Hybrid Powertrain Concept for Small Air Transport (HYPSAT)

Helmut Kühnelt, AIT

2021 Revised-Capacity Model

Martin Dimo, AIT

Introduction

Starting in 2016, the Austrian Institute of Technology researched the effectiveness of hybridizing the propulsion systems of various single-engined light aircraft. The aircraft that were utilized for virtual modeling were the following:

Diamond DA40 NG
-4 seater, powered by a 168 horsepower Austro AE300 Diesel engine

Pipistrel Alpha Electro
-2 seater, powered by an 80 horsepower Pipistrel PEM 60MVLC electric engine

To calculate initial predictions of fuel consumption, efficiency, and economic feasibility, the flight behavior and physical attributes of the above aircraft were modeled in Dassault Systemes *Dymola*, a simulation environment for systems engineering based on Open Modelica. A digital library composed of real aircraft data, environmental variables (weather, terrain, etc.), and detailed propulsion system models was created under the name HYPSAT.

The hybrid propulsion systems that were analyzed differed slightly between both aircraft in terms of utilization and purpose. The Diamond DA40 NG was modeled with a parallel hybrid propulsion concept, in which the internal combustion engine connects to an electric generator in parallel to optimize fuel consumption by splitting the power load during high-performance segments of a flight. The Pipistrel Alpha Electro, in contrast, was modeled with a serial hybrid propulsion configuration, allowing for singular operation of either the electric generator or combustion engine whenever deemed beneficial. The figure below visually illustrates the different configurations that were constructed for the HYPSAT library.

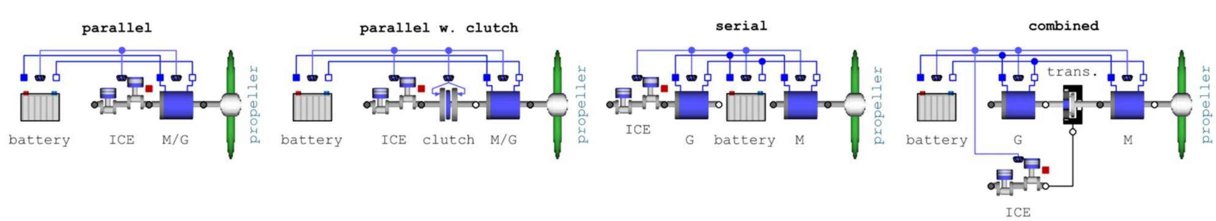


Figure 1. Several propulsion configurations modeled by the HYPSAT project.

