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Analysis of the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) Concept

Francisco M. Capristan and Nathaniel J. Blaesser
Langley Research Center, Hampton, Virginia

August 2019

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Abstract

The Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) vehicle is a regional aircraft concept that uses electric and hybrid-electric propulsors located strategically to obtain aerodynamic and mission benefits. Traditional aircraft analysis tools are not well suited to analyze the PEGASUS aircraft due to the different propulsor types used. This report summarizes a methodology that addresses some of the mission analysis challenges expected in modeling this vehicle concept. An initial baseline design is selected and sensitivity studies are performed to further understand the potential benefits of the concept.

1 Introduction

Electric propulsion can provide potential benefits over conventional (gas turbine) propulsion systems, which can ultimately translate to a decrease in operational costs, carbon footprint, and noise. These potential benefits are in part due to the fact that electric propulsors scale better than their fuel-powered counterparts. Antcliff et al. [1] showed that parallel hybrid-electric regional aircraft could reduce operational cost by reducing the propulsive energy needed to complete a mission. A follow-up paper by Antcliff and Capristan [2] proposed the use of a novel configuration that utilizes multiple propulsors strategically located to provide aerodynamic benefits. This vehicle is called the Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) concept. The aerodynamic benefits assumed in the PEGASUS concept further decreased the propulsive energy required when compared to a more conventional baseline vehicle. However, the analysis performed in the past required simplifying assumptions and was limited because the tools used could not properly handle multiple propulsor types working at the same time. This work presents an update to the PEGASUS concept using an analysis approach that can handle multiple propulsors and aero-propulsive interactions previously ignored.

PEGASUS is a 48-passenger, hybrid-electric regional aircraft based on the ATR 42-500 [2]. The ATR 42-500 was chosen based on previous studies that focused on market and demand [3]. An artist rendering of the vehicle is shown in Fig. 1. The concept consists of two parallel hybrid-electric propulsors at the wingtips, two inboard electric propulsors, and one electric propulsor at the aft of the vehicle. These propulsors are strategically located to provide synergistic benefits due to propulsive and aerodynamic interactions as Ref. 2 outlines. The hybrid-electric propulsors are designed to provide the majority of the thrust during cruise and are located at the wingtips to reduce induced drag. The objective of the inboard propulsors is to provide additional thrust during takeoff and climb. The inboard propellers can be folded during cruise to decrease windmilling effects, but they could easily be turned on during one-engine inoperative (OEI) scenarios. Finally, the electric propulsor at the tail is expected to provide aerodynamic benefits ingesting and re-energizing the fuselage boundary layer [4].

Figure 1: Rendering of the PEGASUS concept with folded inboard propellers. Source credit: NASA/Advanced Concepts Laboratory (ACL).

Earlier studies (see Ref. 2) used the Flight Optimization System (FLOPS) [5] and SUAVE [6] to analyze the PEGASUS vehicle. FLOPS is an aircraft design tool that has been developed at NASA Langley for over 30 years. FLOPS is suited for conventional aircraft and propulsion systems (e.g., gas turbine-powered), but it is not well suited to analyzing electric and hybrid-electric propulsion systems. Previous work implemented a FLOPS-based methodology, in which FLOPS was enhanced with external calculations to handle some of its modeling limitations. On the other hand, SUAVE is a tool developed at Stanford University that supports the analysis of unconventional aircraft configurations. A SUAVE-based methodology was also used to analyze the vehicle, but it had limitations in handling multiple propulsors independently of each other.

This work presents a different analysis methodology that leverages a prototype of the Layered and Extensible Aircraft Performance System (LEAPS) [7]. LEAPS is a new aircraft analysis tool that will enable the analysis of conventional and unconventional vehicles. The methodology can handle multiple propulsors independently of each other and is able to capture aerodynamic and propulsive interactions.

This report presents an updated PEGASUS configuration and the major features in the analysis methodology used. Section 2 provides details of the PEGASUS concept. Section 3 discusses the major features of the analysis methodology. Section 4 presents the analysis performed. Lastly, concluding remarks are provided in Section 5.

2 PEGASUS Concept Design

2.1 Propulsors

The main modifications from the ATR 42-500 include the propulsors used, wing planform, and propulsive energy. The PEGASUS concept uses three different types of propulsors instead of a single type (as in the ATR 42-500). The propulsors are located at the wingtips, inboard, and aft. The wingtip propulsors use a parallel hybrid-electric propulsive system and are therefore powered by an electric motor, gas turbine, or a combination of both. The inboard and aft propulsors are powered by electric motors. A simplified schematic of the propulsor configuration and locations is shown in Fig. 2.

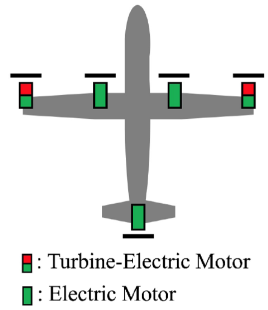


Figure 2: Propulsor configuration and locations.

The wingtip propulsors provide most of the thrust required during the operation of the vehicle. The rotational component of the propeller slipstream is expected to attenuate the wing vortex system, providing a potential aerodynamic benefit [8, 9]. A parallel hybrid-electric propulsion system is used because it can be more efficient in converting stored energy into shaft power than a turboprop alternative. The efficiency of a gas turbine is often on the order of 40%, whereas an electric propulsive system efficiency is on the order of 90%. A combination of the two systems would likely result in an overall efficiency between these values [2]. The ATR 42-500 aircraft uses the Pratt & Whitney PW 127E turboprop. The PEGASUS wingtip propulsive system is a combination of an electric motor and a PW 127E-like gas turbine engine. The new engine model was created by applying efficiency improvements and weight reduction factors to the PW 127E, assuming an entry-into-service (EIS) of 2030. One of the major concerns with wingtip propulsors is the yawing moment produced in a OEI scenario. To simplify the analysis, it is required that the PEGASUS OEI yawing moment does not exceed the yawing moment of the ATR vehicle. This requirement is met by limiting the amount of thrust provided by the wingtip propulsors.

