DISTRIBUTED PROPULSION IN A HYBRID-ELECTRIC AIRCRAFT

Retrofitting the Cessna 310R

AME 502
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Table of Contents

1 Introduction

In the dynamic landscape of modern aviation, the imperatives of sustainability, efficiency, and adaptability have steered the aerospace industry towards innovative solutions. This report endeavors to address a critical challenge facing contemporary aviation: the absence of viable commercial alternatives for current aircraft engines. The overarching objective of this project is to introduce a hybrid-electric distributed propulsion system that seamlessly integrates with the Cessna 310R, maintaining key performance metrics such as range, top speed, peak power, cargo capacity, and passenger space. This retrofit will demonstrate that cutting-edge technology can be harmoniously integrated into existing airframes, offering a tangible and practical solution to the challenges posed by traditional systems.

1.1 Background and Motivations

In the pursuit of sustainable aviation, a fully electric setup was initially explored for retrofitting the Cessna 310R. However, a thorough analysis revealed a significant obstacle: the impractical burden of required battery mass compromised payload capacity, maximum take-off weight (MTOW), and overall vehicle performance. Recognizing these challenges, research shifted towards a distributed hybrid-electric system that integrated the advantages of electric and internal combustion engines by balancing energy efficiency and environmental benefits with the practicality and energy density of internal combustion engines.

This design proposal adopts a distributed propulsion system. This is because recent studies highlight a notable increase in the lift-to-drag ratio with distributed propulsion, particularly along the wingspan (Filipenko, 2017). As part of this hybrid setup, the incorporation of internal combustion engines yields the benefit of rapid refueling, significantly reducing turnaround time, which is crucial for short-range business travel. Conversely, the increased efficiency of electric propulsion aligns with sustainable aviation practices, reducing fuel consumption and lowering refueling costs (Keller, 2023). These strategic design choices economically incentivize the aviation industry to embrace innovative hybrid-electric solutions.

2 Design Requirements

The retrofitting of the Cessna 310R with a hybrid-electric distributed propulsion system is governed by stringent design requirements as highlighted in the following list:

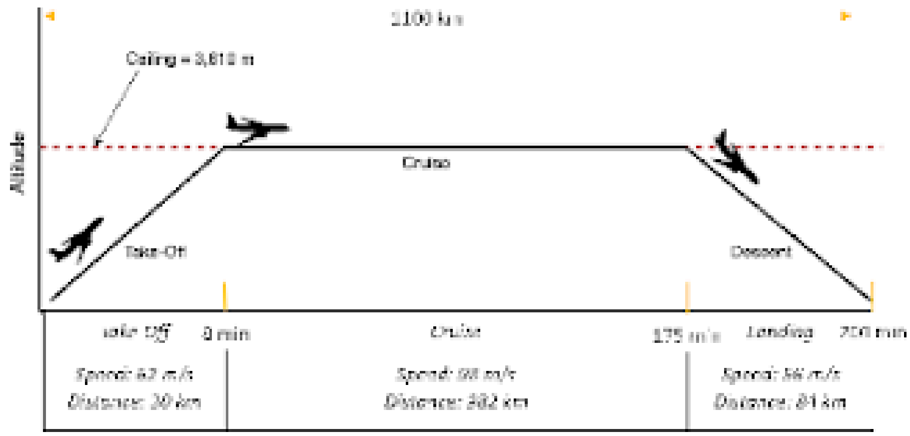
1. The retrofit must maintain the original range capabilities of the Cessna 310R.
2. The retrofit must not compromise the maximum speed of the Cessna 310R.
3. The hybrid-electric system must not diminish the overall power output of the aircraft.
4. The retrofit should not result in any increase in the maximum take-off weight of the aircraft.
5. The retrofit should not impact the mass allocated for cargo and passengers.

There are also certain desirable outcomes that can be achieved but are not considered requirements. These include the following items:

1. The hybrid-electric system is expected to yield reduced flight hour operating costs.
2. An integral objective is the reduction of in-flight carbon emissions.

The design requirements and achievable outcomes described above are valid for a particular set of flight conditions. More specifically, the design baseline must be established as part of the concept of operations (CONOPS). As shown in Figure 1, the Cessna 310R must be able to achieve a cruise speed of 98 meters per second at a cruise altitude of 3810 meters. Furthermore, it should have a total range of 1100 kilometers. This figure represents the total of the maximum safe flying range and the reserve range mandated by FAA guidelines (Cessna 310R Technical Specifications, 2023).

Figure 1. Baseline CONOPS



3 Design Baseline

The design baseline for the retrofitting project involves a strategic reconfiguration of the powerplant on the Cessna 310R, transitioning from its original setup to a hybrid-electric system. In its initial configuration, the aircraft was equipped with two internal combustion engines. The retrofit introduces a transformative shift, incorporating a blend of two battery-powered engines and four internal combustion engines.

