Modeling and Simulation of a Parallel Hybrid-Electric Propulsion System - Electrified Powertrain Flight Demonstration (EPFD) Program

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***Abstract*—Electrified aircraft propulsion concepts have been proposed to meet aggressive future performance and environmental goals for the next generation of aircraft. However, electrified aircraft present a unique modeling and simulation challenge as they introduce multiple energy sources to the propulsion system, providing various means to meet thrust requirements, compared to conventional gas turbine propulsion architectures where only fuel is available. Additionally, the introduction of an electric powertrain to the existing system enables multiple electrified flight modes to exist (i.e. eTaxi, climb boost, takeoff boost, etc.), further increasing the complexity of the modeling environment. As part of the Electrified Powertrain Flight Demonstration program, this paper presents a modeling and simulation framework for a parallel hybrid-electric propulsion concept using the Environmental Design Space simulation tool. Electrical components are modeled in NPSS, and an overall sizing methodology is introduced. Finally, various operational modes of the electric powertrain are modeled and tested and their impact on key performance parameters is evaluated.**

I. INTRODUCTION

Hybrid-electric concepts combining traditional fuel-based engines with electric motors have emerged as potential viable options to meet NASA's aggressive N+3 performance goals (I) for future generation aircraft. Although hybrid electric concepts have the potential to meet these goals, they present a unique modeling challenge.

TABLE I: NASA Future Gen. Aircraft Performance Goals [1]

Technology Benefits	N+1 (2015)	N+2 (2025)	N+3 (2035+)
Aircraft Fuel / Energy Consumption (rel. to 2005 best in class)	-33%	-50%	36.25%
Noise	-32dB	-42dB	-52dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%

Conventional gas turbine aircraft employ a single energy source: fuel. For this configuration, a single engine power setting is needed to command the required thrust across the entire flight envelope. In contrast, hybrid-electric concepts can generate power from multiple energy sources: fuel through the use of gas turbines and electricity stored on-board energy storage systems (i.e. battery packs). As a result, various combinations of power settings can produce the required thrust. In addition, multiple operational modes of the electric powertrain exist (motor, generator, offline), enabling different flight modes (eTaxi, climb boost, takeoff boost, etc.), thereby increasing the complexity of the model. Choosing when to implement each flight mode and how much electric power to provide or extract can lead to large variations in total mission fuel burn. As part of the Electrified Powertrain Flight Demonstration program (EPFD), the purpose of this research paper is to present the modeling and simulation framework of a parallel hybrid-electric propulsion system, as well as to show the different modes of operation available and the impact of those modes on the system's key performance parameters (KPP), such as Thrust Specific Fuel Consumption (TSFC), fuel flow, and total installed electric power.

II. PARALLEL HYBRID-ELECTRIC POWERTRAIN ARCHITECTURE

The parallel hybrid-electric propulsion system consists of two separate powertrains: the conventional gas turbine powertrain and the electric powertrain, which are connected to the same engine shafts. The gas turbine model is based off of the Pratt & Whitney PW1127G-JM geared turbofan engine, capable of providing approximately 120 kN (27,000 lb) of thrust and weighing about 2,857 kg (6,300 lbs) [2]. The geared turbofan engine incorporates two shafts, a low pressure (lp) shaft and a high pressure (hp) shaft, connecting the low pressure and high pressure compressor/turbine pair respectively. On each of the two shafts an electric machine is attached, capable of operating either as a motor or a generator. A power converter connected to each electric machine is then used to convert power between AC and DC and vice versa. Both power converters are connected to a high voltage DC bus via power cables. A large battery pack is connected to the DC bus, providing power to the motors. Finally, an additional connection to the DC bus provides electric power to the airplane non-propulsive electrical loads. This setup is replicated on both sides of the airplane. The parallel hybrid-electric propulsion concept under study is shown in Fig. 1.