The main purpose of the inboard propulsors is to provide additional thrust during takeoff and climb; however, they can also help mitigate difficult control characteristics that arise in OEI scenarios. These propulsors create swirl which translates to a non-optimal spanwise lift distribution on the wing. To alleviate this effect, the inboard propellers are folded during cruise and descent.

The purpose of the aft propulsor is to decrease the propulsive power required to operate the aircraft by using boundary layer ingestion (BLI). Previous studies have suggested that capturing and reenergizing the boundary layer can lead to the recovery of the momentum deficit [4, 10]. Unlike the inboard propulsors, this propulsor operates during all phases of the mission. Gray et al. [11] suggested that it is possible to obtain between 1% to 4.5% reduction in the total power required during cruise with a BLI system. Note, however, that this result is for a different flight condition and configuration than PEGASUS.

XROTOR [12] was used to design the propellers. In this study, six-bladed propellers were used at the inboard, wingtip, and aft. Table 1 shows the main characteristics of the propellers used. The outputs from XROTOR for the design of each propeller are located in Appendix A.

Table 1: Propeller Features

	Wingtip	Inboard	Aft
Number of Blades	6	6	6
Blade Radius (ft)	5.33	4.00	3.28
Hub Radius (ft)	1.07	0.81	0.66
Shaft Power (hp)	1600	1600	1000

The baseline vehicle considered in this study incorporates a 10% induced drag reduction when the wingtip propellers are operating. This assumption was used in the previous study [2] and is comparable with the results obtained by Blaesser [13], where the induced drag with the wingtip propellers operating was 9% lower than for a clean wing. Blaesser also predicted a 4% induced drag reduction from using the wingtip propulsors compared to using inboard propulsors. This information was used to estimate an induced drag penalty of 4.4% when the inboard propellers are operating. A conservative assumption of no BLI benefit was used for the baseline vehicle. Section 4 shows sensitivity studies for the induced drag reduction due to the wingtip propellers and the assumed BLI benefit.

2.2 Wing Selection

The maximum takeoff weight of the ATR 42-500 aircraft is approximately 40,000 lb. The PEGASUS vehicle is expected to have a larger takeoff weight mainly because of the battery weight required. For this reason, the wing planform needs to be adjusted to ensure that the wing loading for the PEGASUS concept is comparable to the ATR vehicle. The ATR 72-500 vehicle has similar characteristics to the ATR 42-500 vehicle but has a 10,000 lb higher takeoff weight. Therefore, a scaled version of the ATR 72-500 wing is used for the PEGASUS concept. The reference wing area of the ATR 72-500 is 657 ft^2 and the wing has an aspect ratio of 12. The approximate wing loading for this vehicle is 76 lb/ft^2, which is the target wing loading used for the baseline PEGASUS vehicle.

2.3 Mission Profile

The transportation demand study by Marien [3] predicted the potential demand for short-haul aircraft in the U.S. for the year 2030, assuming a point-to-point network of trips shorter than 900 nmi. It was found that 50% of the regional trip demand was for trips of 200 nmi or less, and 90% of regional trip demand was for trips of 400 nmi or less. The PEGASUS concept is designed to perform two different missions informed by the results of this study. The first is a 200 nmi mission during which the hybrid-electric propulsors only use electric power. The second mission is a 400 nmi hybrid-electric mission during which the wingtip propulsors use both fuel and electric power. Both missions have an approximate cruise altitude of 20,000 ft.

A previous study found that the PEGASUS vehicle weight is highly sensitive to the requirements for the reserve mission [2]. The ATR 42-500 published reserve mission performance includes an 87 nmi range to an alternate airport and a 45 minute hold. For this study, the reserve mission is modeled by adding an effective reserve range to the mission. An effective reserve range of 300 nmi is computed by considering the alternate airport distance of 87 nmi added to 45 minutes at 284 knots. It is important to note that the same reserve mission is flown for both missions and that the reserve mission has an effective range that is greater than the electric mission.

Conventional metrics to size the aircraft are not fully applicable for this vehicle. In the past, minimum fuel or minimum ramp weight metrics were used as the objective for sizing the aircraft. These objectives served as a proxy for minimum operational or acquisition cost. However, hybrid-electric aircraft also rely on electric energy. This poses challenges in selecting the appropriate metric for sizing.

The mission analysis methodology used [14] computes the optimum conditions for different weight and energy levels. This approach can compute the minimum rate of energy consumption required to fly at a given instant but it does not have the capability to look at the entire trajectory. This is of particular interest because a trajectory based on minimizing the rate of energy consumption required at each given instant will emphasize the use of electric propulsors since they are more efficient (electric systems have efficiencies of about ∼90% while gas turbines have an efficiency of about ∼40%); however, the overuse of electric propulsors could result in a large battery and vehicle weight that can ultimately lead to a trajectory that uses excessive amounts of energy or vehicles that are too heavy to complete their desired mission.

3 Analysis Methodology

Mission analysis requires numerous modeling components. These components could include propulsion, weight estimation, aerodynamics, and atmospheric analysis modules. These modeling components often need to share data among themselves and it is possible to have complex interactions and feedback loops. The LEAPS version used for this study contains weights, aerodynamics, and atmospheric components that were connected via OpenMDAO [15]. This OpenMDAO model is coupled with a mission analysis methodology based on the energy method [14]. The resulting analysis approach provides new capabilities and allows interactions (e.g., aerodynamics and propulsion) that are often ignored by conventional analysis tools.

3.1 Aircraft Definition

The mission analysis methodology requires weight, propulsion, and aerodynamic data at different flight conditions. The current early version of LEAPS was used to provide empty weight and aerodynamic information. LEAPS variables are initialized with an input text file containing vehicle information. After initialization, all input and output variables are accessible in memory. The aerodynamic module is created by using the LEAPS aerodynamic information. The propulsion information is also gathered and wrapped into a module. These modules are used to create an OpenMDAO model that provides aircraft performance parameters at different flight conditions to the mission analysis methodology. Figure 3 shows how information flows among the different components.