3.1 Engine Selection

An essential aspect of the retrofit involved the selection of internal combustion engines that could easily integrate with the new distributed propulsion system. The driving issue was the incompatibility of the original engines, primarily due to their size. Rather than undertaking extensive analyses for engine scaling, a decision was made to opt for entirely new internal combustion engines. The chosen internal combustion engines were carefully selected to complement the distributed propulsion system, ensuring optimal performance while adhering to the spatial and weight limitations of the retrofit project.

The table below shows a top-level comparison between the original and retrofitted versions of the aircraft (Cessna 310R Technical Specifications, 2023).

Parameter	Original	Modified
Aircraft	Cessna 310R	Cessna 310R
Electric Motor	None	(x2) Hypothetical scaled from HEX HPDM 250
Internal Combustion Engine	(x2) Continental IO-520-Ms	(x4) Rotax Aircraft Engines 916 iSc A
Peak Power	440 kW	444 kW
Continuous Power	330 kW	331 kW
Range (with Reserves)	1100 km	1100 km
Maximum Take-Off Weight	2495 kg	2495 kg

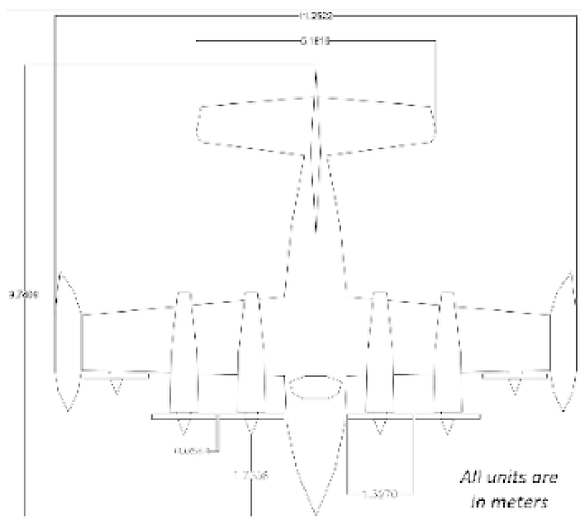
Table 1. Design Baseline Comparison

3.2 Propeller Design

The most substantial modifications to the original aircraft design focused on propeller sizing, necessitated by the integration of six propellers in the modified configuration. The initial challenge arose from the impracticality of sustaining the large propellers featured in the original design, given the need to accommodate three equally spaced propellers along each wing of the new hybrid aircraft. Research supported using the largest propellers that could comfortably accommodated along the wingspan to optimize the efficiency of the distributed propulsion system (Aircraft Engine and Propeller Sizing, 2022). To further simplify the design process, only fixed-pitch propellers with three blades were considered.

The original aircraft design consisted of two propellers, each approximately 1.94 meters in diameter. The modified design reduced propeller diameters to 1.4 meters, allowing for three equally spaced propellers on each wing as shown in the figure below. It was determined through research that the recommended inter-propeller spacing is approximately 4% of the propeller diameter.

Figure 2. Modified Aircraft Top-View



3.3 Center of Gravity

In determining the center of gravity (CG) in the modified design, the weights of all components were calculated and situated with respect to a datum point, selected as the tip of the nose. The CG location relative to the mean aerodynamic chord (MAC) was then derived by dividing the sum of these weights by the sum of the resulting moment arm. For the hybrid configuration, the CG was established at 1.6 meters from the nose tip, corresponding to 37.2% of the MAC. Employing the same methodology for the original aircraft, its CG was computed to be 35.9% of the MAC. The close alignment between the new and original CG locations suggests that the proposed design is anticipated to operate safely without encountering issues related to changes in weight and balance.

4 Analyses

The robustness and viability of the modified hybrid-electric design were meticulously evaluated through a series of numerical analyses. These assessments spanned critical aspects of the retrofit, providing a thorough examination of various components and their interactions. The finalized key parameters and performance accomplishments resulting from these assessments are highlighted in the following sections.

4.1 Engines, Batteries, and Power

The following table compares the original and modified aircraft engines, electrical energy, and total power output. It should be noted that the total power in the modified configuration, 444 kW, matches the original aircraft power to within 1%.

Parameter	Original (Combustion)	Original (Electric)	Modified (Combustion)	Modified (Electric)
Engine Quantity	2	0	4	2

Engine Efficiency	.42	N/A	.42	.97
Power Output	440 kW	0 kW	298.2 kW	146.7 kW
Percent Power	100%	0%	66%	33%
Battery Energy	N/A	0 kWh	N/A	135 kWh

Table 2. Analysis Results: Engines, Batteries, and Power

4.2 Propeller Design and Center of Gravity

In addition to the new engine configuration, the propellers also significantly impacted the characteristics of the modified aircraft. The table below highlights the most important changes made to the propellers, as well as the overall impacts on center of gravity.

