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HYBRID PROPULSION SYSTEM PERFORMANCE MODELING FOR REGIONAL TURBOPROP AIRCRAFT

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Abstract: *This paper presents the development and validation of an aircraft performance model for regional turboprop aircraft, with a focus on integrating hybrid propulsion systems. Hybrid propulsion technologies, combining traditional gas turbines with hydrogen fuel cells, offer a promising solution to reduce aviation's carbon footprint, addressing the sector's impact to global CO_2 emissions. The model, programmed in MATLAB, incorporates key flight phases (take-off, climb, cruise, descent, approach) and accounts for altitude-dependent variations in air density, weight, and thrust requirements. Validation of the model was conducted using reference data from standard turboprop aircraft, demonstrating accurate fuel consumption and performance predictions across missions of 200 NM and 300 NM. The results confirm the model's reliability in supporting hybrid propulsion optimization while meeting mission operational requirements.*

Keywords: Hybrid propulsion, Turboprop aircraft, Performance modeling, Fuel cells

1. Introduction

Hybrid aircraft technology aims to address the environmental impact of aviation, which is responsible for 2-3% of global CO_2 emissions as stated for example by Graver et al. (2018). Hybrid-electric propulsion offers a solution by potentially reducing emissions by up to 50%. Thus, advancing hybrid aircraft technology is a critical step towards a more sustainable aviation industry, aiming to meet international climate targets and reduce the sector's is carbon footprint. The AMBER project, involving a 21-member consortium, seeks to develop a hybrid system combining hydrogen fuel cells with traditional gas turbines for short-haul routes. This shows the need for a performance model of a turboprop aircraft, which has been developed and will be described below.

The current state of knowledge in the field of hybrid aircraft propulsion mostly focuses on finding the optimal energy distribution to minimize the output parameters including energy/fuel quantity, time and emissions. Most of the articles are dated in the last few years, demonstrating the topicality of the issue and the need to develop an aircraft performance model for a variable aircraft. The combination of a standard gas turbine with internal combustion and hydrogen fuel cells or batteries into a single hybrid propulsion is optimized without affecting the proposed flight mission, as published by Rostami et al. (2022), Rajashekara et al. (2008) or Sliwinski et al. (2017).

Finally, basic mission constraints are provided, and the optimum aircraft configuration and the use of hybrid propulsion are sought in several publications of Ruscio et al. (2021), Friedrich and Robertson (2015) and Seitz et al. (2022).

2. Methods

The aircraft performance model is programmed using MATLAB. Each time step updates atmospheric conditions, aircraft weight, engine parameters, and thrust requirements.

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A key Eq. (1) defines the aircraft thrust T_t. The force F_n represents the thrust from the propeller due to the engine power, the force F_g represents the residual thrust due to the engine exhaust gases. Based on the internal combustion engine power P_{ICE}, the thrust T_t produced by the aircraft is calculated using the propeller efficiency eff_{prop} defined in Eqns (2) and (3).

$$T_t = F_n + F_g = \frac{P_{ICE} * eff_{prop} * n_e}{TAS} + F_g, \quad (1)$$

$$J = \frac{TAS}{\frac{\pi}{30} * RPM * D_p}, \quad (2)$$

$$eff_{prop} = max\,[f(J, \beta)], \quad (3)$$

where n_e is number of engines, TAS is True Air Speed, J is propeller speed constant, RPM is rotations per minutes, D_p is propeller diameter and β is pitch of the propeller blade.

The software accounts for altitude-dependent variations in air density and temperature, updating fuel consumption and weight loss throughout the mission. Mission phases (take-off, climb, cruise, descent, approach) are handled by the software. For example, when conditions are met, such as climbing to the desired altitude, the climb switches to cruise which ensures accurate thrust and power calculations through iterative loops. The software evaluates the aircraft's evolving weight and environmental conditions, adjusting the required thrust and power. Engine torque and calculated produced power P_{ICE} for flight mission are shown in Figure 1.