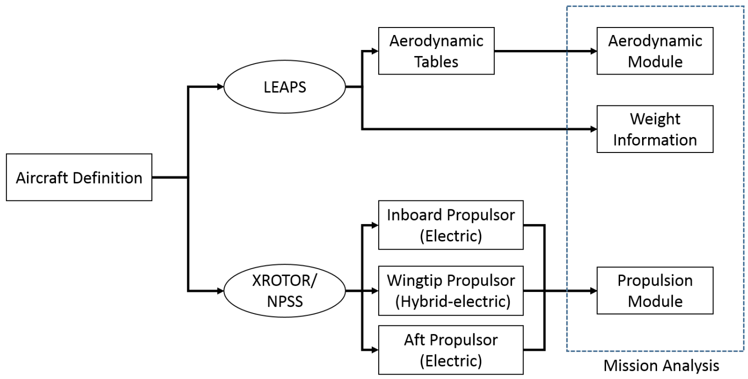


Figure 3: Generation of aircraft data for mission analysis.

The wingtip propulsors are based on the PW 127E turboprop. This PW 127E-like engine was modeled in the Numerical Propulsion System Simulation (NPSS) [16]. The engine components were adjusted to predict the performance of a PW 127E-like engine in the year 2030. More details regarding the PW 127E analysis can be found in Refs. 1 and 2. The engine was scaled to match the desired power during flight. Sizing of the propellers (wingtip, inboard, and aft) was done using XROTOR. The data generated serves as an input to the mission analysis module. Future versions of LEAPS will have mission analysis capabilities built-in; thus, reducing the amount of work required by the analyst.

3.2 Mission Analysis

The mission analysis methodology is based on work presented in Ref. 14. This methodology was derived from FLOPS and contains some of the same features, but it was extended to handle hybrid-electric and electric aircraft. The mission analysis methodology is also able to handle multiple propulsors independently; thus, allowing the analyst to identify which propulsor setting would satisfy a given objective function. The mission is divided into independent segments each with their own objective function. The objective functions for the climb segment can include minimum time-to-climb, minimum fuel-to-climb, or minimum energy-to-climb. Similarly, for the cruise segment it is possible to specify maximum range or maximum endurance missions based on fuel or energy used by varying the altitude, velocity, and thrust for each propulsor class. The use of energy in the objective functions allows the user to include different energy sources. Also, the user can specify the desired balance between electric and fuel energy as an objective function.

The mission analysis methodology uses the OpenMDAO model that includes propulsion, aerodynamics, and atmospheric modules to evaluate the desired metrics of interest. This information is passed to an optimization process to generate the necessary optimization tables to determine the mission trajectory [14]. The schematic shown in Fig. 4 shows the potential interactions between components that can be included in the model. The inputs into this model include altitude, velocity, and throttle parameters for each propulsor class.

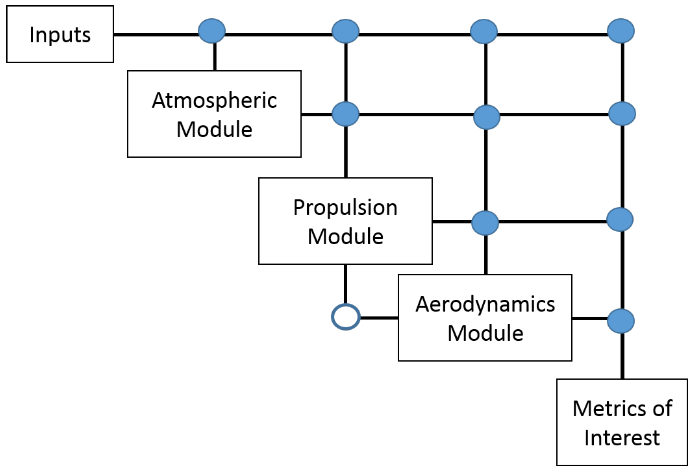


Figure 4: Schematic of the analysis model used in the mission analysis methodology and its potential component interaction.

As previously discussed, the PEGASUS concept is designed to fly two missions: a 400 nmi hybrid mission and a 200 nmi all-electric mission. The 400 nmi mission includes a minimum time-to-climb segment and a minimum energy (electric and fuel) cruise segment. The 200 nmi all-electric mission includes a minimum time-to-climb segment and a minimum electric energy cruise segment. Also in both missions, the inboard propellers are folded during cruise and descent. The methodology finds the best velocity and propulsor power settings during the cruise segments. For this study, the flight altitude for the 200 nmi and 400 nmi missions was effectively held constant during cruise.

4 Results

Two of the challenges faced when sizing this aircraft are the large design space and the lack of a well-defined objective function. The design space of the PEGASUS concept is larger than what is typical in the design of a conceptual conventional aircraft. Some of the design variables that can be considered include: wing area, geometry and design conditions for each propeller class, amount of hybridization, and the power split among propulsors during flight. As discussed in Section 2.3, choosing an appropriate metric to size the vehicle is not trivial. The selection of a proper metric is beyond the scope of this paper; however, a baseline vehicle was selected by examining ramp weight, battery weight, and energy required. The battery was sized to ensure that the hybrid (400 nmi), all-electric (200 nmi), and reserve missions can be flown. It is important to note that the electric energy required to complete the 400 nmi hybrid mission is not necessarily greater than or equal to that required for the 200 nmi all-electric mission because of the use of fuel. For this reason, both missions were modeled to ensure that the battery is sized appropriately.

For this initial investigation, the design space was simplified to wing area and the percent of hybridization. The hybridization is represented by the gas turbine factor or scale (GT scale). For example, consider an engine with standard power output of 2400 shp and a GT scale of 0.8, the resulting gas turbine would provide a standard power output of 1920 shp (80% of 2400 shp). The rest of the power would be provided by the electric system. The wingtip propulsors will first use the power available from the gas turbine before relying on electric power. This design space allows us to evaluate and refine the vehicle, but further analysis is needed to determine if there is a more suitable design space.

