented with the same approach of take-off, requiring a vertical rate of descent instead of climb. A warning message is produced in case target altitude is higher than present one.

#### Hover (HOV)

Hover power requirement is presented in eq. (2.48). The user needs to provide the following inputs:

- duration;
- figure of merit;
- mechanical efficiency.

The main difference with respect to VTO and VLND is that hover is based on a target duration, instead of target altitude.

### Complete mission

The complete design mission (fig. 2.6, table 2.4) can now be built on APD Engineering workbench. The result is shown in fig. 3.10: each port is connected in a subsequent way hence each connection creates a temporal link, giving the last condition of each port (weight, altitude, time, etc) as starting point for the subsequent segment.

## 3.2.3. Composite structures

The targeted case study has full composite structure. Raymer suggests an approach with fudge factors estimating the reduction in mass with respect to a more traditional solution. Structure weight prediction for conventional aircraft is already implemented on APD, with the possibility to insert a *Mass factor* for each component in order to modify

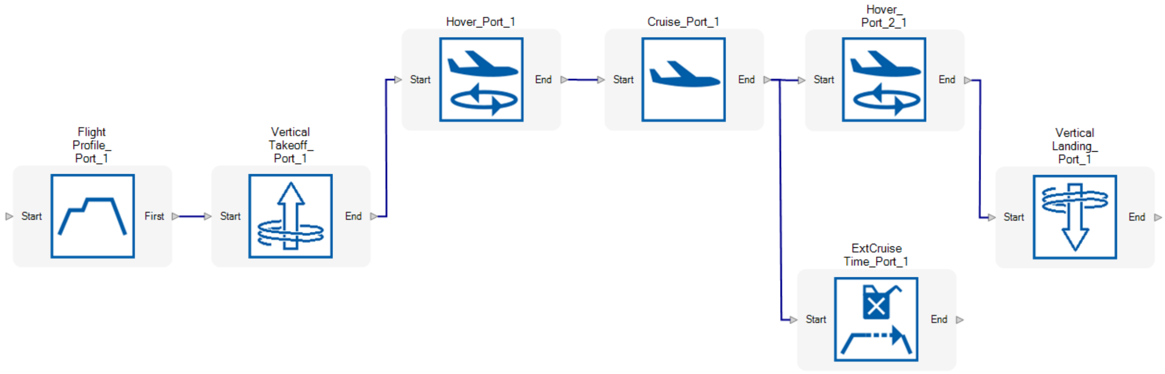



Figure 3.10: Design mission on APD.

their estimation as needed. Fudge factors from Raymer are collected in table 3.4.

| Component | Mass factor |
|---|---|
| Wing group | 0.85 |
| Fin upper and canard | 0.8 |
| Fuselage | 0.9 |
| Landing gear | 0.95 |

Table 3.4: Composite materials mass factors [19].

## 3.3. Results

This section is dedicated to the results on the case study. First of all geometries and mass breakdown is proposed, then a better insight on the design mission performance will follow. In order to better acknowledge the design space and opportunities, sensitivity studies on turbogenerator power and batteries nominal energy are run on APD and reported here.

### 3.3.1. Mass and geometries

Table 3.5 presents the mass breakdown in its most important components while geometries are described in table 3.6. Please note that mass estimation come from classical methods of Raymer and Torenbeek, which are based on historical regression for transport, cargo or military aircraft. No weight method specific for UAM aircraft category has been implemented and no historical regression can be created due to their innovative nature. Whenever an estimation model would be available, a more detailed mass breakdown can be made.

| General | | Propulsion | | Structure | |
|---|---|---|---|---|---|
| Component | Value | Component | Value | Component | Value |
| MTOW | 1204.5 kg | Fuel | 90 kg | Wing | 42.80 kg |
| OEW | 334.12 kg | Batteries | 599.7 kg | Fuselage | 109.25 kg |
| Payload | 100 kg | Turbogenerator | 80.7 kg | | |

Table 3.5: Mass breakdown.

### 3.3.2. Performances

Once the case study is entirely represented on APD Engineering Workbench, the design mission can be solved and analysed. The time evolution of some data of particular interest are reported here. Graphs are created with the dedicated APD tool. In order to read the graphs it is useful to know the temporal subdivision of the different segments throughout the mission: see table 3.7.

| Segment | Duration | Start-end minute |
|---|---|---|
| Vertical take-off | 6 min | 0 - 6 |
| Hover 1 | 3 min | 6 - 9 |
| Cruise | 120 min | 9 - 129 |
| Hover 2 | 3 min | 129 - 132 |
| Vertical landing | 6 min | 132 - 138 |

Table 3.7: Mission segments time subdivision.

In fig. 3.11 the evolution of altitude and distance is graphed. It is clear that climb and descent are performed at the same rate and that distance is not credited during vertical segments.

| Component | Parameter | Value |
|---|---|---|
| Wing | Area | 12.7 $m^2$ |
| | Span | 6.8 m |
| | Aspect ratio | 3.642 |
| | Taper ratio | 0.373 |
| | Mean aerodynamic chord | 1.98 |
| | Wetted area | 22.13 $m^2$ |
| Canard | Area | 3.11 $m^2$ |
| | Span | 3.77 m |
| | Aspect ratio | 4.57 |
| | Taper ratio | 0.398 |
| | Mean aerodynamic chord | 0.88 m |
| | Wetted area | 2.20 $m^2$ |
| Fin upper | Area | 1.41 $m^2$ |
| | Span | 1.13 m |
| | Mean aerodynamic chord | 0.63 m |
| | Inclination | 24 deg |
| Fuselage | Length | 8.15 m |
| | Height | 1.34 m |
| | Width | 0.95 m |

Table 3.6: Geometrical results.