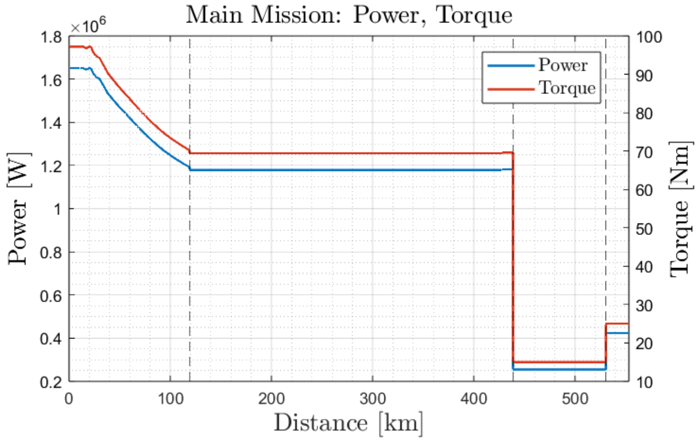

Fig. 1: Power & torque on main flight mission for 1 engine.

Eqns (4) and (5) represent equation of motion. These computations are recalculated at each time step, ensuring accuracy across all flight segments. Based on this, the gamma angle γ defined by Eq. (6), is determined and the flight profile is shown in Figure 1.

X: $$C_D * \frac{TAS^2}{2} * \rho_H * \mathrm{S} - \sin\gamma * W_e * \mathrm{g} = T_t \quad (4)$$

Y: $$C_L * \frac{TAS^2}{2} * \rho_H * \mathrm{S} - \cos\gamma * W_e * \mathrm{g} = 0 \quad (5)$$

$$\gamma = \sin^{-1}\left(\frac{Rate}{TAS}\right) \quad (6)$$

3. Flight mission

The flight mission includes key phases: take-off, initial climb, cruise, descent, and approach as shown in Figure 2. Each phase has a specific speed based on the aircraft's characteristics and thrust requirements. Rate of climb is calculated based on the angles from Eqns (4) and (5). The climb rate ranges from 1500 ft/min during the initial climb to 400 ft/min at FL200, descent is around 1200 ft/min.

Approach rate is then 600 ft/min. Together with gamma angle γ representing the angle of ascent/descent shown in Figure 3. The cruise altitude for this mission is 20 000 ft (FL200). Taxi phases involve specific allowances for power and fuel consumption. During taxiing, minimal fuel is consumed, and thrust requirements are low, this phase is taken with a fixed segment fuel.

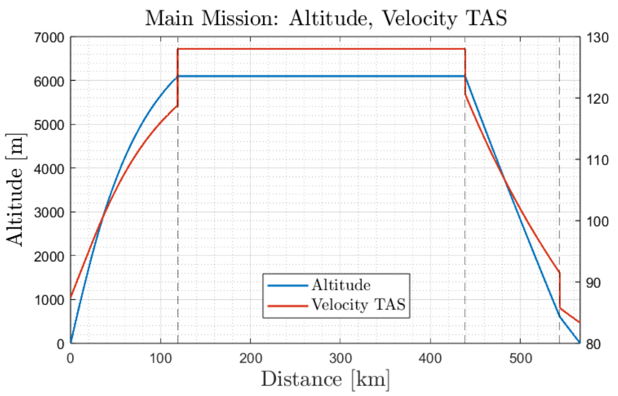

Fig. 2: Altitude (blue) & CAS Speeds (red).

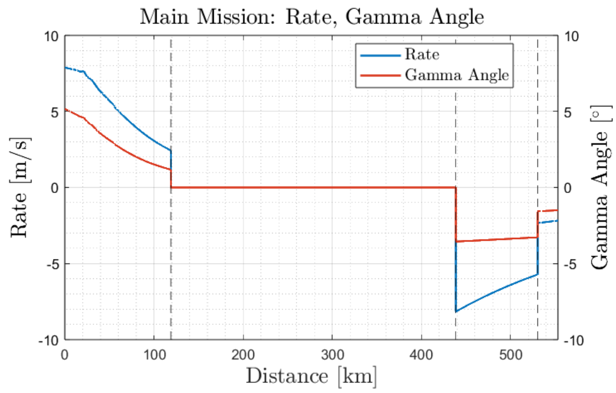

Fig. 3: Flight rate (blue) & Gamma angle of climb (red)

In order for the envisaged flight mission to meet the necessary mission operational requirement, it is necessary to consider an alternate mission in addition to the main mission. This is defined after reaching the final destination as a diversion to an 87 nm alternative airport at FL100 cruise speed and then a 45-minute holding time. This brings the need to model an alternate mission for which the initial conditions are just the final conditions from the main mission.