Figures 5 to 7 show how the energy used (fuel and electric), ramp weight, and battery weight change as a function of GT scale and wing area. The energy used is computed by integrating the electric power throughout the mission and converting the fuel used to its equivalent energy by using an energy density of 42.8 MJ/kg. The blue line represents the wing loading constraint of 76 lb/ft^2. The region defined by the solid and dashed lines is the infeasible region (wing loading greater than 76 lb/ft^2). The area above the solid line corresponds to the feasible region. The star represents the point selected to provide a baseline configuration for the PEGASUS concept. As expected, a lower GT scale results in a lower energy required (Fig. 5) while corresponding to larger ramp and battery weights (Figs. 6 and 7). The baseline configuration was selected to provide a balance between battery weight, energy usage, and wing area. This configuration uses a GT scale of 0.82 and a wing area of 700 ft^2.

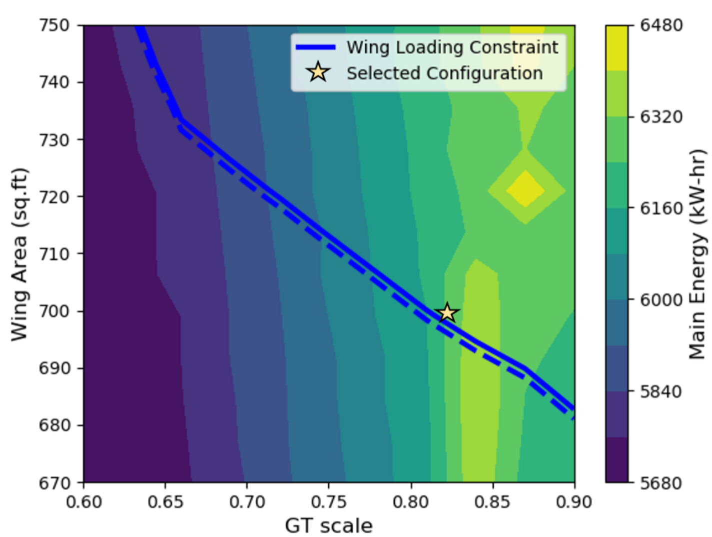


Figure 5: Energy required to complete the 400 nmi mission with a wing loading constraint of 76 lb/ft^2.

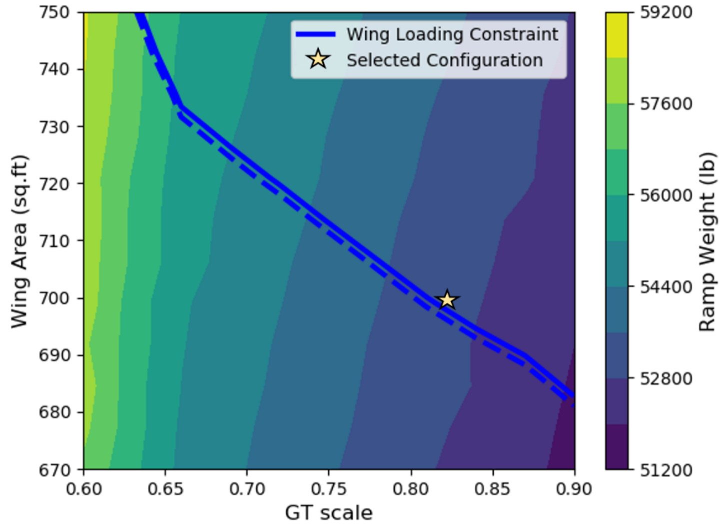


Figure 6: Maximum ramp weight results with a wing loading constraint of 76 lb/ft^2.

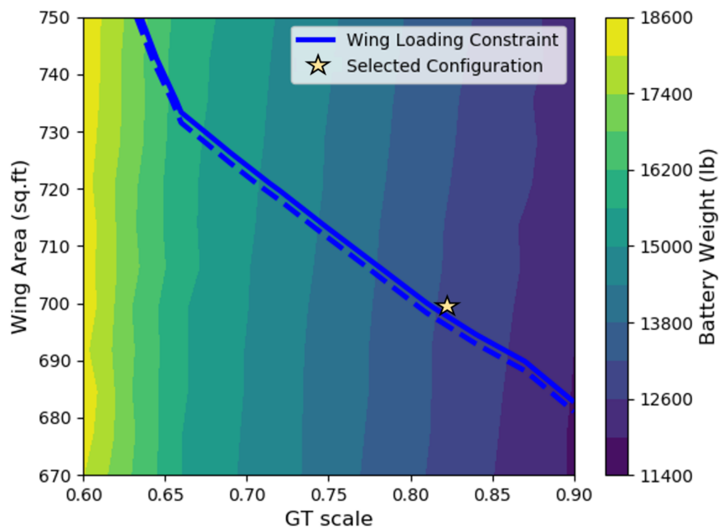
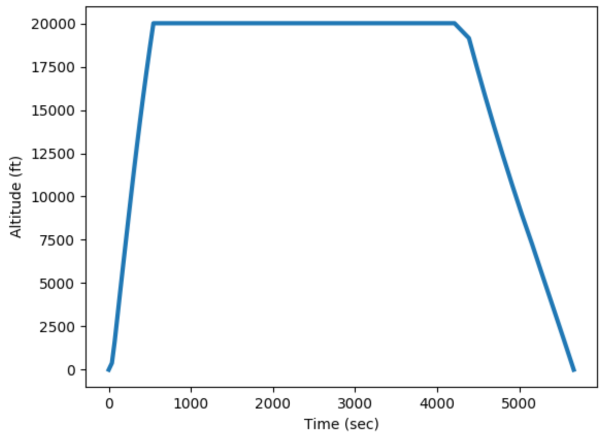
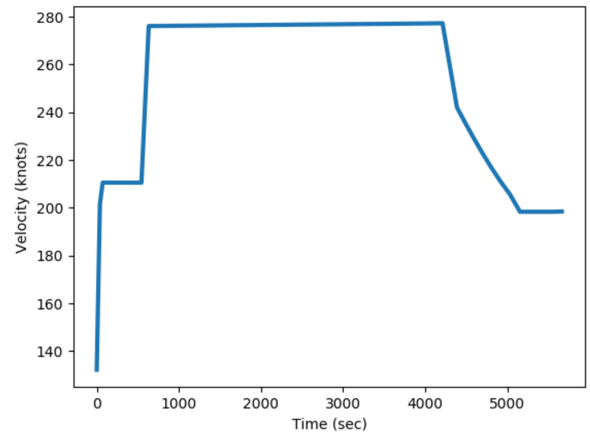


Figure 7: Battery weight results with a wing loading constraint of 76 lb/ft^2.

