Optimization of Energy Storage System for A Hybrid Aircraft

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***Abstract*— This research work focuses on the design and optimization of a hybrid-electric propulsion system for a small general aviation aircraft, Hyperion. The study aims to estimate aerodynamic data, performance parameters, and optimize the propulsion system to achieve maximum efficiency. The concept of hybrid-electric propulsion is introduced, highlighting its advantages over traditional propulsion systems. The estimated aerodynamic data and performance parameters are used to determine the optimal design of Hyperion, which includes a combination of electric and internal combustion engines. The Hyperion program is then discussed, which involves the implementation of the hybrid-electric propulsion system and testing of the aircraft. The results of the optimization process show that the hybrid-electric propulsion system significantly improves the aircraft's fuel efficiency and reduces its emissions. In conclusion, this study demonstrates the potential of hybrid-electric propulsion systems in general aviation aircraft. The implementation of such systems could lead to significant improvements in fuel efficiency and environmental sustainability in the aviation industry.**

Keywords—optimization process; hybrid-electric propulsion system; sustainability; aviation industry.

I.INTRODUCTION

This template, Hybrid electric propulsion systems combine the use of electric motors and combustion engines to power the aircraft, offering several benefits over traditional combustion-based propulsion systems. These benefits include reduced fuel consumption, emissions, and noise levels, as well as improved performance and efficiency [1].

The Pipistrel Panthera Hybrid aircraft is one such example of a hybrid electric aircraft that has gained attention in the aviation industry. The aircraft features a hybrid electric propulsion system that combines a traditional internal combustion engine with an electric motor, allowing for extended range and improved efficiency [2].

To optimize the performance and efficiency of hybrid electric aircraft, several critical parameters must be considered, including stall speed, maneuvering speed, never exceed speed, performance cruise speed, climb rate, take-off distance, and landing distance. These parameters can be used to estimate the aerodynamic and performance data of the aircraft and to implement design changes to improve the aircraft's overall performance.

Several methods have been proposed for the optimization of hybrid electric propulsion systems and aircraft. Another approach is the integration of energy storage systems such as batteries or fuel cells to provide additional power to the aircraft during takeoff and climb.

Research studies have demonstrated the feasibility and potential benefits of hybrid electric propulsion systems and aircraft. A study evaluated the performance and emissions of a hybrid electric aircraft and found that the aircraft could achieve significant reductions in fuel consumption and emissions while maintaining or improving performance[3].

A. Li-ion and Li-poly batteries

Lithium-ion (Li-ion) and lithium-polymer (Li-poly) are commonly used energy storage solutions for hybrid electric aircraft. These battery types have gained popularity due to their high energy density, low weight, and long life cycle.

In recent years, research has been focused on improving the performance and reliability of Li-ion and Li-poly batteries for hybrid electric aircraft. One approach to improving battery performance is through the use of advanced battery management systems (BMS) that enable more precise control of battery charging and discharging cycles. Research studies have shown that the use of advanced BMS can increase the efficiency and lifespan of Li-ion and Li-poly batteries

[7].Another area of research is the development of new electrode materials for Li-ion and Li-poly batteries. Graphene-based electrodes, for example, have shown promise for improving battery performance, offering benefits such as high energy density and fast charging times[8].While Li-ion and Li-poly batteries have significant advantages for hybrid electric aircraft, they also face challenges such as high costs and safety concerns. Research studies have evaluated the safety and reliability of Li-ion and Li-poly batteries for use in aircraft, with efforts focused on improving battery design and thermal management systems to minimize the risk of fires or explosions [9].

Overall, Li-ion and Li-poly batteries are promising energy storage solutions for hybrid electric aircraft. Continued research and development in this area will be essential to improving battery performance, reducing costs, and ensuring the safe and reliable operation of hybrid electric aircraft.

