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Range Estimation Of A Novel Concept Electric Aircraft Based On Modified Breguet Equation

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Abstract. The electric vertical-take off and landing aircraft are able to perform vertical flights, equipped with an electric propulsion and energy storage system. This kind of aircraft has gained more and more importance during the last decades, in particular for urban aerial mobility. Its design is function of several project specifications, among them the range to cover a cruise flight mission profile. The present work is intended to show a modified Breguet equation for the range estimation applied to a novel electric aircraft concept. The advantage of this equation is to avoid the knowledge of parameters which are difficult to be found a-priori in a preliminary design phase. It is worth noticing that the modified Breguet estimated range needs further corrections to obtain a correct effective cruise range. For this reason, the estimated range is compared with the effective cruise range obtained with an energy balance equation. Results show that the estimated and theoretical range values are very close and comparable, hence the modified Breguet equation for electric aircraft is correct. In order to validate the present results, a comparison with several urban air mobility aircraft is performed.

INTRODUCTION

In recent years, the electric aircraft are gaining popularity, in particular the ones able to perform vertical flights, the electric VTOL (eVTOL) aircraft. A large number of companies are currently developing different types of eVTOL. In [1], [2], [3] multiple configurations of prototype eVTOL aircraft are studied and compared.

Design of an eVTOL aircraft requires a reliable theoretical design. One of the crucial problems during the design is the range estimation based on a desired mission profile and aircraft characteristics. Multiple a-priori information are needed, for example the required energies for the climb, cruise and descent phases, which may be difficult to be computed. This is more evident in the case of special-purpose aircraft for urban air mobility, because they are unconventional.

A modified version of the Breguet range equation (from now on eBreguet equation), [4], well known in the flight mechanics field, can be exploited for electric aircraft range estimation. The advantage of this formula is that includes only basic information about the aerodynamic performances of the aircraft and its mass properties.

Firstly, the present work is intended to estimate, for a novel urban aerial mobility concept aircraft, the cruise range required by using eBreguet equation. Afterwards, the obtained estimated range is compared and validated with the theoretical value obtained from an energy balance. In addition, the novel concept aircraft results are compared with several urban air mobility aircraft, showing the differences by varying the estimated ranges, total aircraft mass, passengers payload and the available energy.

METHODOLOGY

Estimated range - Breguet modified equation

In this section a demonstration of the eBreguet range equation for electric aircraft is presented.

The energy of an aircraft battery C_b can be assumed, in terms of a differential equation, as $-dC_b = \Pi_b dt$, where Π_b is the continuous power required by the aircraft motors, along a single cruise mission profile phase.

The overall efficiency from the battery to the rotors is $\eta_b = \eta_c \eta_m \eta_p$ DoD SOH $(1 - \mathrm{SOC}_{min})$. η_c is the efficiency of the controllers (ESC plus the inverter), η_m is the one of the motors and η_p the one of the propellers. In addition, the battery has a Depth of Discharge DoD (considered equal to 1) and a State-of-Health SOH (considered as 0.9). SOC_{min} is the lower and upper bound values of the state of charge of the battery, it can be considered equal to 10 %.

Taking into account the efficiency reduction, the net aircraft power for the straight flight can be defined as $\Pi_n = TV_\infty = (\mathrm{MTOW}\ V_\infty)/E = \eta_b \Pi_b$, which is equivalently the required power to balance the aircraft resistance D during flight. In the last equation, the thrust force is $T = D = L/E = \mathrm{MTOW}/E$ coming from forces equilibrium equation, $E = L/D$ is the aircraft efficiency, V_∞ is the wind speed and MTOW = MTOM g is the maximum take-off weight of the aircraft (with MTOM as the mass of the aircraft).

For demonstration purposes, eBreguet range equation is derived as function of the battery energy, instead of the battery mass. This is because the mass of the battery doesn't change during flight phases, instead the total energy decreases over time until it reaches a minimum value (for simplicity considered as zero). With this condition, the range of the aircraft can be defined as

$$ds = V_\infty dt = -V_\infty \frac{dC_b}{\Pi_b} = -\frac{E\eta_b}{\mathrm{MTOW}} dC_b \tag{1}$$

Equation 1 can be integrated between the initial and final aircraft positions $[S_0, S_1]$ and the energies in the range $[C_{b0}, C_{b1}]$, to find the eBreguet range equation shown in Equation 2. It is assumed that the flight is performed at constant angle of attack (constant E), the aircraft weight MTOW is assumed constant and known a priori, the energy at the end the flight mission is considered $C_{b1} = 0$ Wh.

$$S_{eBG} = \int_{S_0}^{S_1} ds = -\frac{E\eta_b}{\mathrm{MTOW}} \int_{C_{b0}}^{C_{b1}} dC_b = \frac{E\eta_b}{\mathrm{MTOW}} C_{b0} = \frac{E\eta_b}{\mathrm{MTOW}} C^\star m_b = E\eta_b C^\star R_b \tag{2}$$

where $C_{b0} = C^\star m_b$, with $C^\star$ and m_b respectively the specific energy (expressed as Wh/kg) and the total mass of the battery (expressed as kg). The battery to aircraft maximum take-off weight ratio is $R_b = m_b/\mathrm{MTOW}$.