The mission profile is shown in Fig. 8. The main advantage of using the mission analysis methodology proposed by Capristan and Welstead [14] is that each propulsor can be operated independently and the optimizer can pick the best power split between the wingtip and aft propulsors to satisfy the desired objective function (inboard propellers are folded during cruise and descent). Figure 9 shows the mass and thrust profile for the 400 nmi mission. Note that there is a thrust limit for the wingtip propulsors to ensure that OEI yawing moment does not exceed the limits for the ATR vehicle.

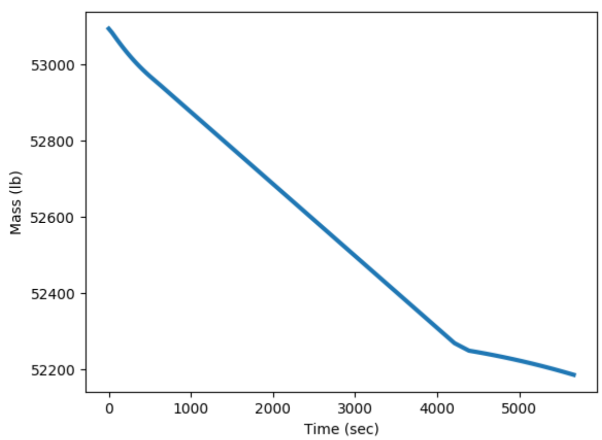


(a) Altitude profile

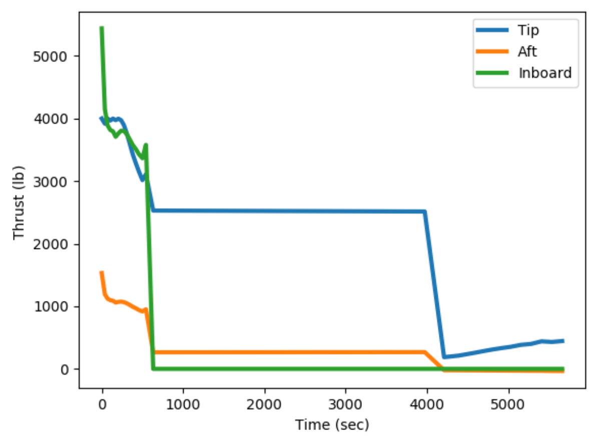


(b) Velocity profile

Figure 8: Mission profile for the 400 nmi mission.



(a) Mass profile



(b) Thrust profile

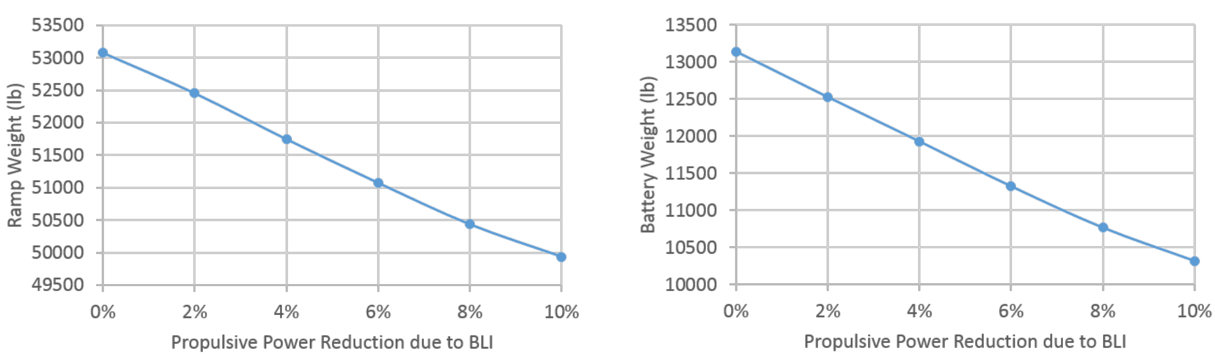
Figure 9: Mass and thrust profiles for the 400 nmi mission.

The resulting vehicle has a battery weight of 13,140 lb and 903 lb of fuel. The energy required to complete the 400 nmi mission is approximately 6,200 kW-hr or 15.5 kW-hr per nmi. In the previous PEGASUS study [2], a similar hybrid-electric conventional vehicle (only one propulsor class located at the wing inboard instead of the three proposed in the PEGASUS concept) required about 20 kW-hr per nmi. This indicates that the PEGASUS vehicle has the potential to use less energy than more conventional configurations. A fuel-only ATR 42-like vehicle with engine components upgraded to reflect a 2030 entry-into-service date (referred to as Conventional Concept) was also designed for a 400 nmi mission and compared to the PEGASUS configuration. The results of this comparison are shown in Table 2. The PEGASUS vehicle uses 19% less energy than the Conventional Concept to complete a 400 nmi mission, but it is 49% heavier.