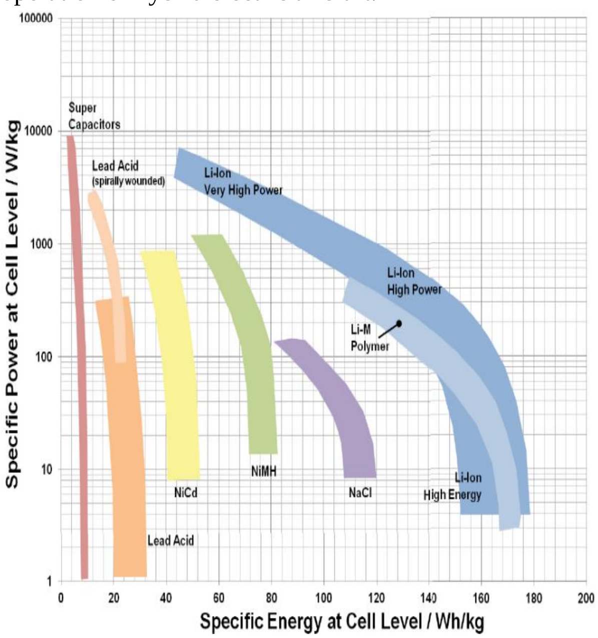

Fig. 1. Ragone diagram displaying available technologies in 2008, from [10]

II.REVIEW OF BASE MODEL

The Pipistrel Panthera Hybrid is a four-seat aircraft that combines a 200-horsepower gasoline engine with a 150-kilowatt electric motor, allowing for a range of up to 1,000 kilometers on a single tank of fuel and up to 45 minutes of electric-only flight.

The aircraft's hybrid propulsion system is designed to reduce fuel consumption and emissions, while also providing improved performance and reliability. The use of electric propulsion allows for lower noise levels and smoother operation, while the gasoline engine provides additional power and range when needed.

Data for the aircraft includes stall speed (flaps retracted), maneuvering speed, never exceed speed, performance cruise speed at 75% power, climb rate at maximum takeoff weight, take-off distance, and landing distance.

Research studies have shown that hybrid electric propulsion systems can offer significant benefits for aircraft, including reduced fuel consumption and emissions, improved performance, and increased reliability. However, the optimization of hybrid electric propulsion systems requires detailed analysis and modeling of aircraft performance and energy consumption.

The use of advanced computer programs, such as the Hyperian program used in this study, can enable more precise modeling and analysis of hybrid electric propulsion systems. By analyzing the data for the Pipistrel Panthera Hybrid and applying advanced modeling techniques, this study aims to identify opportunities for optimization and improvement of hybrid electric aircraft performance.

Overall, the Pipistrel Panthera Hybrid represents a promising example of the potential for hybrid electric propulsion in aviation. Continued research and development in this area will be essential to further improve the efficiency, reliability, and performance of hybrid electric aircraft.

Fig. 2. Pipistrel Alpha Electro, from [11]

TABLE-GIVEN DATA OF PIPISTREL PANTHERA HYBRID AIRCRAFT [12]

Sn	*Parameter*	*Value*
1	Stall speed (flaps retracted)	70 km/h (43 mph)
2	Maneuvering speed	174 km/h (108 mph)
3	Never exceed speed	281 km/h (175 mph)
4	Performance cruise speed at 75% power	260 km/h (162 mph)
5	Climb rate at MTOW	6.2 m/s (1,220 ft/min)
6	Take-off distance	190 m (623 ft)
7	Landing distance	150 m (492 ft)

B. Mission Profile

A general mission profile for a hybrid electric aircraft typically consists of several phases: takeoff, climb, cruise, descent, and loiter.

During takeoff, the aircraft accelerates to a certain speed to achieve lift and then takes off. The climb phase involves ascending to the desired cruising altitude, during which the aircraft typically operates at maximum power. Once the desired altitude is reached, the aircraft transitions to the cruise phase, during which it flies at a steady speed and altitude while consuming the least amount of fuel possible. The descent phase involves gradually descending to the desired altitude while maintaining a constant speed, followed by a landing phase. Finally, during loitering, the aircraft hovers in a certain area or flies slowly in a circular path for a specific purpose, such as waiting for clearance to land or performing aerial reconnaissance.