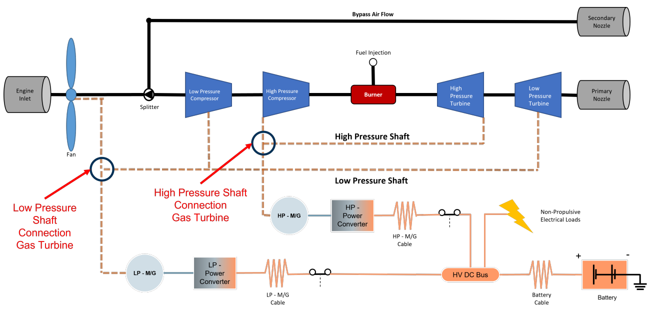

Fig. 1: Parallel Hybrid-Electric Propulsion Concept

A dedicated thermal management system (TMS) is required to carry away excess heat generated by onboard aircraft electrical components. Modeling of this system is performed using the Numerical Propulsion System Simulation software (NPSS) including the construction and incorporation of novel air-liquid and liquid-liquid heat exchanger elements. A 50/50 propylene-glycol water mixture is used to transport excess heat generated onboard the powertrain's battery, motor, and other high-power electronics to either a ram air stream, a fuel stream, or the turbofan bypass airflow for disposal. The TMS analysis performed in this work estimates the added weight of the system, the supplemental power required to drive coolant pumps and an auxiliary fan, and the added drag incurred by additional ram air cooling flow.

III. Modes of Operation

Multiple electric powertrain modes of operation can be modeled depending on the operating mode of the electric machines and the battery. Each of the two electric machines can operate as a motor, a generator, or be offline (three possible operational states), while the battery can operate in discharge mode, recharge mode, or be offline (three possible operational states). A total of 27 powertrain modes are possible based on the available operational modes of the electrical components, enabling different electrical functions (electric taxi, takeoff boost, climb boost, and battery recharge) to be performed. However, considering that electric power must be available to power non-propulsive electrical loads, and that several identified powertrain modes have no use cases during flight, the modes of interest can be narrowed down according to the electrical functionality they enable. A total of 6 operational modes are identified and considered for the purposes of this study:

- **Electrical Taxi (eTaxi)**: Compared to a conventional airplane, a parallel hybrid-electric powertrain enables electric taxi, wherein the gas turbine remains offline, and the battery provides power to the low pressure (lp) electric motor, so as to provide thrust for taxi. Three different motor power levels are utilized to characterize normal taxi operations: acceleration, runway crossing, and steady state aircraft taxi.
- **Takeoff Boost**: Electric torque is provided to each of the two shafts (hp and lp) via the battery during takeoff, thereby reducing the gas turbine fuel flow requirements to generate the same amount of thrust compared to a conventional engine. Additionally, by providing power during takeoff and climb, the engine core can be down-sized and sized for cruise conditions compared to takeoff conditions.
- **Climb Boost**: Electric torque is provided to each of the two shafts via the battery during climb. Electric power is provided to maintain a minimum climb rate during climb.
- **Cruise Off-Takes**: During cruise, the hp-shaft connected generator can provide power to non-propulsive electrical loads versus extracting the power directly from the engine itself. Additionally, power from the generator can be used to recharge the on-board energy storage system (battery).
- **Turbine Electrified Energy Management (TEEM)**: Use of both electric machines to maintain efficient shaft speeds during transient operation of the engine. This enables tighter engine control and design for smaller surge margin.
- **Sub-Idle Descent - Electric Power Transfer (EPT)**: For a conventional engine, flight idle thrust is constrained by a minimum hp-shaft speed. By extracting power from the lp-shaft (generator) and transferring power to the hp-shaft (motor), the power requirements for maintaining a minimum hp-shaft speed can be reduced, thereby enabling reduced fuel burn during descent. Additionally, generator power can be used to recharge the battery.

Each of the electric operational modes are shown in Fig. 2. For each mode, the operational status of each of the three main components is shown (hp-elec machine, lp-elec. machine, and battery), as well as the source of power for the non-propulsive electrical loads.