Table 2: Conventional Aircraft Compared to PEGASUS

	Conventional Concept	PEGASUS
Cruise Altitude (ft)	25,000	20,000
Cruise Mach	0.43	0.45
Total Engine Weight (lb)	3,675	5,558
TOGW (lb)	35,539	53,041
Wing Area (ft^2)	586	700
Mission Fuel (lb)	1,421	903
Battery Weight (lb)	0	13,131
Mission Energy (kW-hr)	7,663	6,186

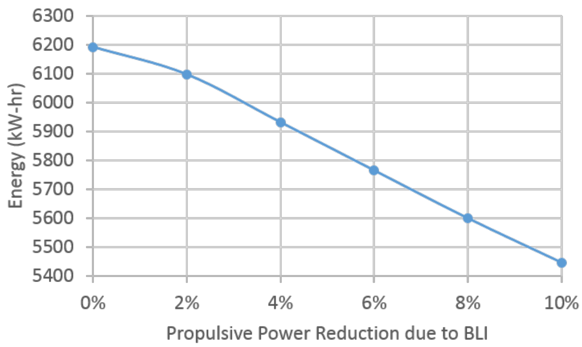
Two of the main assumptions in this study are the wingtip propulsor and BLI system benefits. Sensitivity studies were performed to evaluate how changes in these assumptions can affect the ramp weight, battery weight, and energy required. Figure 10 shows the ramp and battery weight changes as the assumed BLI power reduction varies. Figure 11 shows the energy required to complete the 400 nmi and 200 nmi missions. The BLI power reduction represents the overall propulsive benefit for all propulsors throughout the entire mission. The initial assumption of 0% benefit provided a conservative vehicle size. As seen in Fig. 10, a 10% benefit can decrease the battery weight by over 2,000 lb and substantially decreases the energy required.



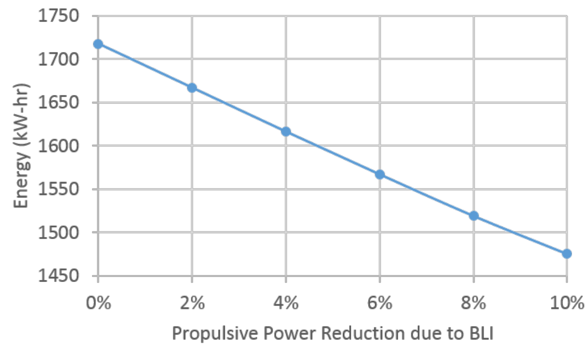
(a) Ramp weight.

(b) Battery weight.

Figure 10: Ramp and battery weight as a function of BLI power reduction benefit assumed.



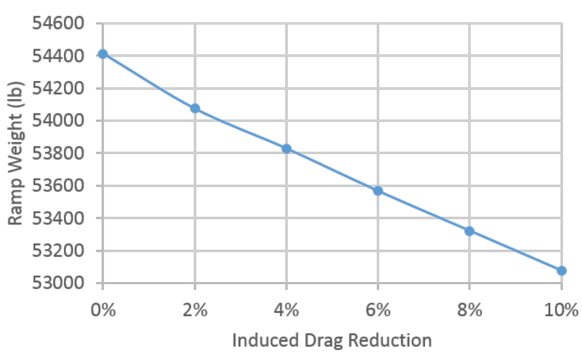
(a) Energy required for the 400 nmi.



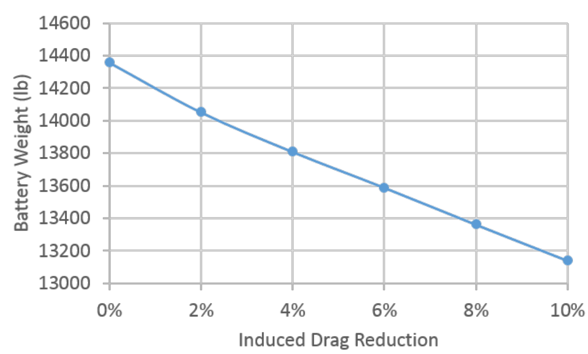
(b) Energy required for the 200 nmi.

Figure 11: Total energy required for the 400 nmi and 200 nmi missions as a function of BLI power reduction benefit assumed.

Figures 12 and 13 show the effects of the wingtip induced drag reduction assumption on weight and energy. The results show that the change in battery weight is less than 2,000 lb for an induced drag reduction between 0 to 10%. Similarly, the energy required to complete the 400 nmi decreases approximately by $\sim$ 200 kW-hr ($\sim$ 3% reduction) when the assumed induced drag reduction varies from 0 to 10%. The weight and energy reductions associated with the wingtip propulsor induced drag benefit are moderate because induced drag only accounts for a portion of the total drag. Other considerations, such as laminar or turbulent flow over areas of the wing behind the propeller wakes, can also provide further benefits. Also, note that results at 0% induced drag reduction represent the case where there is no induced drag and BLI benefit. For this case, the energy required to complete the mission is 6,400 kW-hr, which is a $\sim$ 1200 kW-hr (16%) decrease with respect to the Conventional Concept (see Table 2).

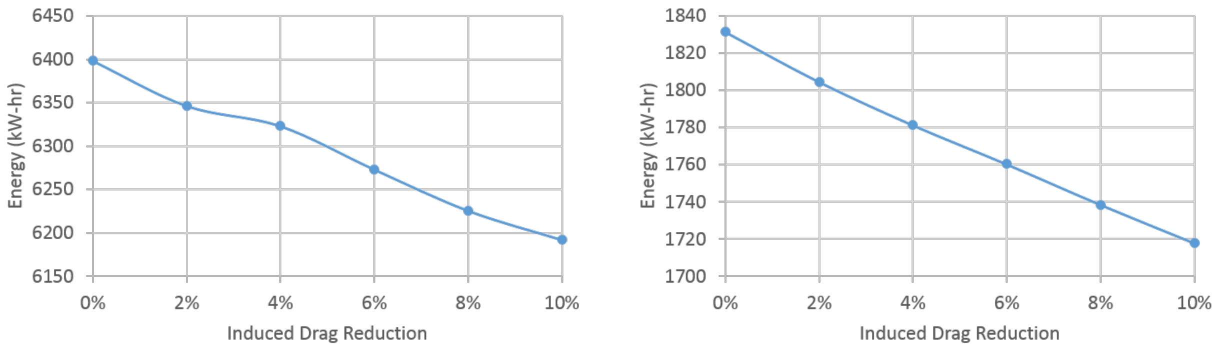


(a) Ramp weight.



(b) Battery weight.