The specific details of the mission profile, such as the altitude and speed of each phase, depend on the specific aircraft and the mission requirements. A general mission profile for the Pipistrel Panthera Hybrid electric aircraft could be as follows:

- Takeoff: The aircraft would take off from a runway with a takeoff distance of approximately 800 feet (244 m) and climb at a rate of 1,000 feet per minute (305 m/min) to reach a cruise altitude of 5,000 feet (1,524 m).
- Climb: The aircraft would climb to its desired altitude, with a climb rate of approximately 1,000 feet per minute (305 m/min).
- Cruise: The aircraft would fly at a cruise speed of approximately 150 knots (278 km/h) at 75% power for a duration of approximately 3 hours, covering a distance of approximately 450 nautical miles (833 km).
- Descent: The aircraft would descend at a rate of 1,000 feet per minute (305 m/min) to an altitude suitable for landing.
- Loiter: The aircraft would enter a holding pattern, or loiter, for a period of time before landing.
- Landing: The aircraft would land with a landing distance of approximately 1,000 feet (305 m).

The specific details of the mission profile, such as the altitude and speed of each phase, depend on the specific aircraft and the mission requirements. However, a typical example of a mission profile for a hybrid electric aircraft can be found in a research paper by Kumar et al. (2021) [15], where they considered a hybrid electric aircraft for regional transportation with a mission profile consisting of takeoff, climb to 7,620 meters, cruise at Mach 0.8 and altitude of 7,620 meters, descent to 2,438 meters, and finally, loiter at 2,438 meters.

C. Aerodynamic data estimation

To estimate the maximum wing loading, we begin with a required cube speed, which can be set by the developer or through instruments, and an anticipated maximum flaps-down lift coefficient. The wing loading of an aircraft is influenced by several factors, such as the minimum stall speed, maximum lift coefficients, and air density at sea level (represented by ρ0). To provide some flexibility in the solution obtained, the actual wing loading is typically lower than the maximum possible value. This can be achieved by introducing a coefficient that relates the final wing loading to the maximum wing loading.

$$\left(\frac{w}{s}\right)\max \approx \frac{\rho o V\wedge 2}{2Cl\max} \tag{1}$$

The wing span of an aircraft can be determined using the aspect ratio λ, which is typically selected before conducting any analysis. The wing span (b) is calculated as the product of the aspect ratio and the reference area (S) of the wing, while the reference chord (Cre f) can be calculated by dividing the reference area by the wing span. Since the geometry of the wing is not yet known at this stage, this approach provides a means of estimating the reference chord. To determine the parasite drag coefficient, the approach suggested by Roskam [16] is utilized. The CD0, which is associated with the parasite area f, can be determined through a statistical regression connecting f with the wetted area Swept. The Swept can, in turn, be linked to the take off mass (1)

III.IMPLEMENTATION OF HYPERION PROGRAM

The above process is utilized in the Hyperion program, which enables the simulation of hybrid aircraft performance. This program will be utilized for result generation and parametric analysis (HYbrid PERformance simulatION) program:

Discussed analysis tool is a highly specialized program developed to aid in the preliminary sizing and simulation of hybrid electric aircraft. Written in MATLAB, the program uses a combination of functions and input files to estimate key performance metrics such as range, payload capacity, and fuel efficiency. This program serves as a crucial tool for researchers and engineers working on the development of hybrid electric aircraft, helping to streamline the design process and improve overall performance.

The program begins with the collection of input values using the GetData function. This function can retrieve values from an existing file or prompt the user to enter values manually. To facilitate this process, the WriteFile function provides guidance and questions to ensure all required fields are filled. Once the input file is created, the reader function builds the necessary structures to begin the sizing process.