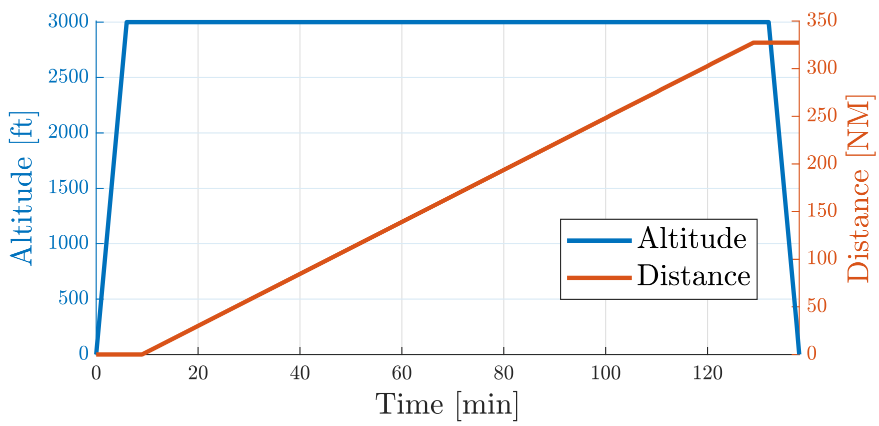



Figure 3.11: Altitude and distance during design mission.

True Air Speed (TAS) and VROC change in time as prescribed by the design mission, see fig. 3.12.

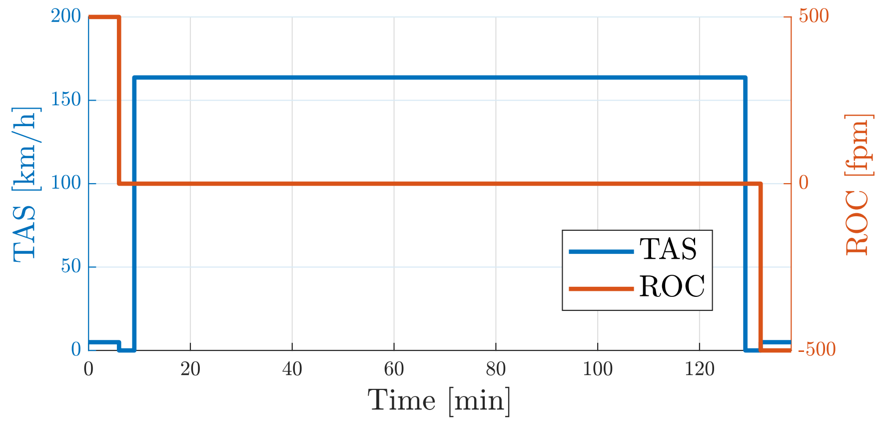



Figure 3.12: TAS and VROC during design mission.

Looking at total thrust and power in fig. 3.13 it is evident how vertical segments are significantly more requiring with respect to cruise. This explains the need of vertically fixed EDFs boosting available power with respect to horizontal segments.

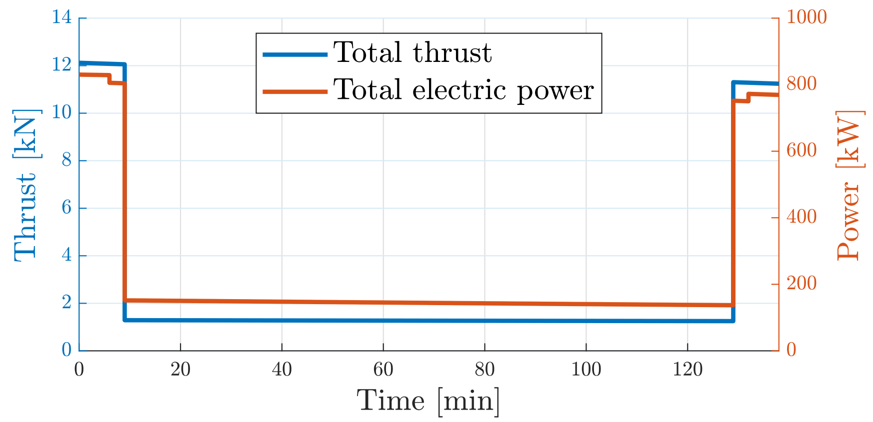



Figure 3.13: Total thrust and power during design mission.

The thrust provided by a single EDF in the wing propulsion group and in the fuselage one are compared in fig. 3.14. As modeled, available thrust is proportional to fan area during vertical flight, whereas only tilting EDFs are driving cruise.

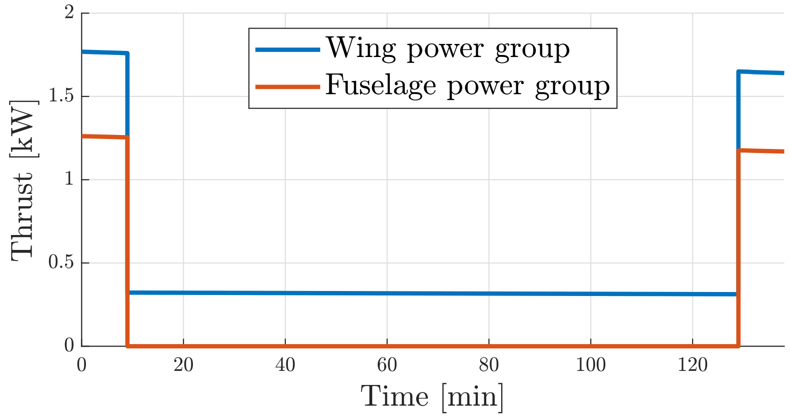



Figure 3.14: Single EDF thrust during design mission; "Powerplant1" refers to wing propulsion group while "Powerplant5" refers to the fuselage one.