Figure 12: Ramp and battery weight as a function of induced drag benefit assumed for wingtip propulsors.



(a) Energy required for the 400 nmi mission.

(b) Energy required for the 200 nmi mission.

Figure 13: Energy required as a function of induced drag reduction assumed for wingtip propulsors.

5 Concluding Remarks

The mission analysis methodology used in this work leveraged a version of the Layered and Extensible Aircraft Performance System (LEAPS). This version was coupled with a mission analysis methodology that enables modeling of aerodynamic and propulsion interactions as well as the ability to throttle each propulsor independently. This functionality is expected to be part of a future version of LEAPS, thus making it a tool suitable for handling unconventional aircraft similar to the PEGASUS concept.

The baseline PEGASUS vehicle was sized to meet a 76 lb/ft^2 wing loading constraint. The amount of total energy used by the aircraft increases as the amount of hybridization decreases (with corresponding decreases in battery weight and ramp weight). This is due to the fact that electric motors are more energy efficient than gas turbines. In future work, a cost function that accounts for the amount of fuel used and electric energy required needs to be defined to properly size the aircraft. The current baseline configuration assumes no propulsive benefit from boundary layer ingestion (BLI) and a 10% induced drag reduction due to the wingtip propellers. The configuration selected has a 700 ft^2 wing area, and the hybrid propulsor can obtain 82% of its power from the gas turbine.

Sensitivity studies were performed to quantify the effects of changes in the BLI propulsive benefit and induced drag reduction due to the wingtip propulsors. By assuming a 10% propulsive power reduction due to BLI, the battery weight decreased by approximately 2,500 lb. Similarly, the energy required to complete the 400 nmi mission decreased by approximately 700 kW-hr. For the 200 nmi all-electric mission, the energy required decreased by over 200 kW-hr (electric energy only). Note that a 10% propulsive power reduction is large and can be difficult to achieve. When assuming a 0% induced drag benefit from the wingtip propellers (baseline vehicle assumed 10% induced drag reduction), the battery weight increased by approximately 1,200 lb. The energy required for the 400 nmi mission increased by 200 kW-hr and the energy required increased by about 110 kW-hr for the 200 nmi mission. These results suggests that BLI and wingtip propulsors can play an important role in decreasing the total energy and battery weight. Future work will focus on decreasing the uncertainty in these parameters to better quantify the potential benefits of the PEGASUS concept.

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Appendix A XROTOR Outputs

Nomenclature

Ω	Angular velocity
β	blade angle
η	Efficiency
σ	Solidity
C_P	Power coefficient
C_T	Thrust coefficient
# bld	Number of blades
h	altitude
J	Advance ratio
P	Power
Pc	Normalized Power
R	Tip Radius
RPM	revolutions per minute
T	Thrust
Tc	Normalized Thrust
V	Freestream speed

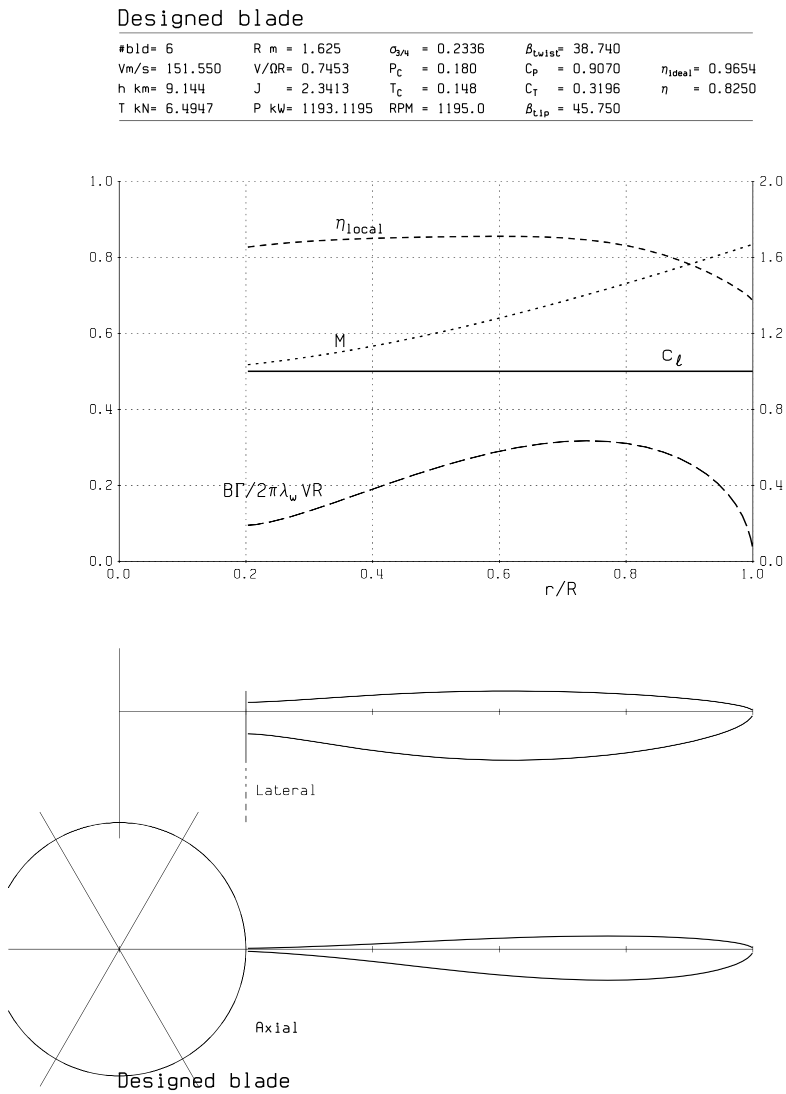

Figure A-1: XROTOR output for the tip propellers.