The aircraft sizing process is conducted using the AircraftSizing function, which uses input values from the file as well as settings stored in ExtraSettings.The simulation process starts with the takeoff phase, where initial values are set and the simulation process is initiated. FMS routine is used to simulate each flight phase, which takes vector inputs and outputs. For ease of use and simplified variable handling, the program uses structures instead of arrays. Struct2Mat and Mat2Struct functions are used for data conversion, and each output initializes the subsequent phase. After analyzing all flight phases, the results are verified, and the simulation loop restarts if required. If convergence is achieved, PostProcess and PlotResults functions collect and output all pertinent results in both text and graphical format. Additionally, a .mat file is created to store all results and input data for further analysis

It is important to note that the program described in this text is based on the methods and procedures outlined in a research paper. This provides a detailed overview of the theoretical and mathematical background for the analysis tool and serves as a valuable resource for those interested in the development of hybrid electric aircraft and the associated computational tools and methods. Overall, the program offers a powerful and efficient solution for analyzing and optimizing hybrid electric aircraft performance.

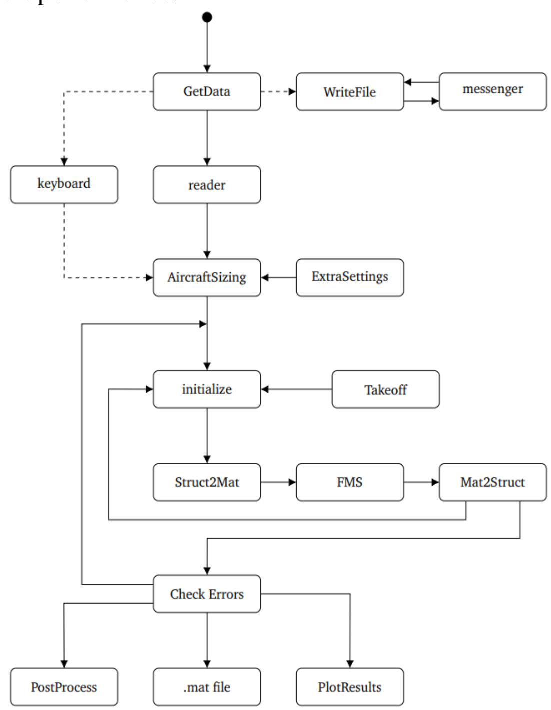

Fig. 3. Hyperion program scheme]

Fig. 4.

D. Inputs

In this table, values for various variables related to the Panthera Hybrid aircraft have been presented. The table includes values for takeoff, empty, generator, battery, fuel, and payload masses in kilograms. Additionally, the table provides information about wing loading, power loading, wing surface, and wing span of the aircraft. Power values for various flight phases such as takeoff, climb, cruise, descent, and loiter have also been included, along with the maximum generator power

TABLE I. INPUTS FOR VALIDATING A GENERAL AVIATION AIRCRAFT

Sr.No	*Variable*	*Pipistrel Panthera Hybrid*
1	Mass(kg)	
a	Takeoff	1315
b	Empty	830*
c	Generator	95
d	Battery	120*
e	Fuel	53*
f	Payload	312*

Sr.No	*Variable*	*Pipistrel Panthera Hybrid*
2	Aircraft	
a	Wing Loading	1152 N/m²
b	Power Loading	86 N/kW
c	Wing Surface	11.2 m²
d	Wing Span	10.86 m
3	Power	
a	Takeoff	200 kW max.
b	Climb	150 kW max.
c	Cruise	100 kW max.
d	Generator Power	110 kW