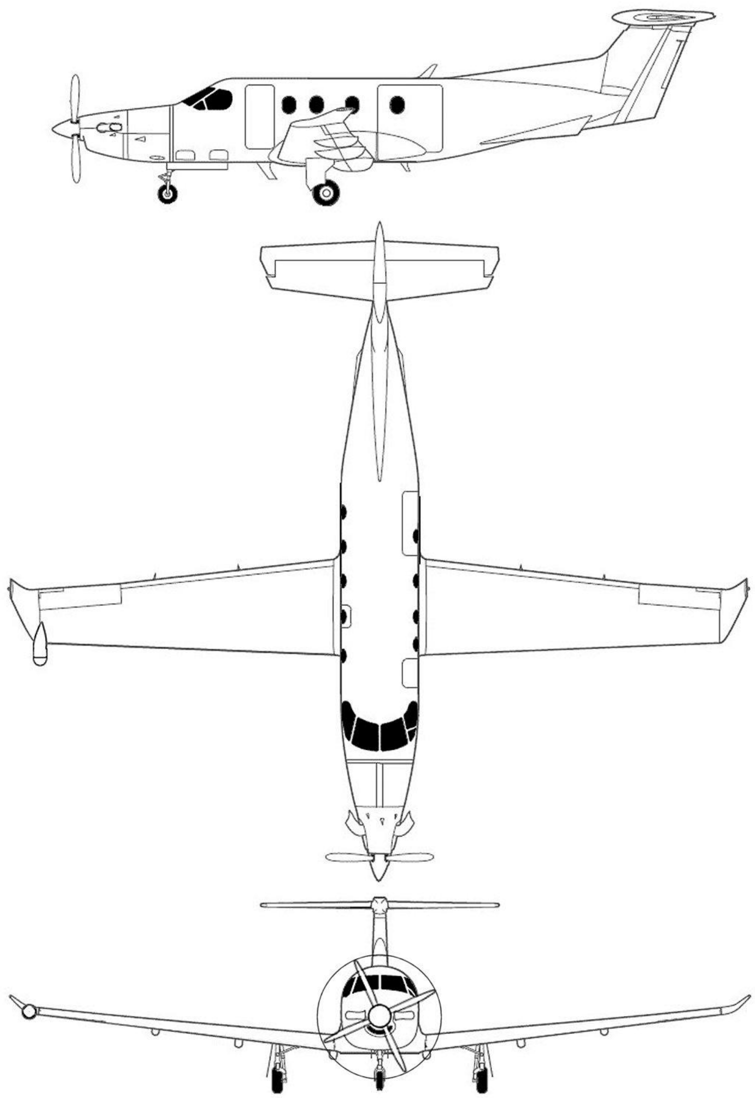
Adaptation

The goal of the Summer 2021 extension to the HYPSAT library was to test the possibility of applying existing hybridization data and propulsion propositions to a larger base aircraft. To adapt the existing HYPSAT library by AIT, the European Union commissioned project UNIFER19 brought insight on how larger airplanes may be utilized to fulfill the hybridization concept. The following table was pulled from the UNIFER19 project itself, as it was a good representation of the CS-23 class of aircraft that qualified for hybridization.

No.	Aircraft	Seats	MTOM [kg]	Range [km]	Cruise Speed [km/h]
1	Pilatus PC-12NG	9	4,740	3,417	528
2	Cessna Conquest II	9	4,468	4,064	480
3	PAC P-750 XSTOL	9	3,402	2,183	259
4	Beechcraft 350ER	11	7,484	4,986	561
5	Mitsubishi MU-2L	12	5,273	2,334	483
6	Cessna 208 Caravan	13	3,629	1,982	344
7	Beechcraft Model 99A	15	4,727	1,686	380
8	GAF Nomad N24A	16	4,264	1,352	311
9	Harbin Y-12 F	17	8,400	1,333	390
10	Embraer EMB 110	18	5,900	1,964	341
11	BAe Jetstream 31	19	6,950	1,260	264
12	Beechcraft 1900D	19	7,764	1,279	518
13	Dornier Do 228NG	19	6,575	2,363	413
14	Fairchild Metroliner III	19	7,257	2,131	318
15	Let L-410 Turbolet NG	19	7,000	2,570	417

Figure 2. Fifteen examples of CS-23 category aircraft and their essential specifications.

Since all aircraft in the aforementioned table would contend as suitable platforms to model, the decision process was based on the availability of flight characteristics of a given aircraft. The HYPSAT library requires lift, drag, and weight calculations, as well as accurate spatial dimensions to couple an aircraft model with parameterized propulsion systems. For the Alpha Electro and the DA40 NG, AIT utilized real flight data and verified characteristics from the manufacturer themselves. Due to the short-term scope of this adaptation to the original HYPSAT project, getting real flight data that wasn't publicly available would have been a great challenge and not an efficient use of time. After further examination, it was determined that the Pilatus PC-12NG would be used as a platform to expand the HYPSAT project.



Pilatus PC-12

Figure 3. A dimensional sketch of the CS-23 commuter class aircraft, Pilatus PC-12 NG

Procedure

To create an accurate compartmentalized model of the Pilatus PC-12, several attributes were necessary:

Wing Area
- The shape and surface area of the main wing directly influences how much lift the aircraft can create.

Airfoil Classification
- The coefficient of lift changes with varying angles of attack depending on the cross-sectional shape of the wing, influencing total wing lift.

Empty weight
- A vital measurement needed to estimate the minimum amount of thrust the hybrid propulsion system will need to produce for flight.

Original propulsion power
- This characteristic guides the modeling process by providing a range of thrust the hybrid propulsion system must produce.

While the two latter specifications are readily available to the public domain in multiple technical documents, the two former specifications, regarding how much lift the wing of the Pilatus PC-12 NG produces, were impossible to find experimentally without contacting the manufacturer. Therefore, mathematical estimations of the coefficient of lift were calculated and tabularized using MatLab software called *Tornado (Vortex Lattice Method).* By using sketches of the aircraft and applying basic geometry to estimate the surface area of the main wing, the Tornado program then models the wing as a lattice and applies various calculations to output the coefficient of lift, the coefficient of drag, and their derivatives. The parameters of the program include, but are not limited to; true airspeed, angle of attack, Reynolds number, and flap setting. The figures in Appendix A display the dimensions of the Pilatus PC-12 NG wing that were used and the full list of data that *Tornado* outputs. The figure below shows the Pilatus PC-12 NG main wing with a 15-degree flap setting, which was one of three flap settings that were analyzed. The range of angle of attack analyzed was between -20 and 20 degrees, providing 41 data points for the coefficient of lift. This dataset was thus used to replace the existing Modelica model that encapsulated the wing lift of either the Alpha Electro or DA40 NG, named “wingtable”. With this substitution, the modeling of the wing of the Pilatus PC-12 NG was now complete.