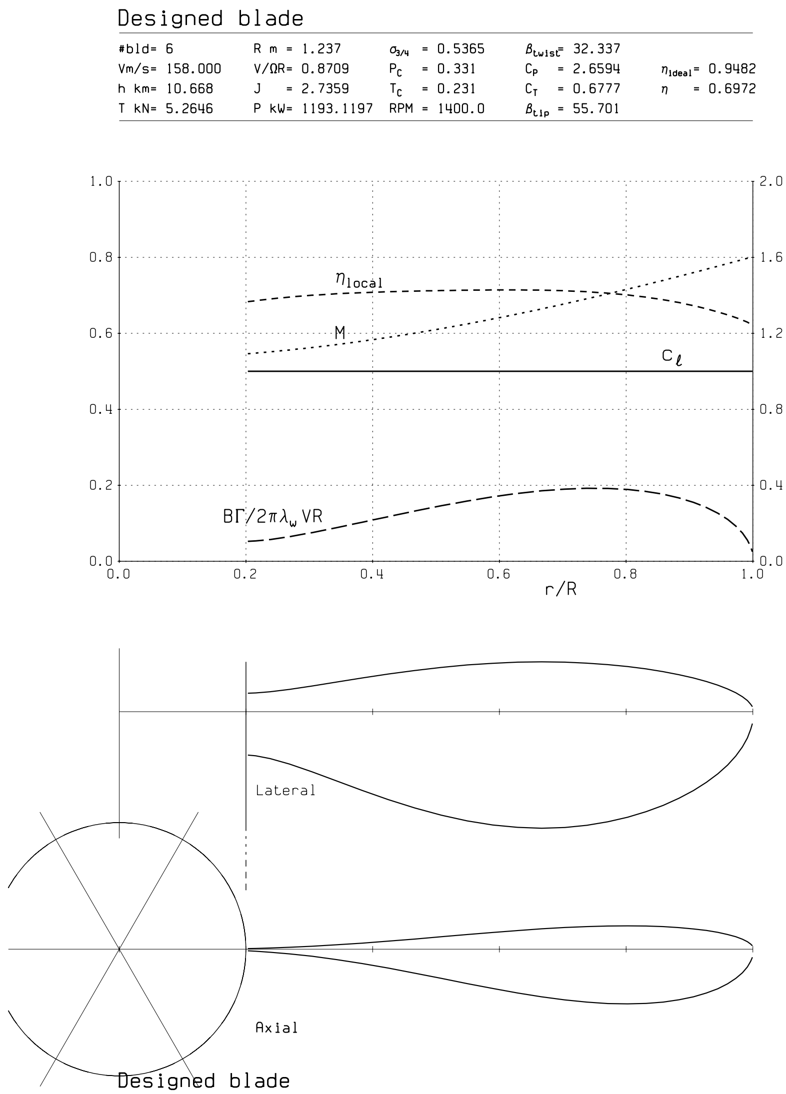

Figure A-2: XROTOR output for the inboard propellers.

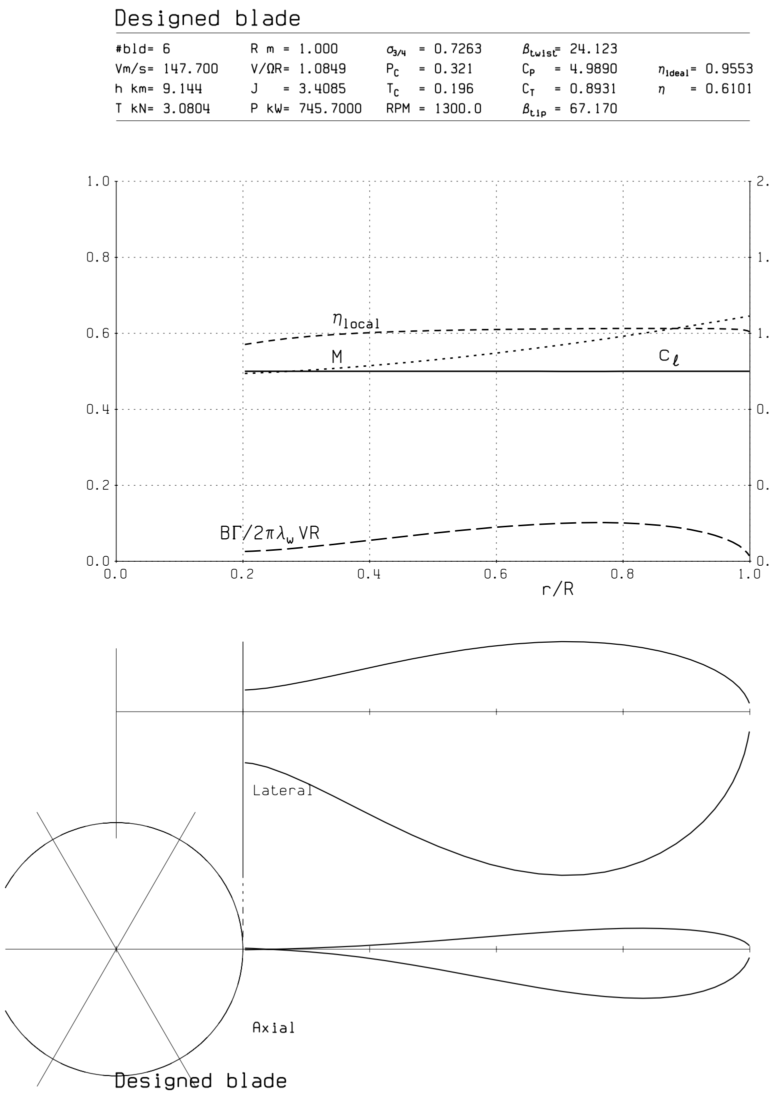

Figure A-3: XROTOR output for the aft propeller.

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14. ABSTRACT
The Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) vehicle is a regional aircraft concept that uses electric and hybrid-electric propulsors located strategically to obtain aerodynamic and mission benefits. Traditional aircraft analysis tools are not well suited to analyze the PEGASUS aircraft due to the different propulsor types used. This report summarizes a methodology that addresses some of the mission analysis challenges expected in modeling this vehicle concept. An initial baseline design is selected and sensitivity studies are performed to further understand the potential benefits of the concept.

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