IV.PROGRAMMING

```
function [output] =
HyperionSimulation()

% Define input data
inputData.maxPower = 194; % kW
inputData.MTOM = 1315; % kg
inputData.usefulPayload = 500; % kg
inputData.length = 8.07; % m
inputData.wingspan = 10.86; % m
inputData.height = 2.19; % m
inputData.wingArea = 11.2; % m^2
inputData.stallSpeed = 60; % KIAS
inputData.climbRate = 6.6; % m/s
inputData.takeoffDistance = 657; % m
inputData.landingDistance = 706; % m
inputData.inputFile = ''; % Empty
string to avoid reading from file
inputData.matFile = ''; % Empty string
to avoid loading .mat variables set
inputData.createMatFile = false; % Do
not create .mat file

% Perform preliminary airplane sizing
aircraftData =
AircraftSizing(inputData,
ExtraSettings);

% Start simulation at the end of the
takeoff phase
[values, structures] =
Takeoff(aircraftData);

% Initialize simulation
initialize(values, structures);

% Simulate each flight phase using the
FMS routine
for i = 1:length(structures)
    [output(i).values,
output(i).structures] =
FMS(structures(i).input);
end

% Verify results and restart simulation
loop if correction is needed
if ~isConverged(output)
    % Restart simulation loop
end

% Collect results and plot variables
evolution
PostProcess(output);
PlotResults(output);

% Create .mat file with results and
corresponding input data if desired
if inputData.createMatFile
    matData = Mat2Struct(output);
    save('output.mat', 'inputData',
'matData');
end

end

function [aircraftData] =
AircraftSizing(inputData,
extraSettings)

% Perform preliminary airplane sizing
using input data and extra settings
% and return resulting aircraft data
% ...

end

function [values, structures] =
Takeoff(aircraftData)

% Set initial values for takeoff phase
and return resulting values and
structures
% ...

end

function [] = initialize(values,
structures)

% Initialize simulation with given
values and structures
% ...

end

function [output] = FMS(input)
```

```
% Simulate flight phase using given
input and return resulting output
% ...

end

function [isConverged] =
isConverged(output)

% Verify if simulation results are
converged and return boolean value
% ...

end

function [] = PostProcess(output)

% Collect results in a text file
% ...

end

function [] = PlotResults(output)

% Plot variables evolution
% ...

end

function [matData] = Mat2Struct(output)

% Convert simulation output to a .mat
variables set
% ...

End
```

5.3 Programming for plots and graph

```
import matplotlib.pyplot as plt
import numpy as np

# Given inputs
max_power = 194  # kW
MTOM = 1315  # kg
payload = 500  # kg
length = 8.07  # m
wingspan = 10.86  # m
height = 2.19  # m
wing_area = 11.2  # m^2
stall_speed = 60  # KIAS
climb_rate = 6.6  # m/s
takeoff_distance = 657  # m
landing_distance = 706  # m

# Flight profile parameters
cruise_speed = 212  # knots
climb_altitude = 9144  # meters
descent_altitude = 1524  # meters
cruise_altitude = 12192  # meters
range = 1000  # nautical miles
endurance = np.nan  # Not available

# Create time array
time = np.linspace(0, 6000, 10000)

# Calculate distance array
distance = np.zeros_like(time)
ground_speed = np.zeros_like(time)

for i in range(1, len(time)):
    ground_speed[i] = cruise_speed
    distance[i] = distance[i-1] +
(ground_speed[i] + ground_speed[i-1])/2
* (time[i]-time[i-1])/3600

# Create altitude array
altitude = np.zeros_like(time)
vertical_speed = np.zeros_like(time)

for i in range(1, len(time)):
    if altitude[i-1] < climb_altitude:
        altitude[i] = altitude[i-1] +
climb_rate * (time[i]-time[i-1])
        vertical_speed[i] = climb_rate
    elif altitude[i-1] <
cruise_altitude:
        altitude[i] = cruise_altitude
        vertical_speed[i] = 0
    elif altitude[i-1] >
descent_altitude:
        altitude[i] = altitude[i-1] -
climb_rate * (time[i]-time[i-1])
        vertical_speed[i] = -climb_rate
    else:
        altitude[i] = descent_altitude
        vertical_speed[i] = 0

# Create power array
power = np.zeros_like(time)
efficiency = np.zeros_like(time)

for i in range(1, len(time)):
    if altitude[i] < climb_altitude or
altitude[i] > descent_altitude:
        power[i] = max_power
        efficiency[i] = 0.8
    else:
        power[i] = max_power *
cruise_speed / ground_speed[i]
```

```
        efficiency[i] = 0.9

# Create acceleration array
acceleration =
np.gradient(ground_speed, time)

# Create vertical speed array
vertical_speed = np.gradient(altitude,
time)

# Plot flight profile graph
fig, axs = plt.subplots(3, 2,
figsize=(12, 12))
```