Fuel and battery consumption in fig. 3.15 show an approximately constant consumption rate. Since SFC is almost constant (fig. 3.7), constant consumption rate means that turbogenerator is always operating at MCP, as expected. Almost 90 kg of fuel are necessary to complete the mission. End SOC is 20.87%, satisfying the minimum 20% for optimal battery life. In cruise no energy is requested from batteries since turbogenerator is sized to perform that segment.

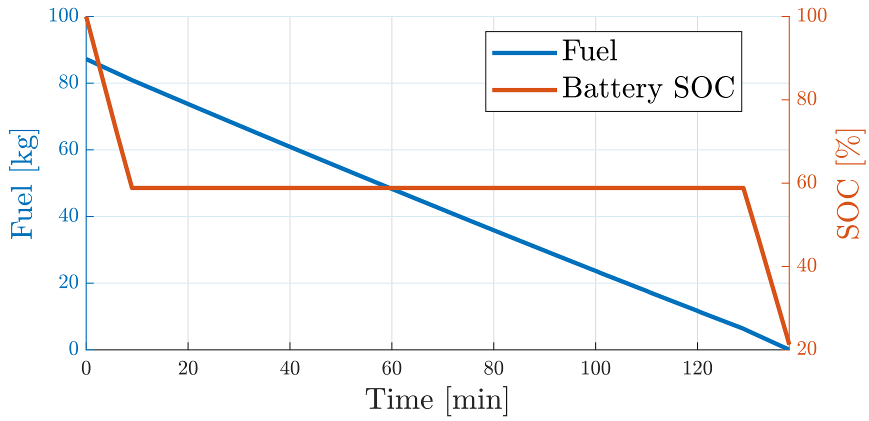



Figure 3.15: SOC and fuel consumption in time.

The extended cruise is considered as a reserve segment and so it is not part of the design flight profile. It is executed with the same setting as the main cruise: only turbogenerator is on and batteries are not consumed. To fly two extra mi only half kg of fuel is needed, and as a result it does not impose extra resources to the aircraft.

### 3.3.3. Pure electric vertical segments: alternative solution

Pacelab APD permits to find easily different solutions in order to compare them. For example, maintaining constant MTOW, one can try to perform fully electric vertical segments using turbogenerator only in cruise. This could benefit in noise and atmospheric pollution near urban areas. In this case, required fuel is decreased (76 kg) while battery are almost unaffected. Maintaining the same battery mass, end SOC would be just a little smaller with respect to previous solution (20.76%) and this can be easily explained:

- cruise was fuel-burning only also in the previous solution (fig. 3.15);
- in vertical segments, the gap between turbogenerator available power and required one is great: vertical climb is performed with 830 kW and turbogenerator contributes only with 160 kW. As a consequence batteries already provided almost the totality of power.

Figure 3.16 shows SOC and fuel consumption for this alternative solution, where is evident that turbogenerator is switched off in vertical flight.

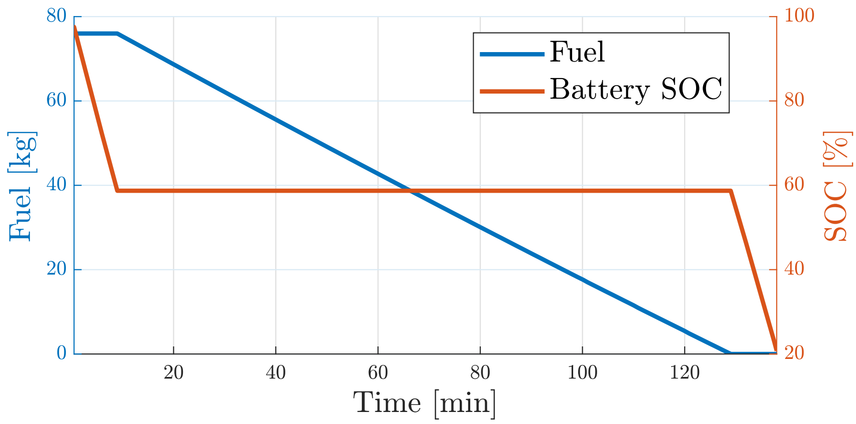



Figure 3.16: SOC and fuel consumption in time in case of Pure electric (PE) vertical segments.

### 3.3.4. Sensitivity

With the help of Pacelab APD the design space can be further explored performing sensitivity studies; please refer to [14] for documentation.