Effective range - Energy balance

The effective range S_{EFF} is the range covered by the aircraft during climb, cruise and descent phases. In particular, S_{EFF} can be found starting from an energy balance equation as $C_b = P_h t_h + P_{tr} t_{tr} + P_{cr} t_{cr} + P_{cl} t_{cl} + P_{des} t_{des}$, by isolating the cruise time t_{cr} and multiplying by the cruise speed V_{cr}. Then, the climb and descent contributions to the total straight distance are added, and the effective range can be found as follows

$$S_{EFF} = V_{cr} t_{cr} + S_{cl,hor} + S_{des,hor} = \frac{V_{cr}}{P_{cr}} \left[C_b - (P_h t_h + P_{tr} t_{tr} + P_{cl} t_{cl} + P_{des} t_{des})\right] + S_{cl,hor} + S_{des,hor} \tag{3}$$

In particular, for the climb and descent phases there is a flight path angle γ to increase or decrease the flight altitude, and the horizontal distances during these phases can be computed as $S_{cl,hor} = V_{cl,hor} t_{cl}$ and $S_{des,hor} = V_{des,hor} t_{des}$. In this case, the decomposed horizontal speed are $V_{cl,hor} = V_{cl} \cos\gamma$ and $V_{des,hor} = V_{des} \cos\gamma$, for climb and descent respectively. $C_b = C_{b0}\eta_b$ is the specific energy available in the aircraft batteries, P_{cr} is the cruise required power, t_{cr} is the required time for cruise, P_h is the hover required power, t_h is the hover flight time, P_{cl}, P_{des} are respectively the climb and descent required powers, t_{cl} is the climb flight time, t_{des} is the descent flight time, P_{tr} is the power and t_{tr} the time required for transition phases. The efficiencies are already present in the computed powers for the mission profile phases.

The first term of Equation 3, $S_{onlyCr} = C_b (V_{cr}/P_{cr})$, is an ideal range covered if the climb and descent phases are not present and all the energy from the batteries is exploited for an horizontal cruise flight. This term needs to be equal to the range computed with Breguet formula, Equation 2. The S_{EFF} is clearly lower than S_{onlyCr} because of the hover, transition, climb and descent terms subtracted. It is worth notice that Equation 3 is only needed to understand the origin of S_{onlyCr} to validate S_{eBG} range, and for the result section only the last two are considered.

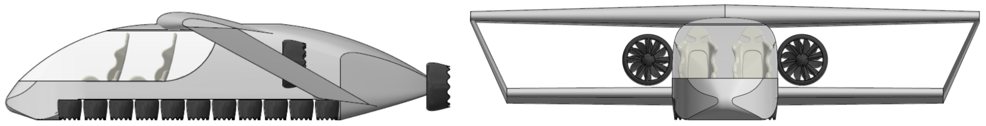

FIGURE 1. Novel aircraft concept preliminary design sketch - Lateral view (left) and front view (right)

TABLE 1. Data for novel concept aircraft and computed eBreguet S_{eBG} and S_{onlyCr} ranges

$S_{cr,des}$ [km]	PAX [-]	m_{PAX} [kg]	MTOM [kg]	m_b [kg]	R_b [%]	E [-]	η_b [-]	P_{cr} [kW]	V_{cr} [km/h]	C_b [kWh]	S_{eBG} [km]	S_{onlyCr} [km]
100	6	540	1563.66	286.96	18	12.16	0.6937	87.66	250	82.64	181.81	181.81
130	6	540	1661.31	352.55	21	12.55	0.6937	90.18	250	101.53	216.91	216.91
160	6	540	1771.41	433.22	23	12.76	0.6937	94.59	250	124.77	254.09	254.09
190	6	540	1897.63	524.36	28	12.93	0.6937	99.99	250	151.02	290.88	290.88
220	6	540	2046.93	630.47	31	13.04	0.6937	106.84	250	181.57	327.18	327.18
250	6	540	2232.04	759.83	34	13.09	0.6937	116.03	250	218.83	362.79	362.79

TABLE 2. Data for urban air mobility prototype aircraft (source: [5], [6] [7], [8])

Aircraft name	PAX [-]	m_{PAX} [kg]	MTOM [kg]	m_b [kg]	R_b [%]	C_b [kWh]	E [-]	η_b [-]	S_{eBG} [km]	$S_{declared}$ [km]
Lilium Jet	5	450	3175	950	30	273.60	18.26	0.65	375.34	261
Wisk Cora	2	180	1269	293.1	23.1	84.41	10.8	0.65	171.36	100
Pipistrel 801	5	450	2950	758	25.7	218.30	9.1	0.65	160.63	97
Airbus Vahana α	1	90	711	138	19.4	39.74	7.4	0.65	98.67	60
Bell Nexus 6HX	5	450	2730	785	28.7	226.08	9.2	0.65	181.73	97 (only electric)
Joby S4	5	450	1961	374.6	55	287.39	11.3	0.65	395.03	241
EHang-216	2	180	382	95.7	25	27.56	3.3	0.65	56.79	35