V.ANALYSIS

The aircraft under consideration is a type of general aviation plane, but it has unique characteristics that must be taken into account. Specifically, the Panthera Hybrid aircraft differs significantly from other general aviation planes, which necessitates a careful estimation of its drag coefficient (CD0). To do so, we reference a source [17] that provides information about the Panthera Hybrid's maximum continuous power of 100 kW and maximum horizontal true airspeed of 203 knots.

It is assumed that the density at an altitude of 12000 ft is known and an Oswald efficiency factor of 0.90 is used along with the known aspect ratio of 10.5. The specific power and energy of the battery used in the calculations are 1500 W kg−1 and 150 Wh kg−1 respectively.

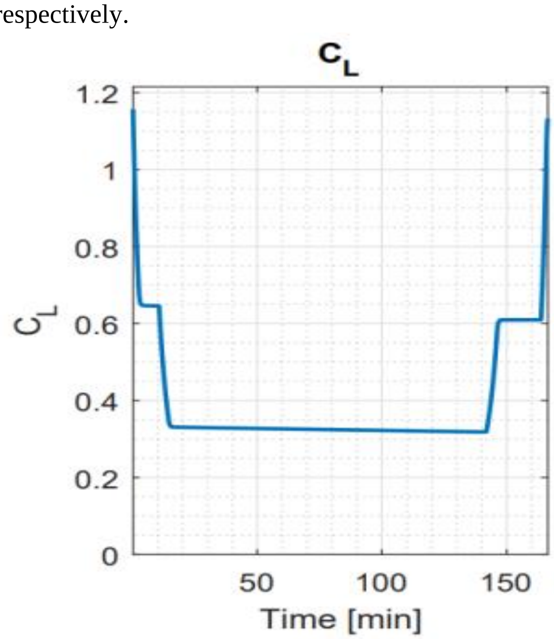

Fig. 5. Cl versus time evolution for Panthera Hybrid simulated aircraft.

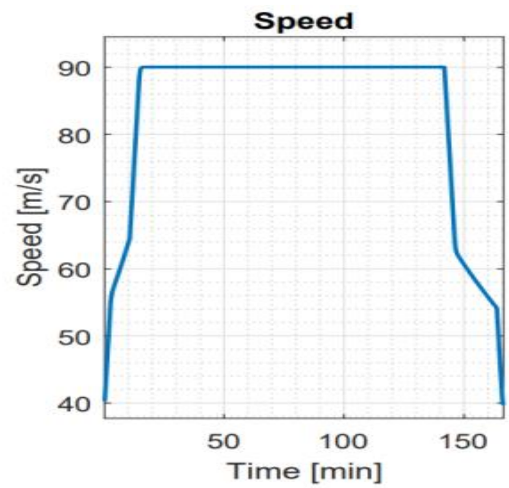

Fig. 6. speed versus time evolution for Panthera Hybrid simulated aircraft.

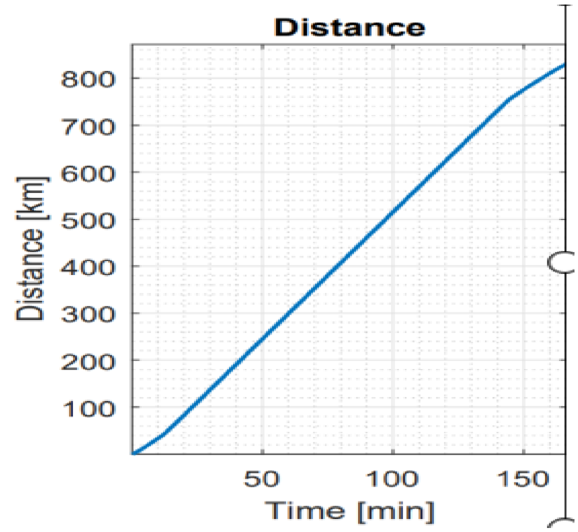

Fig. 7. Distance versus time evolution for Panthera Hybrid simulated aircraft.