Battery nominal energy and turbogenerator power are varied, creating a mesh where MTOW, trip fuel, battery mass and end SOC are observed, in order to check the feasibility of the mission with the given inputs. Figure 3.17 presents the results. As can be

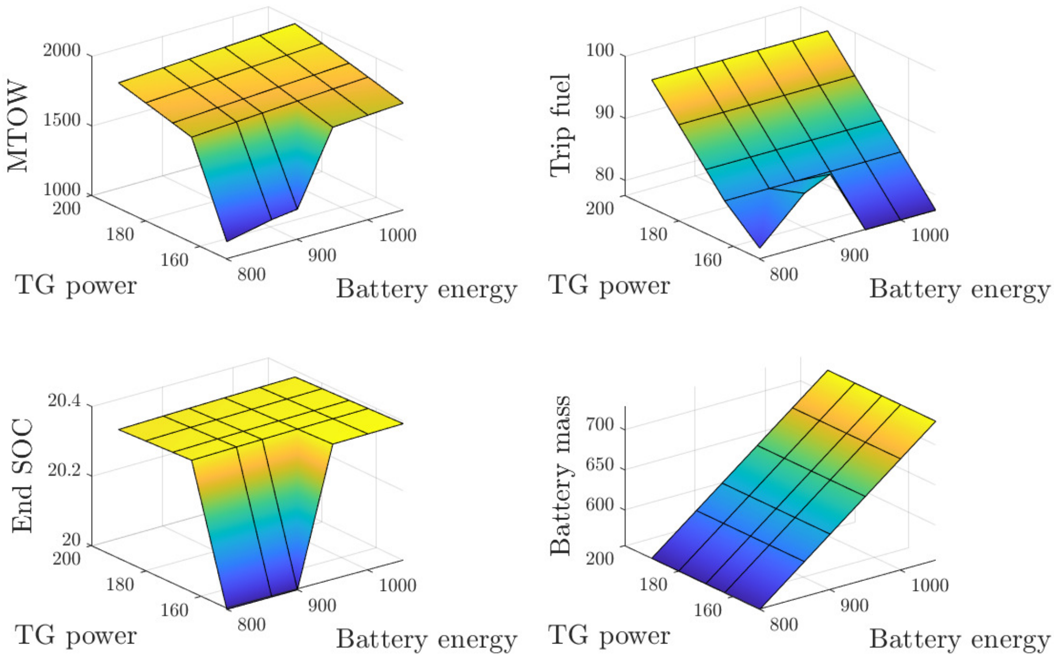



Figure 3.17: Sensitivity analysis results.

clearly seen take-off weight increases both with turbogenerator and battery energy, with a greater trend with the first instead of the latter. Trip fuel has the same trend with turbogenerator power but, at higher powers, becomes independent with battery nominal energy. Mission final SOC is almost independent with respect to the two inputs: the only variance is of 0.001 order of magnitude. This is totally expected since minimum SOC is constrained during the solving process to stay at 20% for optimal battery life. Battery mass is linearly increasing with battery nominal energy but is independent on engine power. This sensitivity analysis does not suggest a change in input parameters for a more optimal solution.

# 4 | Conclusions and future outlook

This final chapter has the purpose of drawing the conclusions of the work, highlighting the achievements as well as the weaknesses. Eventually, future developments and improvements are proposed.

## 4.1. Work summary

The present work fits the research field that has been one of the main focuses in the aerospace world: hybrid-electric propulsion and urban air mobility. As can be noted after a market research, more and more aircraft concepts propose feasible solutions for the near future; the most important examples are Lilium and Manta Aircraft. Several approaches for preliminary sizing of distributed EDF are present in literature but none of them chooses vertical flight segments as design condition: this is the gap that is aimed.

A new mathematical approach for EDF is proposed and partially validated with simulations. It assumes vertical take-off at sea level as sizing condition but it works also at static flight, i.e. hover. Thrust map is created combining the mathematical model with some simulations run with Javaprop. A simple Joule-Brayton cycle is proposed instead to size the turbogenerator, that, combined with batteries, provides electrical power to EDF, completing the hybrid-electric powertrain.

Vertical flight segments are modelled with momentum theory, setting power requirement for the mission. Market and literature research combined with model ANN2 specifications lead to the definition of a UAM mission.

Pacelab APD is then customized. In detail, new implementations for EDF, turbogenerator and vertical flight segments are coded and installed in the Engineering Workbench. The case study, inspired from the reference model ANN2 by Manta Aircraft, is represented and the conceptual design is successfully achieved with the performance map and dimensions defined by the mathematical model. Eventually, APD software permits to compute sensitivity analysis on some input parameters, namely nominal battery energy and turbogenerator power, and explore the design space.

## 4.2. Improvements and future outlook

What has been proposed in this report, can't be considered exhaustive for the current sizing problem: some approximations have been done and some techniques can be improved. Even if some considerations were already discussed throughout the report, here below all the lacks are reported for the sake of awareness and inspiration for future improvements.

The most relevant problem that was encountered during the project is the performance deck for ducted fans. At the end an hybrid solution is found, combining mathematical model and Javaprop but a better approach would be to simulate everything on other software that can deal also with quasi static and static flight condition, i.e. at very low inlet Mach numbers ($< 0.1$) at vertical take-off and hover. In this way, other than having a more dense set of data that would go beyond the few operational points of the mission, the assumption of constant fan efficiency can be finally removed. Once this is achieved, ducted fans could be applied also in different flight ranges reaching high subsonic for different aircraft concepts. Moreover, an interesting comparison between multiple ducted fans and propellers can be done just interchanging the performance maps on Pacelab APD.

As regards the application on the case study, the most limiting issue is the lack of a mass method specific for UAM and eVTOL. At the moment, historical relations coming from Raymer and Torenbeek for general aviation are used, corrected with mass factors to account for full composite structure. It is difficult to make reliable and generic predictions due to the innovative character of those technologies but, for the time being, the reader should be aware of this inaccuracy.

For similar reasons, aerodynamic estimation can be improved. Pacelab APD permit to insert data retrieved with external aerodynamic simulation software on the specific case study. This is considered out of the scope of this preliminary sizing approach so aerodynamic approximation is done with calibration factors and regression from traditional methods. For example, remember how the effect of fuselage downwash in vertical flights is estimated with a constant coefficient. The accuracy could be improved, validating a tailored method for eVTOL configurations.