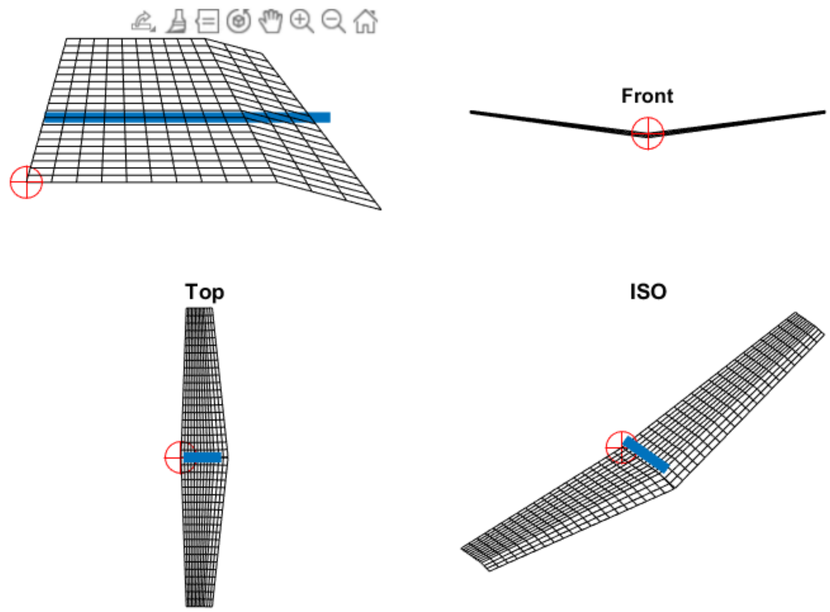


Figure 4. Scaled representation of the Pilatus PC-12 NG wing with 15 degrees flaps, equally partitioned for mathematical modeling.

The plane body model itself was not altered, as the aerodynamics of the rest of the airplane are not taken into account in the original HYPSAT library. Thus, the empty (dry) weight of the Pilatus PC-12 NG was found online and substituted to adjust the parameters associated with the plane body model. Likewise, the lift and aerodynamic effect produced by the empennage was neglected in the original model and not taken into account for the adaptation.

The most complicated conversion was that of the propulsion system model. For reference, the Pilatus PC-12 NG model that was evaluated was based on a cruise flight evaluation of the DA40 NG with a parallel hybrid propulsion system. The graphic of this reference model can be seen below.