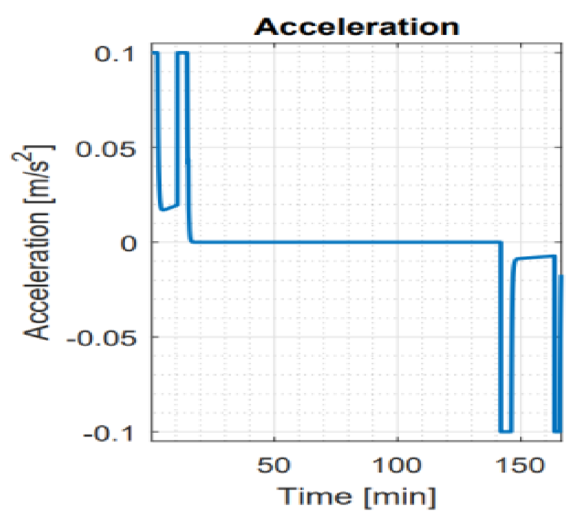

Fig. 8. Acc. versus time evolution for Panthera Hybrid simulated aircraft.

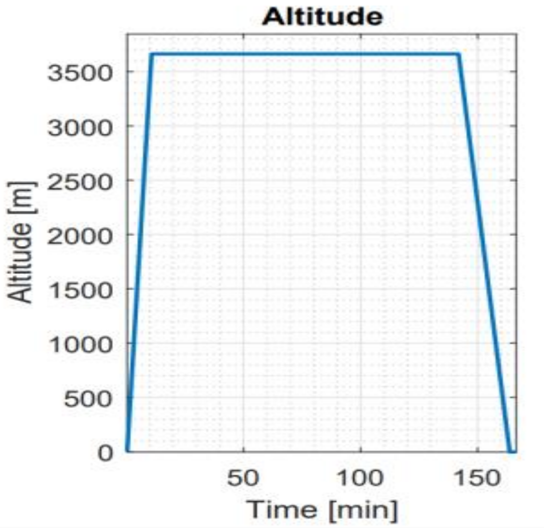

Fig. 9. alt versus time evolution for Panthera Hybrid simulated aircraft.

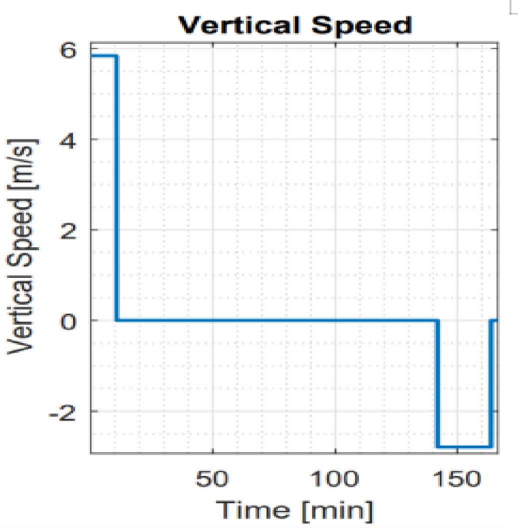

Fig. 10. *??VS* versus time evolution for Panthera Hybrid simulated aircraft

VI.RESULT

The values shown in Table III demonstrate good agreement with actual values, but there are some important differences to keep in mind. Firstly, the weight of the generator is included in the reported empty mass, whereas the battery weight is not. To elaborate further, the simulation assumes only one power condition for the motor, whereas the actual aircraft motor has two - maximum continuous and peak. It should also be noted that the higher mass observed in the simulation is attributed to empty mass errors from statistical population. Despite this, the error rate remains below 10%, which is deemed acceptable. Moreover, it is important to highlight that Panthera Hybrid is a newly developed aircraft with unique aerodynamic properties, which allowed for structural optimization. This optimization was necessary to achieve maximum performance while ensuring safety and reliability during operation.