Once this is solved, on APD one could improve the implementation to increase the flexibility of mission management. For example, the possibility of recharging in flight can be explored: if batteries are recharged in cruise by the turbogenerator, landing can start at full charge and embarked battery mass can be diminished by almost half. Required power in cruise will be increased, sustaining both flight and recharging, leading to an increase in turbogenerator and fuel mass, but the saving in battery mass is estimated to be greater.

Moreover, alternative power managements can be explored. For example, wing group EDFs can be powered only by the turbogenerator and fuselage ones by batteries: it could be interesting investigating the effect on the whole design. Distributed propulsion inevitably increases the number of applicable strategies and, with that, the possibility to find the most efficient one for the case study.

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# A | Appendix A: Pacelab APD

## A.1. Geometry and configuration on APD: procedure overview

The following appendix shall provide an overview of the configuration steps for the representation of the case study on APD Engineering Workbench. For a more detailed and general documentation, please refer to [14]. A customized version 8.0 is employed in the present work.

The creation of the case study on the Engineering Workbench started from the baseline of Pilatus PC 12-NG, that is already implemented as template in the software. As a matter of fact, the recommended approach is to start from an existing similar aircraft, among the proposed ones, and modify it as desired. The user can select a proper starting feasible solution among the 40+ aircraft in the database.

After loading, solving and analysing the template, the next step is to modify its configuration. This can be easily done by selecting the predefined configuration options through *Aircraft configuration* button in the Home ribbon tab, highlighted in red in fig. A.1.

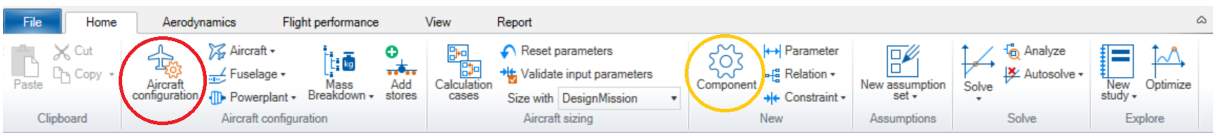


Figure A.1: APD Engineering Workbench Home ribbon tab.

Clicking on *Aircraft configuration*, a window opens (fig. A.2). There the user can easily set up predefined types and arrangement of wing, winglet, canard, propulsion, undercarriage, tail, passengers classes and more. The tip is to set one characteristic at time. The 3D view and Structure View will update accordingly, having the possibility to modify the required parameters, as dimensions or other specific properties.

Then, fuselage can be designed. APD implements a 2D editor in order to manually model the fuselage contours with conic curves, following a drawing like shown in fig. A.3.

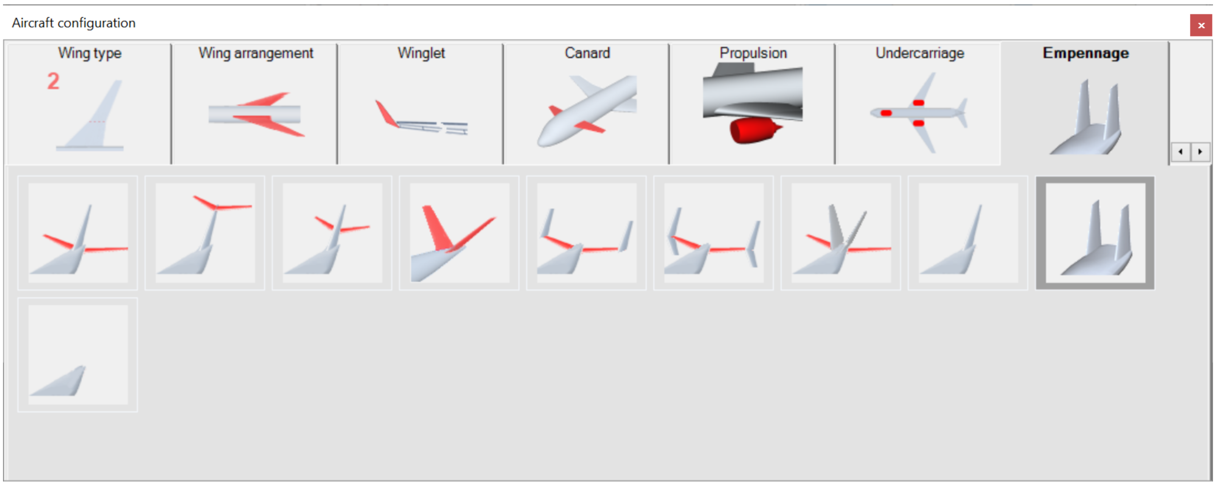


Figure A.2: Aircraft configuration window, focus on empennages.