Functionality	Gas Turbine	HP-Elec.Machine	LP-Elec.Machine	Battery	Subsystems
eTaxi	Offline	Offline	Motor	Discharge	APU/Battery
Takeoff / Climb Boost	Online	Motor/Generator	Motor	Discharge	Battery/Generator
Cruise Off-Takes	Online	Generator	Generator	Offline/Recharge	Generators
TEEM (Accel. / Decel.)	Online	Motor	Offline/Generator	Discharge/Offline	Battery/Generator
EPT Descent	Online	Motor	Generator	Offline/Recharge	Generator

Fig. 2: Electric Operational Modes

IV. Modeling and Simulation Environment

The Environmental Design Space (EDS) vehicle sizing and simulation tool is used as the basis of the modeling framework to perform an integrated analysis of aircraft performance, source noise, and exhaust emissions at the aircraft level. EDS has been used for open rotor [3], direct drive, and geared turbofan engines [4], and can simulate both tube-and-wing and hybrid wing body airframe configurations [5] [6]. Fig.

3 shows the flow of information during the execution of EDS for a single aircraft. Modules of particular importance include:

- **Numerical Propulsion System Simulation (NPSS)**: Engine cycle design and analysis. Performs a thermodynamic cycle analysis of the propulsion system. Calculates the engine design parameters so that engine performance targets and constraints are satisfied.
- **WATE**: Engine flow path analysis and weight estimation.
- **Flight Optimization System (FLOPS)**: Vehicle sizing and synthesis and mission analysis.

Each module's capabilities will be expanded to allow the execution of an integrated a hybrid-electric propulsion system analysis. These modifications/additions are presented in the next few sections.

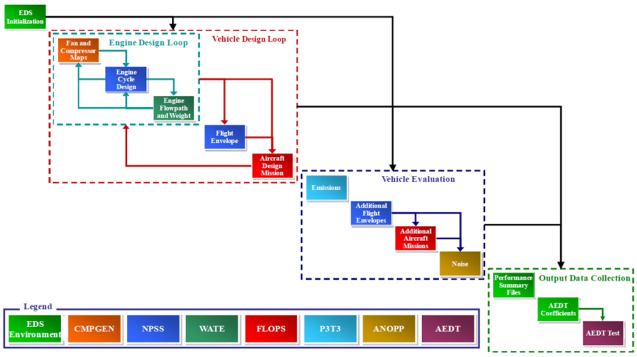

Fig. 3: EDS Architecture

V. Electric Component Modeling

The standard NPSS library does not include electrical elements. New elements were created in NPSS for each of the electrical components shown in Fig. 1. Similar to how the conventional propulsion NPSS elements exchange flow rate, temperature, and pressure information between one another to maintain flow/fluid continuity, the electric powertrain elements exchange current and voltage information to maintain electrical continuity across the electric powertrain. Each electric machine is linked to the gas turbine engine shafts, enabling the addition and subtraction of torque from the shaft, with the shaft speed and torque determining efficiency using a scalable map. The electric machine can either operate as a motor, wherein the battery discharges to provide the required power, or as a generator, wherein the battery can be recharged and the electrical non-propulsive electrical loads powered. In general, the torque of the electric machine is varied by an NPSS solver to achieve a target electric machine power, battery recharge current, or overall engine thrust target. Internal calculations ensure powertrain continuity, including the state of charge of the battery. Bus voltage is set by the battery according to battery current and capacity based on a discharge curve equation from the work performed by Tremblay et al. [7]. Electric machine and power converter specific powers and efficiencies are inputs to the model. The work performed by Pastra et al. [8] and Hall et al. [9] include projections for electric machine and power converter specific power and efficiency levels through 2050, respectively. The weight of these electrical components is calculated as a function of specific power and rated power. The weight of the battery pack is calculated as a function of chemical weight and packaging weight, where the chemical weight is calculated based on the specific energy of the battery cells, and the packaging weight is based on the total number of cells in the battery pack. Technological factors can be used to scale the battery weight to account for improved packaging construction and materials.