THE NOVEL CONCEPT AIRCRAFT

The novel concept aircraft is intended for passengers transportation in a smart urban aerial mobility scenario. The aircraft has the following main characteristics: able to perform take-off and landing phases with vertical flight (VTOL aircraft), full electric, able to transport five (5) passengers with their luggages plus a pilot for the aircraft flight operations control, equipped with a fixed-wing. The main novelty is that the aircraft is equipped with a patented propulsion system solution called ThrustPod, developed by the Polytechnic of Turin. ThrustPod patented propulsion system is made by a number of modules placed in the bottom part of the fuselage, as it can be seen in the preliminary design model in Figure 1. Each module contains a certain number of motors and rotors. The modules are extractable outside the fuselage and retractable inside the fuselage, thanks to an horizontal linear guide system. During the take-off and landing operations the modules are extracted externally to show the rotors and to allow the vertical flight. Instead, during climb, cruise and descent flight phases, the ThrustPod system modules are retracted internally, and the horizontal flight phases are performed with a fixed-wing and the rotors in the rear part of the fuselage.

RESULTS

This section presents the results of the eBreguet range estimation, validated for the novel concept aircraft and tested for several urban air mobility aircraft with different aerodynamic properties. A preliminary iterative design algorithm, explained in detail in [9], is considered to obtain the novel concept aircraft aerodynamic and performance properties, and to find an optimal configuration to reduce at minimum the aircraft MTOM: its relevant characteristics are shown in Table 1. The novel concept aircraft results are parametrized for multiple desired cruise range values $S_{cr,des}$, spanning from 100 to 250 km (the typical ranges for regional flight missions). From Table 1 it can be clearly seen that the battery to MTOM ratio R_b increases as the $S_{cr,des}$ increases, hence if $S_{cr,des}$ is known the ratio R_b can be approximately computed, to be inserted in Equation 2. In the same table the Breguet range S_{eBG} can be validated by looking at S_{onlyCr}: the two values coincide precisely, hence the estimated ranges obtained with the modified Breguet equation are correct.

To better understand and validate the results, a comparison between several urban air mobility (UAM) aircraft and

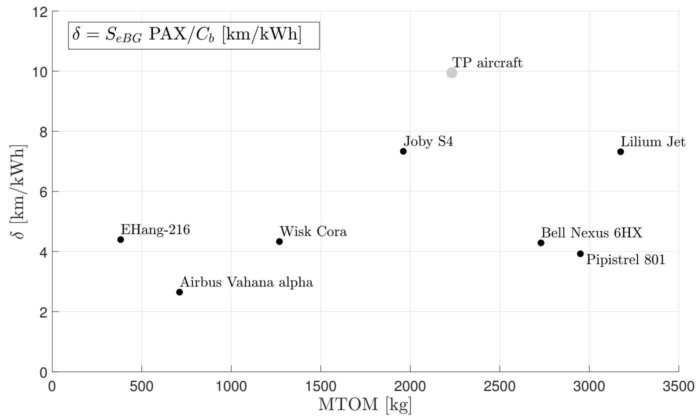

FIGURE 2. Comparison between UAM aircraft and novel concept aircraft delta parameter and MTOM

the novel concept aircraft is shown in Figure 2. In particular the MTOM for every aircraft is present in the x-axis, and a parameter $\delta = S_{eBG}\mathrm{PAX}/C_b$ in the y-axis, as the ratio of the eBreguet range by the total passenger number divided by the available energy. In the figure every point is denoted by the corresponding name of the aircraft, whereas ”TP aircraft” is the novel concept aircraft point obtained with $S_{cr,des} = 250$ km. The data for the UAM aircraft are shown in Table 2, where very similar C_b and η_b parameters are taken to perform an equal comparison with the novel concept aircraft. The specific energy $C_b = C^\star m_b (1 - \mathrm{SOC}_{min})$ is computed by considering $C^\star = 320$ kWh/kg, equal for all the aircraft. In the table is also present the range declared by each aircraft company, called $S_{declared}$, which is lower than the eBreguet range, as already explained in the Section ”Effective range - Energy balance”.

It can be seen that the novel concept aircraft results to be the best aircraft among the selected ones, able to cover a good range (comparable with the one of Lilium Jet and Joby S4), carrying an high number of passengers (5) with a quite low energy required (hence a low δ). Instead, the aircraft with lower MTOM have lower δ values (Airbus Vahana α, Wisk Cora and EHang-216), indicating a very low range covered per passengers and per available energy: this is mainly because they can accommodate only 1 or 2 passengers as payload. On the other side, the aircraft with higher MTOM are commonly able to cover more range, and the δ value results to be higher: this is the case of Joby and Lilium Jet, since they can transport up to 5 passengers. Exceptions to the last trend are the Bell Nexus 6HX (accounting only the electric part of its hybrid propulsion) and the Pipistrel 801, which have a low δ because of their low aerodynamic efficiencies ($E \approx 9$ for both), which considerably reduces the eBreguet range even if the passengers payload is high (5).

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