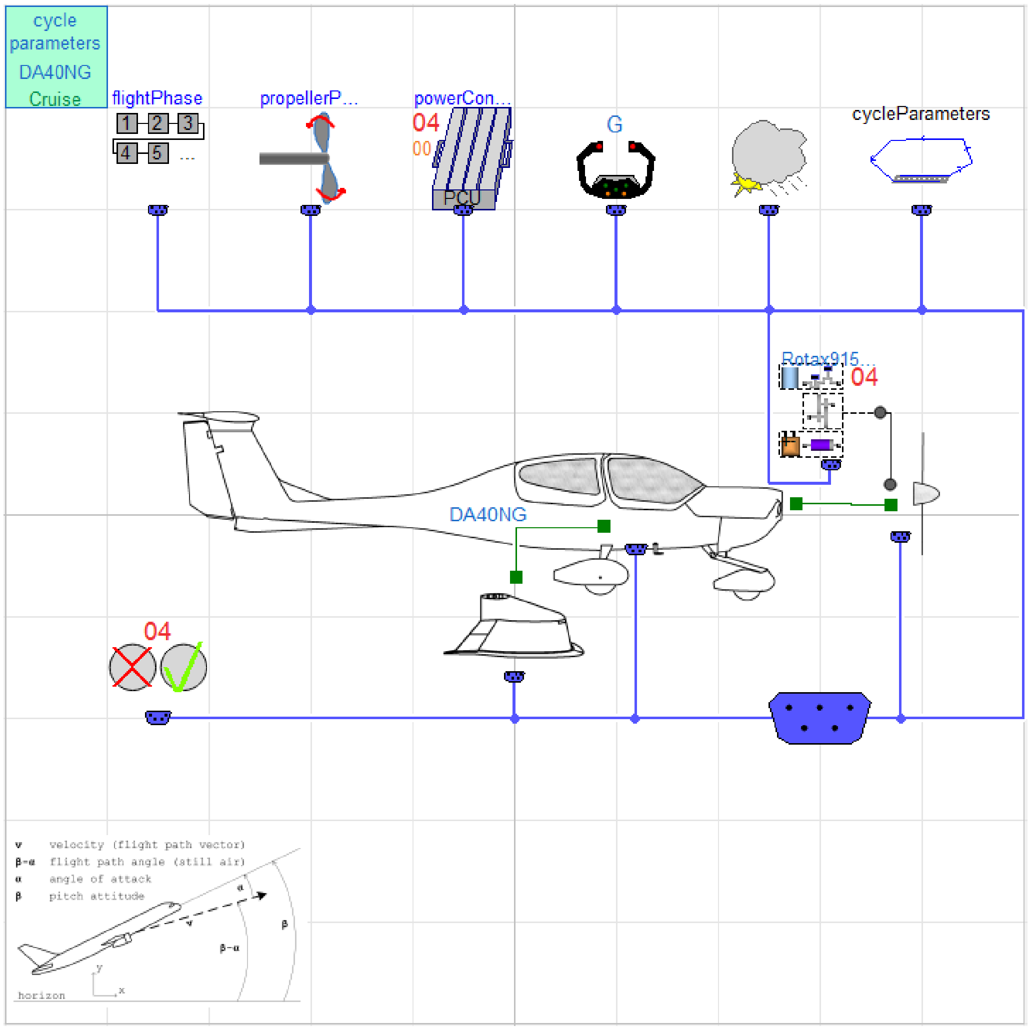


Figure 5. Graphical view of the DA40 NG Cruise flight pattern with all components and models configured in Dymola

The DA40 NG uses a Rotax 915 in parallel with a motor-generator in this configuration. The power output of the propulsion system is controlled by a singular power control unit, and the flight input stems from the flight parameters and flight phase. For the Pilatus PC-12 NG, one hybrid propulsion system wouldn't have been nearly enough to provide sufficient power for takeoff. To match the original power production of the Pratt & Whitney PT6A-67P turboprop, multiple propulsion systems per aircraft model were necessary.

The original HYPSAT library contains variations of purely combustion engines, hybrids, and all-electric propulsion systems. To stay on track with the goal of the adaption (expanding hybridization to larger aircraft), it was decided that the additional propulsion systems added to the model of the Pilatus PC-12 NG would be all-electric. Taking the Emrax 268 into consideration, a compact electric motor-generator creating 107 kW of continuous power, it was determined that multiple units would sufficiently supplement the hybrid propulsion system. An advantage of the Emrax 268 is its ability to stack two motors onto one driveshaft, producing essentially one larger motor with double the torque. This characteristic was used in the Pilatus PC-12 NG cruise example since two stacks of Emrax 268 motors would supply an additional 428 kW of power to the aircraft. The first iteration of the Pilatus PC-12 NG comprises one Rotax 915 parallel hybrid engine and two stacks of Emrax 268 generators, as seen below.