The aircraft model used is based on a reference turboprop aircraft. Standard rates of climb for reference aircraft is (e.g., 1500 ft/min) and descent (1000 ft/min), mission profile speeds (170kts CAS speed for climb, 270 TAS speed for cruise), wing surface 61 m^2, MTOM up to 22.5 tons and propeller diameter 3,96 m. The lift and drag coefficients are also calculated and a characteristic is a redesigned aircraft drag/lift polar based on known speeds and performance created. This polar is then used in model. Typical fuel burn characteristics for turboprop engines is according to the reference aircraft FCOM and reference engine performance. These values provide a foundation for validating the aircraft's performance under the propulsion model.

Fuel flow is then calculated based on the engine power. This affects the total weight of the aircraft W_e, thus affecting the initial conditions for the calculation. Fuel consumption is calculated at each flight segment, influenced by altitude, weight, and power requirements. As altitude increases and weight decreases, fuel burn efficiency improves, reducing the power needed. As may be see in Figure 4.

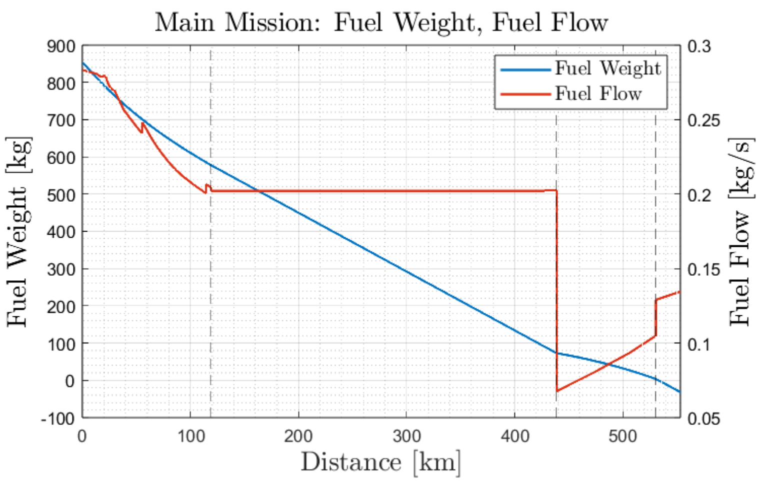

Fig. 4: Fuel weight consumption (blue) & and Fuel flow (red) on flight

The model validation is carried out by comparing block fuel weight across various mission lengths with standard turboprop performance taken from Filippone (2012). This validation in Table 1 demonstrates that the model, after the drag matching activity, is within an acceptable accuracy, providing a reliable basis for further study of hybrid propulsion systems. Validation data are taken from a reference turboprop aircraft.

Tab. 1: Model validation cases.

	ISA+10	Range [km]	Time [min]	Fuel tanked [kg]	Payload [kg]	TOM [tons]	Fuel diff. [kg]
200 NM (370km)	Reference	370	55.4	611	6460	22.5	0
	Model	370	51.1	611	6460	22.5	-15
300 NM (555km)	Reference	555	78	854	6460	22.5	0
	Model	555	75.5	854	6460	22.5	-20

4. Conclusions

This paper presents the development of an aircraft performance model for a regional flight mission. Based on the equations of motion, the required engine thrust was determined and the required engine power was calculated. The results were then compared to a reference turboprop aircraft and validated for reference flight missions on 200 NM and 300 NM sectors.

Future work will focus on optimizing the integration of hybrid-electric propulsion systems, including fully electric or hybrid engines. The model will be extended to minimize CO_2 and non-CO_2 emissions while optimizing fuel efficiency. Further validation of advanced propulsion systems and exploration of alternative flight paths are planned to optimize operational costs and environmental impact.

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CLEAN AVIATION

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