VI. Sizing Methodology

The sizing of the hybrid-electric propulsion system consists of several modules, shown in Fig. 4:

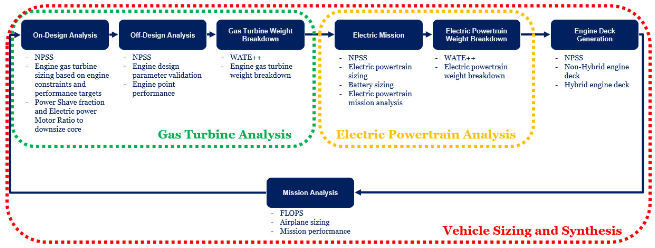

Fig. 4: Vehicle Analysis

A. Gas Turbine Analysis

A multi-design point approach is implemented to size the geared turbofan gas turbine, such that thrust requirements and engine performance constraints are satisfied at five different flight conditions (aerodynamic design point - ADP, takeoff - TKO, top-of-climb - TOC, sea level static installed thrust, and sea level static uninstalled thrust). Additionally, electric power is provided by the electric machines at TKO, TOC, and SLS, thereby allowing the core engine to be downsized. The amount of electric power provided can be parametrically varied using two factors: A hybridization factor and an electric machine power ratio. The hybridization factor determines the electric power required to achieve a target combustor output temperature (T4) at the ADP point as a function of T4 at the TOC point. When the hybridization factor is equal to 1.0 then T4 at ADP is equal to T4 at TOC. When the hybridization factor is equal to 0.0 it is assumed that the propulsion system operates as a conventional fuel-based engine. An example of the impact of this parameter is shown in Fig. 5.

Additionally, the electric machine power ratio is used to determine the amount of power provided by the hp-shaft connected electric machine relative to the power provided by the lp-shaft connected electric machine. A power ratio of 0.0 implies all power required for engine core downsizing is provided by the lp-electric machine, while a power ratio of 1.0, implies both electric machines provide an equal amount of power. Compared to the hybridization factor which has an upper bound limit of 1.0, the power ratio value can exceed the value of 1.0 (hp-elec.machine power exceeds power provided by lp-elec.machine).

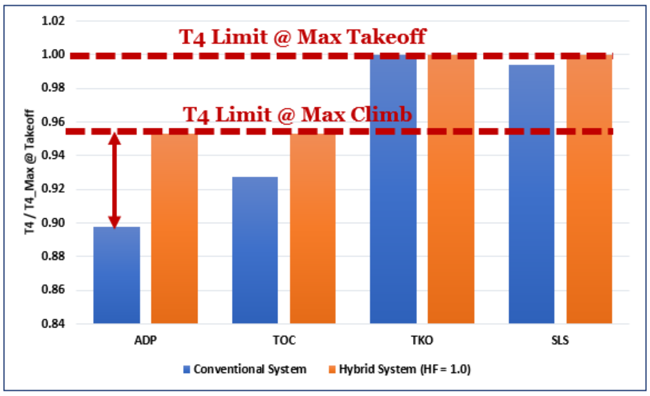

Fig. 5: Gas Turbine On-Design Analysis

During on-design sizing of the gas turbine propulsion system, engine design parameters can be varied to satisfy engine performance targets and constraints. Once the design parameters have been determined, the engine is rerun at the same flight points (ADP, TOC, etc.) in off-design mode (fixed engine architecture/design parameters), using the calculated design parameters, to verify correct representation of the sized gas turbine. Finally, WATE is used to calculate the gas turbine geometry and weight.

B. *Electric Powertrain Analysis*

With the gas turbine sized, the next step is to size the electric powertrain. First, both electric machines are sized based on the most demanding electrical design point. Four points are considered for this purpose. On-design, eTaxi, TEEM, and EPT power requirements are considered during this stage. The next step is to determine the power schedule of the electric machines during flight operation based on which hybrid electrical modes are active, such as eTaxi, takeoff boost, etc., during flight. For example, if climb boost is performed, then the motor power during each flight point during the climb segment is calculated by determining whether the engine is capable of meeting certain climb rate requirements (determined by the user) with or without electric power. Once the power schedules are calculated, the battery is sized based on the electric machine power schedules, such that the discharged battery capacity at the end of the electric mission is equal to approximately 20%. If recharge is performed during the flight, then the generator power schedule is determined as a function of the target recharge current to fully charge the battery by the end of the mission. Finally, with the electric machines and battery design parameters determined, all remaining electrical components are sized based on maximum expected current/voltage levels during flight, while being constrained by the maximum design power of the electrical components and maximum continuous battery current of the battery cells (as defined by battery C-rate). A breakdown of the electric mission is shown in Fig. 6:

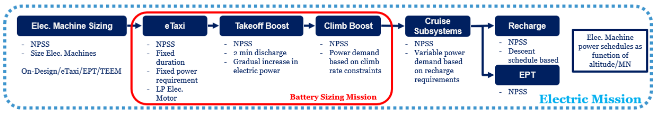

Fig. 6: Electric Mission Analysis

VII. Vehicle Sizing and Synthesis/Integration with Aircraft Level

With the gas turbine and electric powertrain analysis complete, engine decks containing engine performance information are generated. Two types of engine decks are created: a non-hybrid engine deck, used during the non-electrified mission segments, and a hybrid engine deck, used during all other mission segments. For each flight point (altitude/MN combination) in the engine decks, key engine performance metrics are calculated, such as fuel flow, thrust, and ram drag. To create the hybrid engine deck, the power schedules of the motors and generators from the previous section, are used. Once the engine decks are generated, the information is passed to FLOPS which performs the mission analysis portion of EDS using a 150-passenger aircraft model based on the Airbus A320-neo, a large single aisle aircraft weighing approximately 79,378 kg (175,000 lbs) [10]. The airplane design parameters chosen and the design mission used is based on the work by Harish et al. [11]. In their paper, the authors establish an advanced non-electrified 150-passenger aircraft assuming a 2030 Entry-into-Service target date. The mission analysis calculates aircraft KPPs such as mission fuel burn, takeoff gross weight, and mission range and duration, among others. A feedback loop between the FLOPS and the rest of the EDS modules ensures that the climb/descent schedules used during the energy storage system sizing process and the mission analysis are consistent with each other. Additionally, the mission analysis module determines whether the hybrid-electric propulsion system provided is sufficient to meet all mission requirements, and whether the propulsion system needs to be scaled upwards or downwards.

Fig. 7 shows an example electrified mission that the parallel-hybrid electric aircraft would complete:

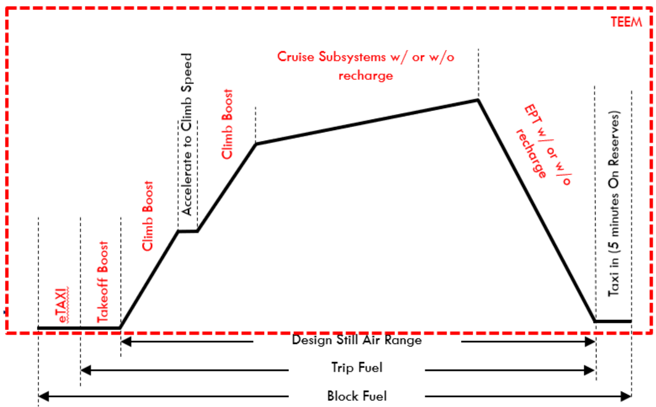

Fig. 7: Electric Mission Illustration

The mission is broken down into 5 main segments which use the electric powertrain. As seen from the figure, the flight mission consists of taxi-out, takeoff, climb, cruise, descent, and taxi-in segments. At each stage of the flight, a different electric operational mode can be performed as shown in the figure. The description of each mode has been presented previously, while the TEEM functionality is applied throughout the flight envelope.

VIII. Subsystem Replacement Approach

In order to fully leverage the benefits of the parallel hybrid electric powertrain proposed above, the functional replacement of several conventional aircraft subsystems with alternative components was explored. Of the various subsystems found on conventional aircraft, three were identified as being easily substituted with components already present in the powertrain configuration: the ram air turbine (RAT), the integrated drive generator (IDG), and the air turbine starter. The RAT is a freestream air-driven propeller, which provides emergency electrical and hydraulic power in the event of total engine failure. Its replacement could be achieved by using the non-propulsive batteries and an independent hydraulic pump. As the RAT is an emergency device, its replacement would require an independent configuration from the primary powertrain. The IDG is an electric generator which provides primary electrical power in conventional aircraft. The replacement of this device is easily achieved with the HP shaft electric machine, which provides similar power generation during cruise, and batteries, for use during transient conditions. Lastly, the air turbine starter provides initial starting torque for gas turbine engines. The LP shaft electric machine is a suitable replacement, as it can provide a similar torque, and would require no modification. Ultimately, replacing the three subsystems with these alternative components could yield significant weight savings, while maintaining similar functionality.