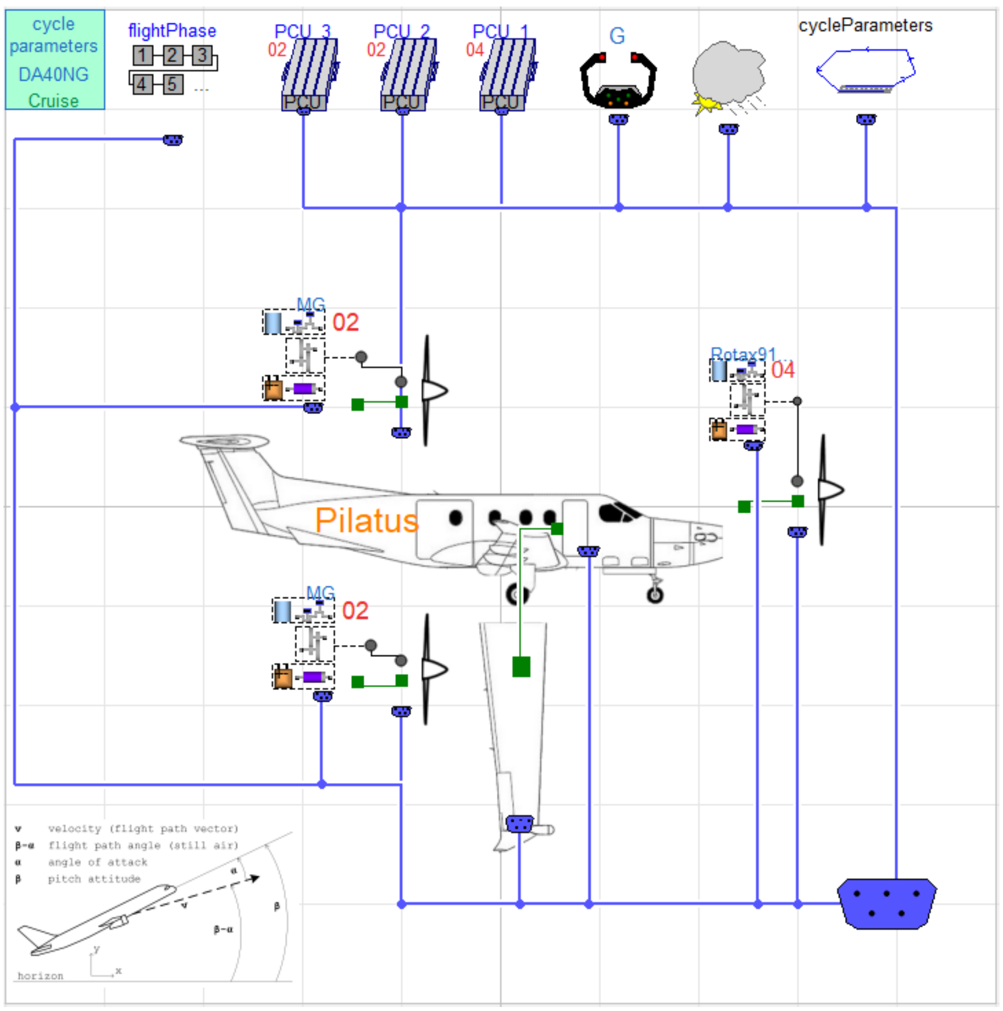


Figure 6. Complete first iteration of the adapted Pilatus PC-12 NG Dymola Model.

Results & Conclusions

The true effectiveness of this configuration in terms of positive gain through hybridization configuration still requires further analysis, as well as a much more detailed plan for battery layout optimization. The latter is essential since, while this model does perform a successful simulated take-off, it does not fly for longer than 750 seconds. This is due to the batteries for both electric generator stacks run out of charge too quickly (Appendix B). Whether it be fault to the configuration not having enough energy storage or the simulation itself (i.e. optimize power usage so that max power isn't constant or to run the electric generators at a slower speed than the main hybrid propulsion system), further iterations of the Pilatus PC-12 configuration could substantially prove that the hybridization works. Further iterations may include creating optimized flight phases and cycle parameters or creating a new model of an internal combustion engine that is built to power an aircraft of the CS-23 class rather than only light trainers. The Emrax 268 stacks have more than enough power and torque to be used as supplemental thrust sources, but the Rotax 915 is definitely a major bottleneck in the performance of the Pilatus PC-12 NG model. However, with the scope of the adaptation being to work within the framework of the existing HYPSAT library, a successful take-off is enough to show that the proof of concept has validity and that the HYPSAT library lays a strong enough foundation to allow for future adaptations to the original project.