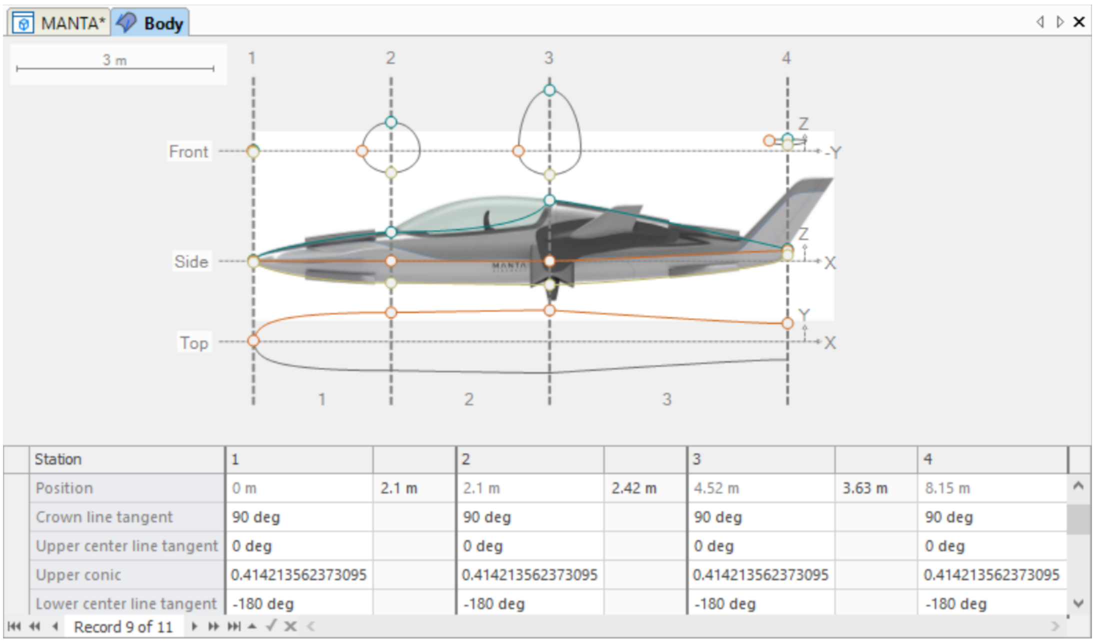


Figure A.3: 2D Editor for fuselage modeling.

The *Component* button (highlighted in green in fig. A.1) is needed to add components that do not come as predefined in Aircraft configuration, as for example the canopy, fuel cell and batteries for propulsive electric energy sources. Canopy is modifiable with a 2D editor similar to the fuselage, while fuel cell and batteries compartments are geometrically placed in the aircraft through a dedicated tool (fig. A.4). Through the *Component* button it is possible to install self defined components on APD Knowledge Designer, like electric ducted fan and vertical flight segments. They will appear as shown in fig. A.5.

To conclude, the result is presented in its three views in fig. A.6.

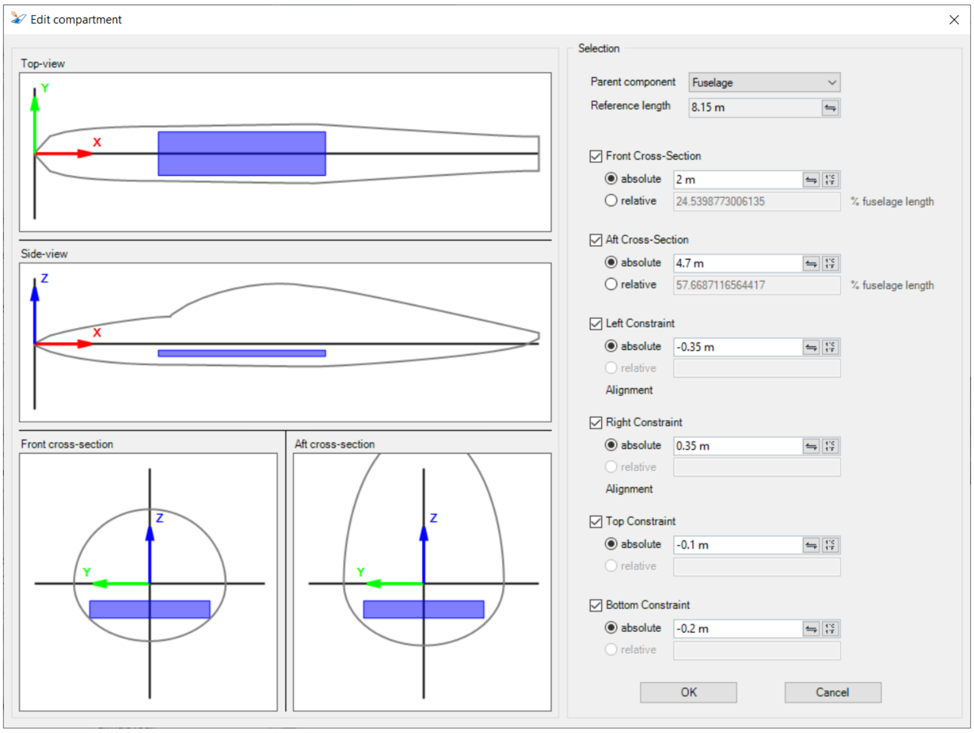


Figure A.4: Edit compartment window for batteries; similar setting applies to fuel cell.