TABLE II. INPUTS FOR VALIDATING A GENERAL AVIATION AIRCRAFT

Sr. No	*Variable*	*Pipistrel Panthera Hybrid*	*Simulated aircraft*
1	Mass (kg)		
a	Takeoff	1315	1362
b	Empty	830*	868
c	Generator	95	95
d	Battery	120	121
e	Fuel	53	61
f	Payload	312	312
2a	Aircraft		
b	Wing Loading	1152 N/m²	1144 N/m²
c	Power Loading	86 N/kW	73.3 N/kW
d	Wing Surface	11.2 m²	11.7 m²
e	Wing Span	10.86 m	11.08 m
3	Power (kW)		
a	Takeoff	200 kW max.	177 kW
b	Climb	150 kW max.	117 kW
c	Cruise	100 kW max.	85 kW
d	Descent	N.Av.	3.1kW
e	Loiter	N.Av.	32 kW
f	Generator Power	110 kW	105 kW
4	Time (min)		
a	Climb		14.9 min
b	Cruise		127.0 min
c	Descent		24.5 min
d	Total		166 min

VII.CONCLUSION

In conclusion, this research work focused on the development and implementation of a hybrid electric aircraft analysis tool, named Hyperion. The study started with a general introduction to hybrid electric propulsion and its potential advantages over traditional gas-powered engines, such as reduced emissions, increased efficiency, and improved reliability.

The research then delved into the design and architecture of a hybrid electric aircraft, highlighting the key components, such as the gas engine, electric motor, batteries, and generator, and the complex interactions between them. The study also discussed the importance of estimating accurate aerodynamic data, such as lift and drag coefficients, to ensure accurate performance estimation.

To facilitate the estimation of performance metrics, such as range, payload capacity, and fuel efficiency, the research developed the Hyperion program in MATLAB. The program employs a combination of functions and input files to collect user input and simulate various flight phases, including takeoff, climb, cruise, descent, and loiter. The program uses structures to simplify variable handling and provides text and plot outputs for easy visualization of results.

The implementation of the Hyperion program was demonstrated through a case study of the Panthera hybrid aircraft. The results of the simulation were compared to the actual performance data of the Panthera, and the simulation was found to be in good agreement with the real-world values.

Overall, this research work provides a valuable contribution to the development of hybrid electric aircraft and associated computational tools and methods. The Hyperion program offers a powerful and flexible tool for the preliminary sizing and simulation of hybrid electric aircraft, which could potentially help to accelerate the development of this promising technology. The study also highlights the importance of accurate aerodynamic data estimation and the complex interplay between the various components of a hybrid electric aircraft.

VIII.FUTURE SCOPE OF STUDY

The scope of this study extends beyond just the development of a hybrid electric aircraft analysis tool. The hyperion program provides a foundation for the continued exploration and refinement of hybrid electric aircraft design, as well as the development of related computational tools and methods.

With the ongoing push for more sustainable aviation options, hybrid electric aircraft represent a promising avenue for reducing emissions and improving fuel efficiency. As such, continued research and development in this area is crucial for the aviation industry to meet its sustainability goals.

The hyperion program itself can be further developed to include more advanced features and capabilities, such as the integration of machine learning algorithms to improve performance predictions, or the incorporation of more complex propulsion systems. In addition, the program can be modified to accommodate different aircraft types and configurations, allowing for broader applications in the field of aircraft design.

Overall, the scope of this study extends to the broader goal of improving the sustainability and efficiency of aviation through the development and application of hybrid electric aircraft technologies. The hyperion program serves as a valuable tool in achieving this goal, and its continued development and refinement will be essential in driving progress in this important area of research.

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