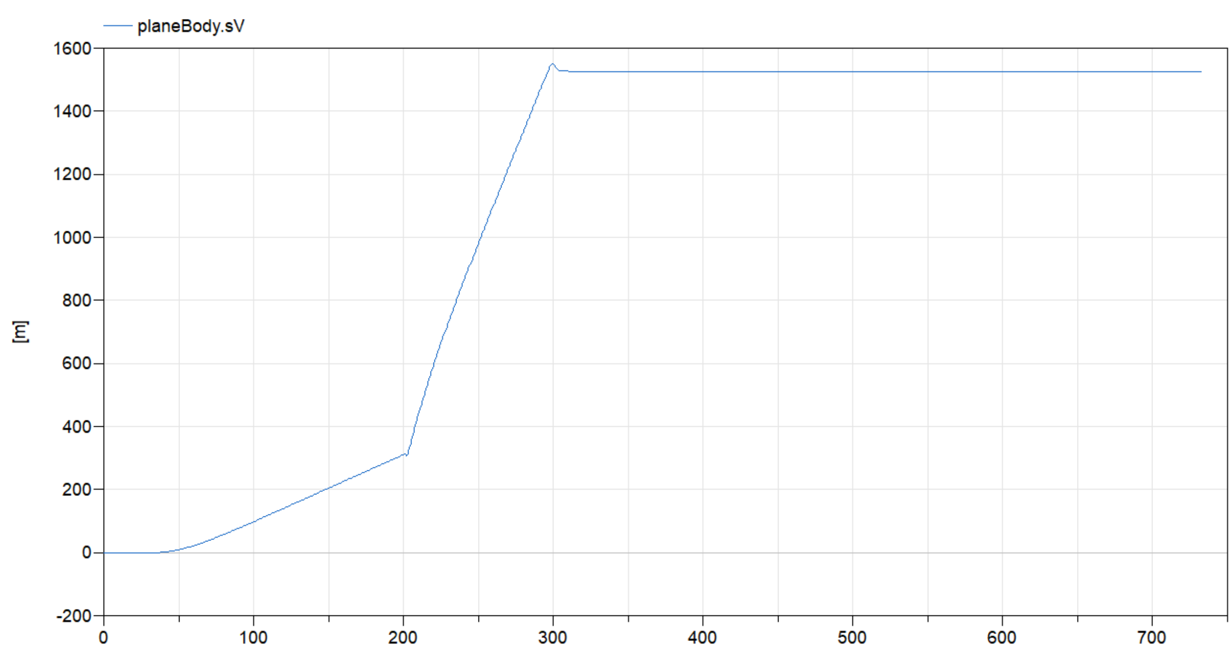
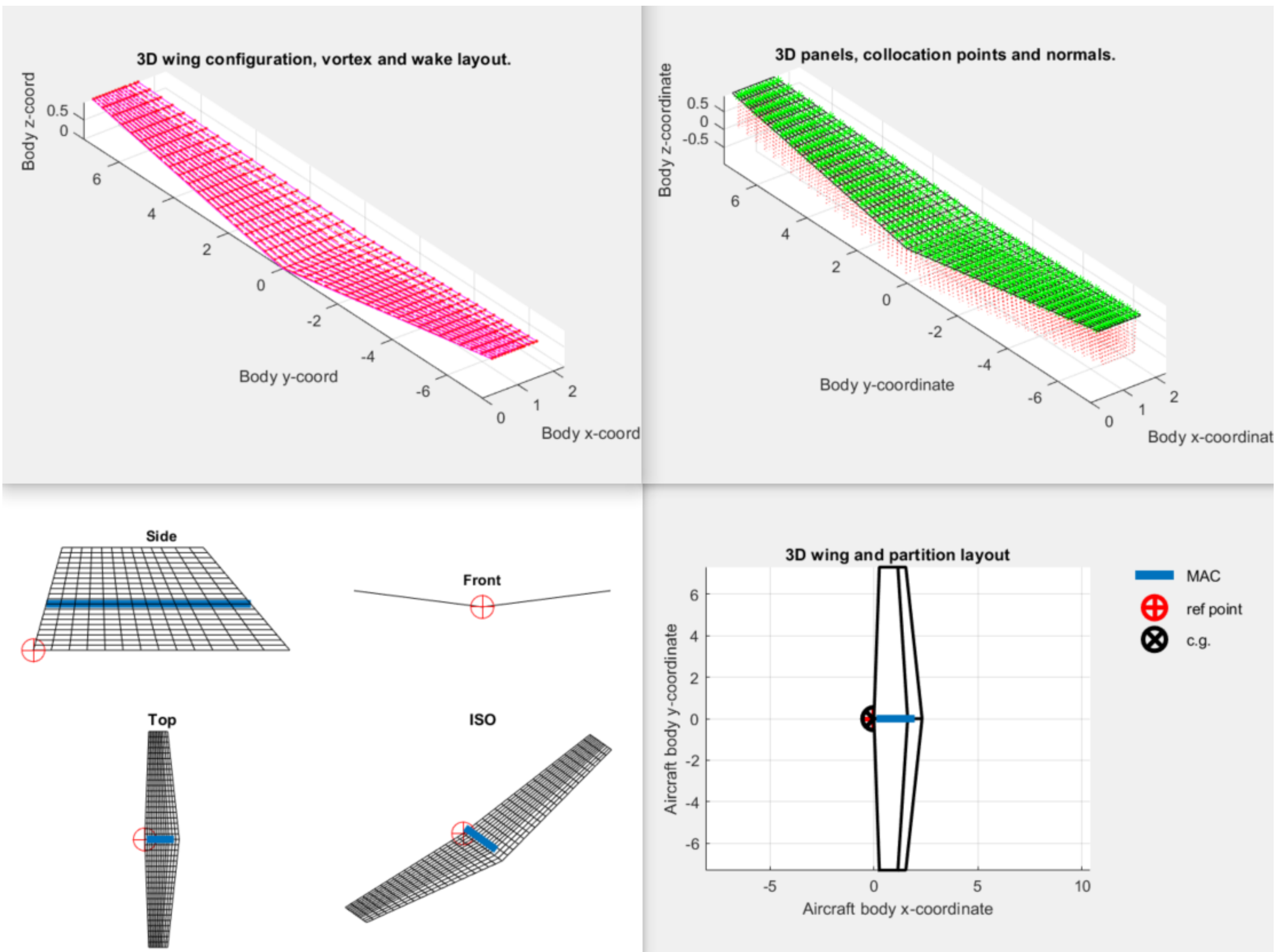