Parameter	Original	Modified
Propeller Diameter	1.94 m	1.4 m
Inter-Propeller Spacing	N/A	.05 m
Battery Location (from Tip of Nose)	N/A	2.7 m
MTOW Center of Gravity (%MAC)	35.9%	37.2%

Table 3. Analysis Results: Propeller Design and Center of Gravity

4.3 Aerodynamics

The key parameters that characterize aircraft aerodynamics must be calculated for take-off and cruise conditions. These values are shown in respective columns in the following table.

Parameter	Original (Take-Off)	Original (Cruise)	Modified (Take-Off)	Modified (Cruise)
Maximum Thrust	4.7 kN	1.89 kN	9.9 kN	2.73 kN
C_L	.78	.19	1.11	.27
Lift	31.9 kN	24.48 kN	45.3 kN	24.48 kN
C_{Di}	.03	.002	.06	.004
C_D	.07	.02	.1	.01
Drag	2.7 kN	1.8 kN	2.8 kN	1.3 kN
L/D	12	13	16.3	18.5

Table 4. Analysis Results: Aerodynamics

4.4 Mass and Fuel Emissions

The mass budget is one of the most crucial elements of the design. All components whose mass was fixed by requirement, and those whose mass changed from the original design, are shown in the table below. This table also reflects the total fuel volume and consequent fuel emissions.

Parameter	Original	Modified
Battery Mass	0 kg	450 kg
Electric Motors Mass	0 kg	9.8 kg
Internal Combustion Engines Mass	426 kg	200 kg
Primary Fuel Tanks Mass	381 kg	147 kg
Wingtip Fuel Tanks Mass	92 kg	92 kg
Cargo Mass	68 kg	68 kg
Other (Non-Removable) Mass	1528 kg	1788 kg
Maximum Take-Off Weight (MTOW)	2495 kg	2495 kg
Total Fuel Volume	378.4 L	239.1 L
Amount of CO2 per Flight	830.7 kg	524.9 kg

Table 5. Analysis Results: Mass and Fuel Emissions

5 Results

Implementing a hybrid-electric distributed propulsion system, the modified aircraft has successfully met or surpassed all stipulated design requirements. The evidence supporting the fulfillment of these requirements is presented comprehensively in the table below. Some of the conditions listed in the middle column may be applicable to more than one of the noted requirements.

Number	Requirement	Condition	Original	Modified
1	Retrofit must maintain original range capabilities.	L/D	13	18.46
		Maximum Range	1100 km	1100 km
2	Retrofit must not compromise maximum speed.	Cruise Speed	98 m/s	98 m/s
3	Hybrid system must not diminish overall power output.	Total Power	440 kW	444 kW
4	Retrofit must not increase maximum take-off weight.	MTOW	2495 kg	2495 kg
5	Retrofit must not impact mass allocated for cargo and passengers.	Cargo Mass	68 kg	68 kg
		Passenger Mass	408 kg	408 kg

Table 6. Demonstrating Met Requirements

Furthermore, the desired objectives were also achieved. These are outlined in the following table.

Number	Achievable	Condition	Original	Modified
1	Hybrid-electric systems yield reduced flight hour operating costs.	Operating Cost (USD)	$308/hr	$125/hr
2	Modified aircraft reduces amount of in-flight carbon emissions.	CO_2 Emissions	830.7 kg	524.9 kg

Table 7. Demonstrating Met Achievable Outcomes

The attainment of these design requirements underscores the success of the hybrid-electric distributed propulsion system, emphasizing its applicability and adaptability to the specific needs of short-range business travel. This achievement positions the newly modified aircraft as a noteworthy advancement in aviation technology, aligning with the overarching goals of sustainability, efficiency, and innovation.

6 Challenges and Future Work

The retrofitting project introduces challenges, notably in turnaround time affected by current charging limitations for swift business applications. Another concern is redundancy, as reliance on electric motors poses a critical failure point, compromising standard operation if these components malfunction. Future work aims to address these issues and enhance the retrofit's efficiency. The assumed 42% increase in lift-to-drag ratio with the distributed propulsion system requires validation through testing, while the current 33% battery density limitation prompts exploration of advancements to expand electric power use. The vision for the future includes transitioning to fully electric aircraft as battery technology progresses, aligning with broader sustainable aviation goals.

The objective of this project was to match the performance parameters of the Cessna 310R. However, with the improvements brought on by electric motors as well as distributed propulsion, the design process revealed that the proposed configuration can exceed the performance of the original aircraft. Future flight plans for this aircraft may therefore change to allow for longer distances and greater cruise speeds.

7 Conclusion

The introduction of a hybrid-electric distributed propulsion system into the Cessna 310R stands as a resounding success. Through extensive numerical analyses spanning propulsion dynamics, aerodynamics, fuel and power systems, engines, emissions, batteries, mass, and center of gravity, the modified design demonstrated its validity, efficiency, and safety without sacrificing any design requirements. This transformative approach not only addresses current challenges but also redefines the future of short-range business travel. By embracing innovation and sustainability, the modified hybrid-electric design positions itself as a pioneering solution, transcending existing limitations and contributing to the evolution of aviation technology.

8 References

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