IX. Results

Figures 8, 9, and 10 show the trends for Thrust Specific Fuel Consumption (TSFC), total installed electric power, and stall margins for the low pressure compressor as a function of hybridization factor (or power shave fraction) and the electric machine power ratio.

In fig. 8, TSFC reduction relative to the baseline vehicle at ADP is shown as a function of the power shave fraction. Each curve represents a different electric machine power ratio. As can be seen in the figure, by increasing the hybridization factor, the core engine is downsized even further, leading to a better TSFC improvement relative to the baseline. At the maximum value (1.0), a 1.3-1.4 % TSFC reduction relative to the baseline can be achieved. Additionally, TSFC trends have a low sensitivity to the power ratio between the two electric machines.

From fig. 8 it is implied that a larger hybridization factor is preferable to a lower one, to achieve maximum TSFC improvement at ADP. However, when looking at fig. 9 it can be observed, that by increasing the hybridization factor, the total amount of installed electric power (equal to the

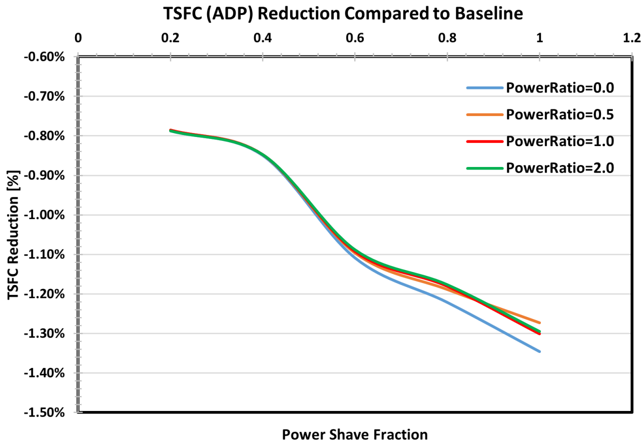

Fig. 8: On-Design TSFC Trends

total amount of power of both electric machines) required to downsize the core, significantly increases. This leads to heavier electrical components, which may offset any potential fuel burn benefits due to a better TSFC. As we can see from the graph, the electric machine power ratio plays a significant role in determining the total amount of power required to achieve a certain amount of power shave. This impact can be clearly seen at high hybridization factors with power ratio values between 0.0 and 0.6. For example, for a hybridization factor of 1.0, if only lp-power is used, then 2.5 MW of power is required to achieve core downsizing, while at a power ratio of 0.5, that number drops to just above 1.5 MW. By increasing the power ratio, we can reduce the amount of power required, which can lead to weight benefits due to the smaller size of the electric components, and therefore improved fuel burn benefits for the final vehicle.

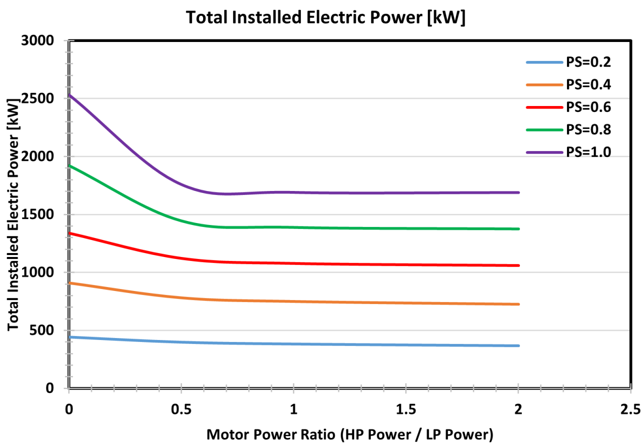

Fig. 9: Total Installed Electric Power [kW]

Figure 10 depicts the constant flow stall margin for the low pressure compressor (LPC) at the takeoff (TKO) point. As we can see, at higher hybridization factors, the LPC stall margin sensitivity to the power ratio increases. Additionally, this graph shows the benefit of using power from both elec. machines during core downsizing. For power ratios of 0.5 and above, the LPC stall margin matches and can exceed the baseline (black line) stall margin, while values less than 0.5 can lead to lower stall margins relative to the baseline, and therefore lead to engine operability issues.