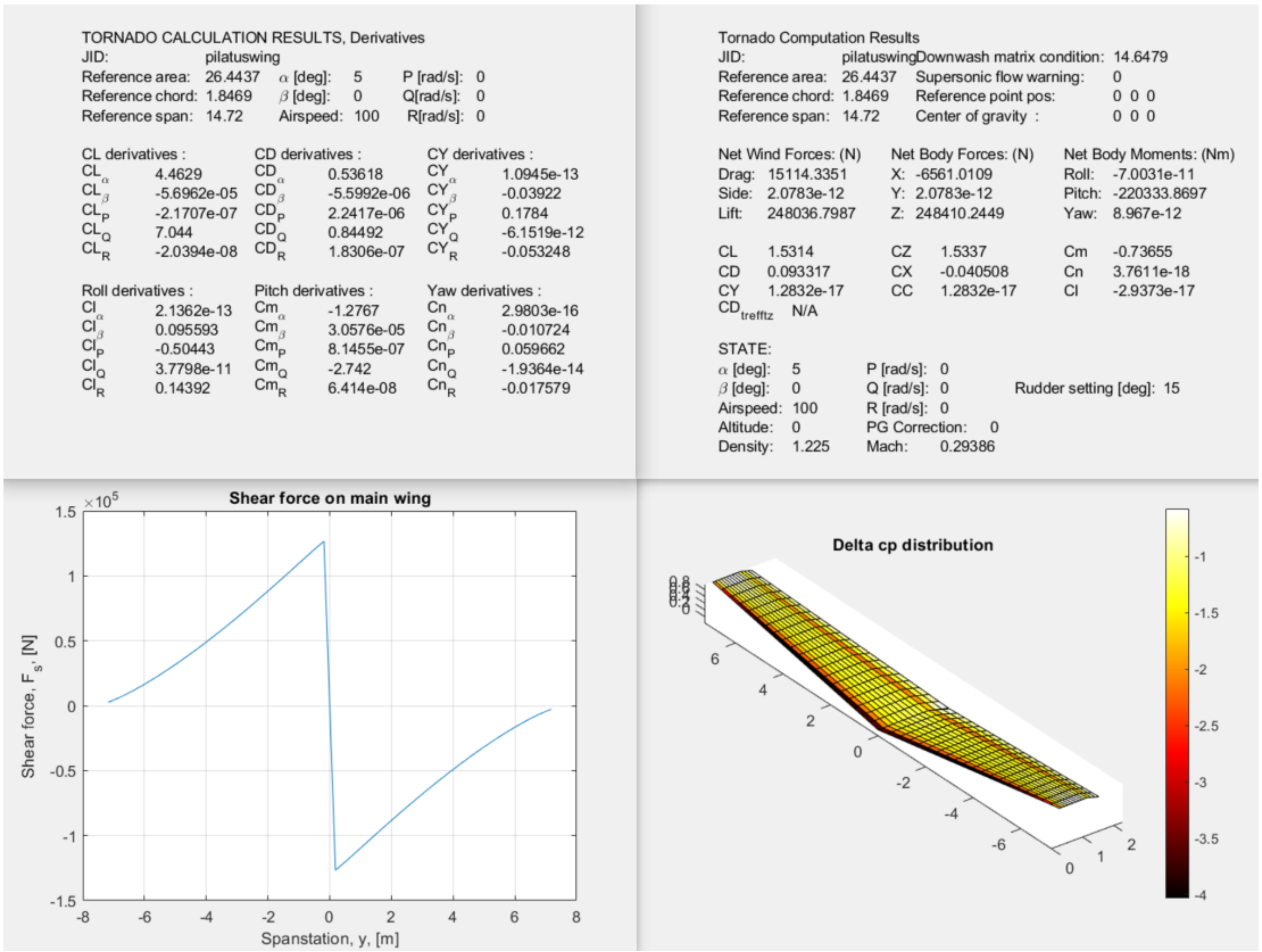