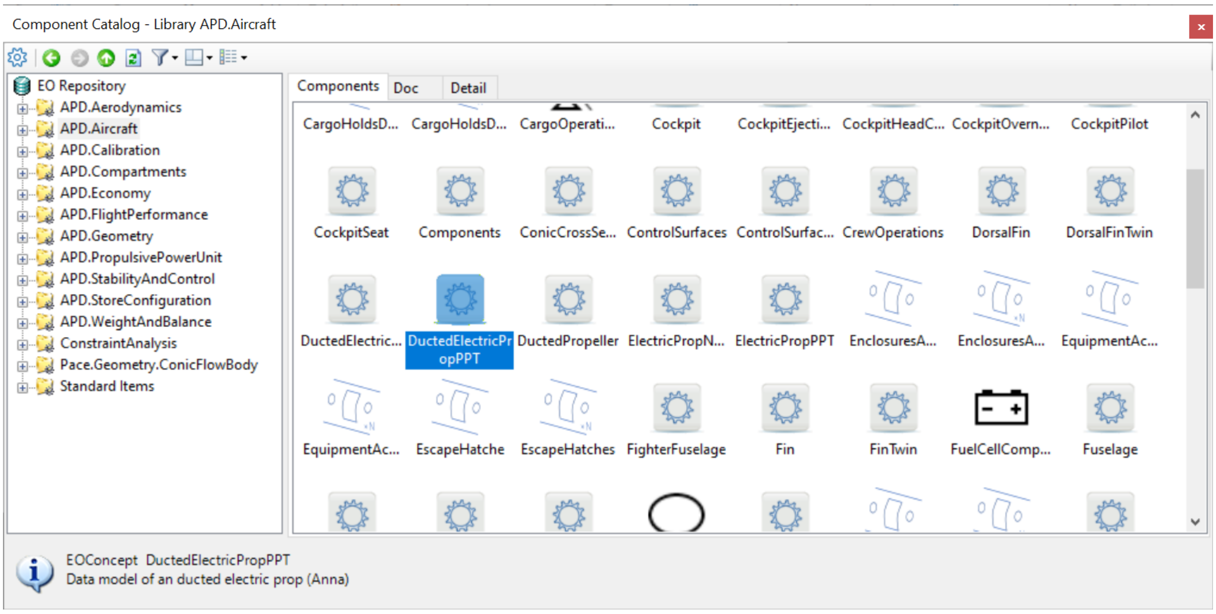


Figure A.5: Component window.

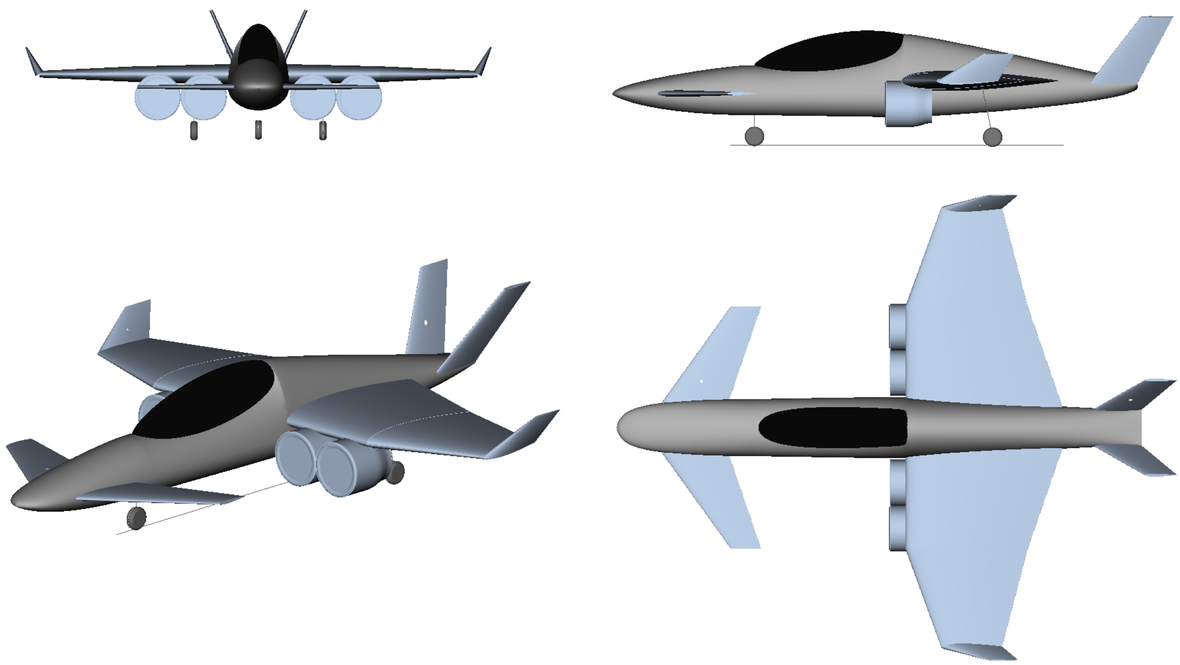

Figure A.6: Case study three views.

## A.2. Electric Ducted Fan on APD Knowledge Designer

The creation of a new power plant on APD Knowledge Designer needs several steps, in order to integrate it correctly in the workspace. It is suggested to start from an existing similar powerplant, following its implementation step-by-step. In the specific case of EDF, electric propeller powerplant is chosen as baseline.

Where needed, new methods and formulas have been coded in C# language.

The following objects are created in the Aircraft Engineering Object.

- DuctedElectricPropPPT, on the fashion of ElectricPropPPT. It can be considered as the final assembly of the power plant, consisting in the nacelle and the performance settings.
- DuctedElectricPropNacelle, on the fashion of ElectricPropNacelle.
- DuctedPropeller, on the fashion of Propeller.

In the Geometry Engineering Object, the following components are created.

- DuctedPropellerGeometry, representing geometrically the fan.

- DuctedElectricPropNacelleGeometry, on the fashion of ElectricPropNacelleGeometry, representing geometrically the nacelle of the electric motor.
- DuctedElectricPropCowlingGeometry, on the fashion of TurboFanCowlingGeometry, representing geometrically the duct.

Volume and cross section computation methods are also modified with respect a simple electric propeller to account for the duct.

The hierarchy of the created items is schemed in fig. A.7.