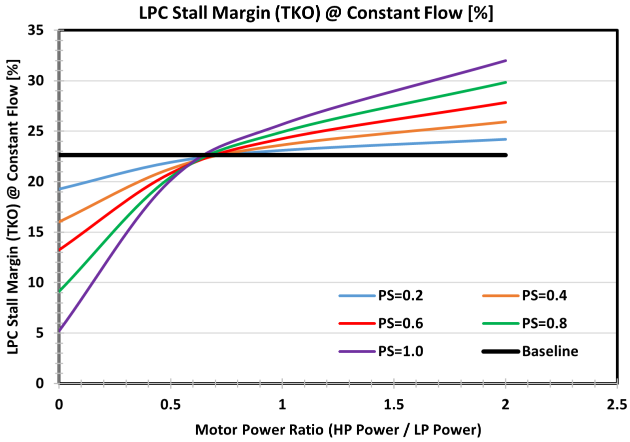

Fig. 10: Low Pressure Compressor Stall Margin [%]

Finally, fig. 11 shows fuel flow trends during descent relative to the baseline conventional vehicle, assuming the parallel hybrid-electric vehicle was sized using a hybridization factor 0.4 and a power ratio of 0.5. Each color represents a different electrical functionality active. The orange line depicts a normal descent of the hybrid vehicle. Approximately, a 0 to 5% fuel flow reduction is achieved due to the smaller core of the engine. The blue line represents descent of the hybrid electric vehicle while the EPT electric functionality is active. By maintaining the minimum hp-shaft speed through electric power vs. core engine power alone, a fuel flow reduction in the range of -20 to -30% relative to the baseline can be achieved. Finally, the purple line represents descent of the hybrid electric vehicle while recharging the battery. By extracting additional power from the core engine, to recharge the battery, descent fuel flow relative to the baseline increases approximately 10 to 20%. Shifts in the shown data represent points at which engine rating structure (maximum allowable combustor temperature and ambient temperature) is varied as a function of altitude and MN.

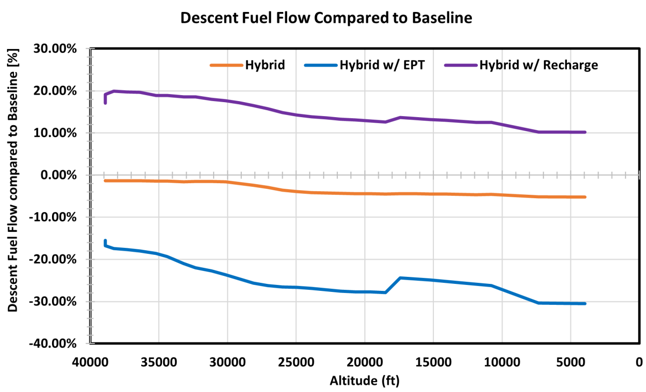

Fig. 11: Descent Fuel Flow Reduction Rel. to Baseline [%]

X. Conclusion

This paper presents a modeling and simulation framework for a parallel hybrid-electric propulsion concept using the Environmental Design Space (EDS) simulation tool. Electrical components are modeled in NPSS, and the overall vehicle sizing and synthesis methodology is analyzed. The methodology is then applied on the Airbus A320-neo (assuming 2030 technology levels), and the impact of different electric operational modes on key performance parameters (TSFC, fuel flow, and installed electric power), is shown and analyzed. The current paper focuses on the modeling and simulation framework, and sample results of the analysis are shown. Detailed vehicle and mission analysis results will be presented in a future paper. Additionally, a bleedless architecture will be considered as part of future work.

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