Figure 7. A graph showing the successful take-off of the Pilatus PC-12 NG model (vertical position (m) vs. time (sec))

Appendix A.

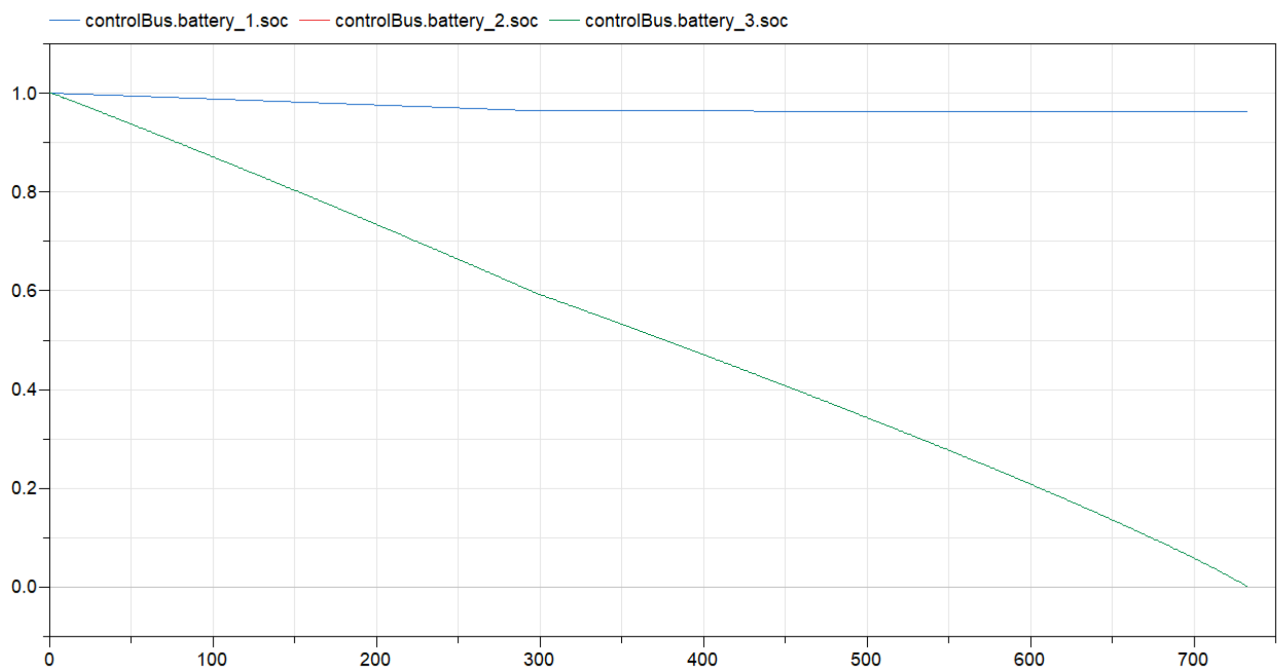


The above figure shows the static geometric plots of the Tornado simulation. The wing and its partitions are visible from multiple orientations in these windows.



The above figure shows the post-processing windows of the program as it calculates for a certain set of parameters. This specific run was set to an angle of attack of 5°, true airspeed 100m/s with a Reynolds number of 60,000 and a flap setting of 15°.

Appendix B



The state of charge throughout the simulated flight for all three batteries, one per propulsion unit. The 1st battery is associated with the Hybrid propulsion system, explaining why it sustains a stable and safe state of charge. Battery 2 and 3(represented by the green line) are attached to the first and second stacks of Emrax 268 respectively, and thus explain why the Pilatus PC-12 NG simulation does not fly past 750 seconds.

References

Kühnelt, Helmut. 2017. HYPSAT Final Report. AIT. Project number 855208.

Trainelli, Lorenzo. 2020. Community Friendly Miniliner 2019. Project number 864901. https://www.unifier19.eu/

Manual for Emrax Motors/Generators. Version 5.4. March 2020