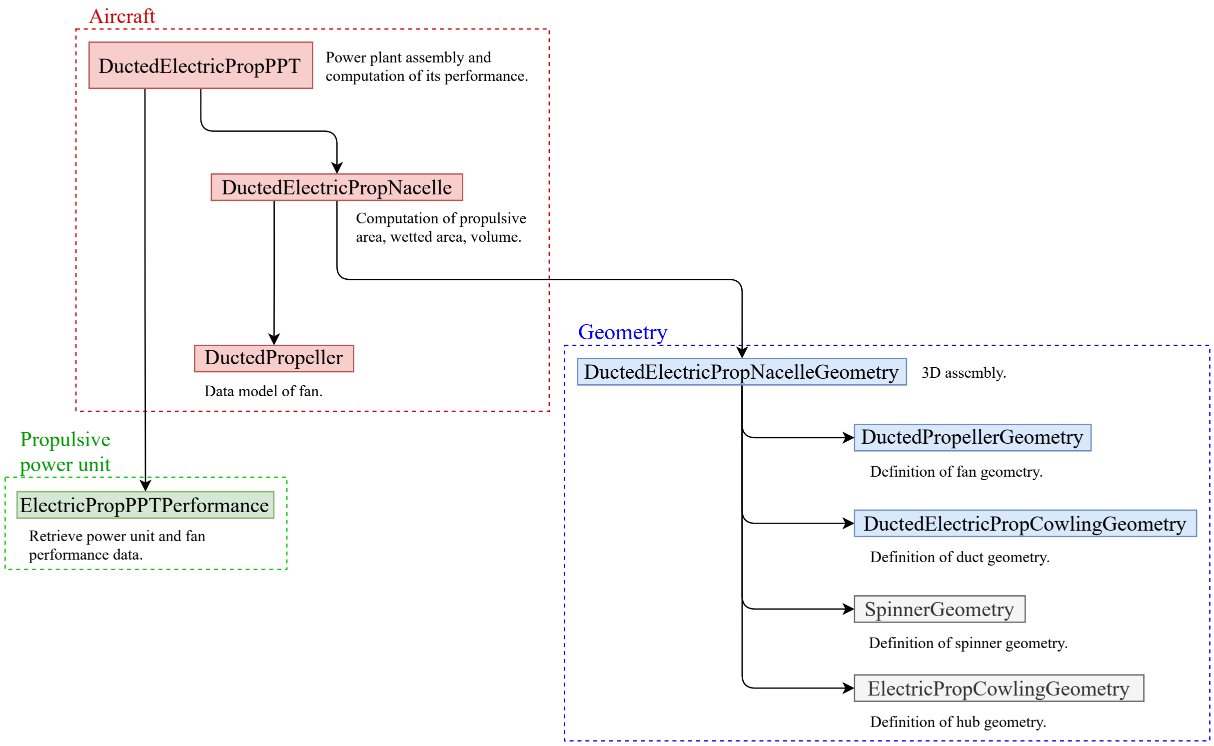


Figure A.7: EDF implementation: structure on APD Knowledge Designer; in gray the untouched items.

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# Acronyms

**APD** Aircraft Preliminary Design

**CR** Cruise

**EDF** Electric Ducted Fan

**EIS** Entry In Service

**EM** Electric Motor

**EO** Engineering Object

**eVTOL** Electric Vertical Take-Off and Landing

**FAA** Federal Aviation Administration

**FoM** Figure of Merit

**FPR** Fan Pressure Ratio

**HeVTOL** Hybrid Electric Vertical Take-Off and Landing

**HOV** Hover

**ISA** International Standard Atmosphere

**MCP** Maximum Continuous Power

**MDT** Multidata table

**MTOW** Maximum Take-off Weight

**OEW** Operational Empty Weight

**PE** Pure electric

**SFC** Specific Fuel Consumption

**SOC** State Of Charge

**TAS** True Air Speed

**TG** Turbogenerator

**UAM** Urban Air Mobility

**V/STOL** Vertical and Short Take-Off and Landing

**VFR** Visual Flight Rules

**VLND** Vertical Landing

**VROC** Vertical Rate Of Climb

**VTO** Vertical Take-Off

**VTOL** Vertical Take-Off and Landing

# List of Symbols

$A$ Area

$H$ Enthalpy

$M$ Mach number

$N$ Number of propulsive units

$P$ Power

$R$ Gas constant

$T$ Temperature

$V$ Velocity

$W$ Weight

$\Omega$ Rotational velocity

$\beta$ Compression ratio

$\chi$ Mass ratio

$\delta$ Area ratio

$\dot{m}$ air flow

$\eta$ Efficiency

$\gamma$ Specific heat ratio

$\mathcal{T}$ Thrust

$\mathcal{V}$ Volume

$\overline{e}$ Specific energy

$\overline{p}$ Specific power

$\pi_p$ Fan Pressure Ratio symbol

$\pi$ Pressure ratio

$\rho$ Air density

$\sigma$ Hub-to-tip ratio

$c_p$ Specific heat at constant pressure

$c$ Coefficient

$f$ Fuselage down-wash correction

$h$ Altitude

$l$ Length

$m$ Mass

$p$ Pressure

$r$ Rotor radius

# List of Super-Subscripts

$CR$ Cruise

$C$ Compressor

$EDF$ Electric ducted fan

$EG$ Electric generator

$EM$ Electric motor

$H$ Hover

$TG$ Turbogenerator

$TS$ Turboshaft

$T$ Turbine

$batt$ Battery

$cc$ Combustion chamber

$fan$ Fan

$fus$ Fuselage

$f$ Fuel

$hub$ Hub

$is$ Isentropic condition

$nozz$ Nozzle

$p$ Polytropic

$ref$ Reference condition

$req$ Requirement

$s$ Static

$t$ Total

$wing$ Wing related

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