Flight Optimization System (FLOPS) Hybrid Electric Aircraft Design Capability

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Social Impact

Over the past few decades, a burgeoning green and sustainability initiative has emerged at the forefront of many technological industries, but only recently has the green initiative taken to the skies. In 2009, NASA began the Environmentally Responsible Aviation (ERA) project with the goals of mitigating the environmental impacts of aviation through increased fuel efficiency and decreased emissions and noise, especially near congested areas. NASA Langley Research Center has been an active force in the development of conceptual design in green aviation, and this study validated a key feature of one of NASA Langley's premier flight optimization tools that allows for the analysis of a hybrid-electric propulsion system—a revolutionary way to make aircraft more environmentally friendly.

Abstract

The goals of this study were to explore the capabilities of the Flight Optimization System (FLOPS) software to model and analyze the feasibility of a hybrid-electric engine propulsion system for commercial airliners. To test the capability of FLOPS to alternate between two engine decks for different segments of flight, an ATR 42-600 commercial airliner model was retrofitted with a hybrid-electric configuration, in which batteries power the aircraft during taxi, takeoff, climb, and descent and a traditional internal combustion engine powers the aircraft and recharges the batteries during cruise. Initial results revealed a successful utilization of the FLOPS double engine deck capability, which had never been successfully used before. Results also revealed that existing commercial airliners retrofitted with current hybrid-electric engine configurations were less fuel efficient than the non-hybrid airliner. Both serial and parallel hybrid-electric engine configurations, as well as models equipped with 2025 aircraft technologies, were tested. Only the 2025 hybrid-electric model was more fuel efficient and only for shorter distances. The results made evident that the use of a retrofit severely limited the flexibility of optimization because of having to adhere to the constraints of the existing systems.

Introduction

The NASA Environmentally Responsible Aviation (ERA) project's goals are to reduce aircraft fuel consumption, emissions, and noise in order to mitigate the harmful effects of aviation on the environment. One of the solutions being examined now is the development of hybrid-electric engines for aircraft, especially for commercial aircraft. Using batteries in conjunction with traditional internal combustion engines could be a way through which fuel efficiency could increase and emissions and noise could be reduced. During the summer of 2012, the Aeronautical Systems Analysis Branch of the Systems Analysis and Concepts Directorate at NASA Langley Research Center (LaRC) sought to explore the possibility of using its premier flight optimization code, Flight Optimization System, or FLOPS, in the preliminary phases of conceptual hybrid-electric aircraft design.

The purpose of this project was to determine a way for the FLOPS aircraft performance code to analyze a hybrid-electric aircraft and use this capability to test the feasibility of scaling up current hybrid-electric engine technologies for existing commercial airliners. FLOPS operates on variable-driven inputs to produce optimized output variables (McCullers, 2011). Engine decks are files used by FLOPS to simulate the performance of the aircraft's propulsion system; FLOPS was written with a capability to alternate between two different engine decks, enabling the analysis of a hybrid-electric aircraft design. A hybrid-electric aircraft would operate with one deck for the battery powered engine and one for the traditional internal combustion engine. This capability had never been tested prior to this experiment in the summer of 2012, therefore our project aimed to verify that FLOPS could alternate between two different engine decks for different segments of flight.

For the purpose of aligning with ERA's goal of reducing noise and emissions near airports and otherwise congested areas, the battery-powered engine was assigned to the taxi, takeoff, and climb segments of flight and the traditional internal combustion engine to the cruise, during which the batteries would be recharged for the descent and landing.

In order to test the FLOPS capability to read a double engine deck, we used the hybrid-electric engine design of the DA-36 E-Star, a two-seater motor glider jointly manufactured in 2011 by Siemens, the European Aeronautics Defense and Space Company (EADS), and Diamond Aircraft (Figure 1). The DA-36 E-Star's hybrid-electric configuration follows a serial architecture, where a rotary engine drives the propeller through a motor-generator, and a battery-powered engine provides additional power to the plane during takeoff and climb, and it is recharged during cruise. Siemens claimed that the design of the DA-36 E-Star battery-powered propulsion system could be scaled up for larger aircraft (Paur, 2011), thus this became the basis for the design we would test in FLOPS.

To test this claim of scalability for the DA-36 E-Star, the FLOPS capability to alternate between two engine decks was tested with a baseline commercial airliner, the ATR 42-600 (Figure 2), chosen for its medium size and twin-turbo propeller architecture which would facilitate the integration of the DA-36 E-Star concept, also a twin-turboprop aircraft.

Figure 1. The DA-36 E-Star two-seater motor glider by Siemens AG, Diamond Aircraft, and EADS.

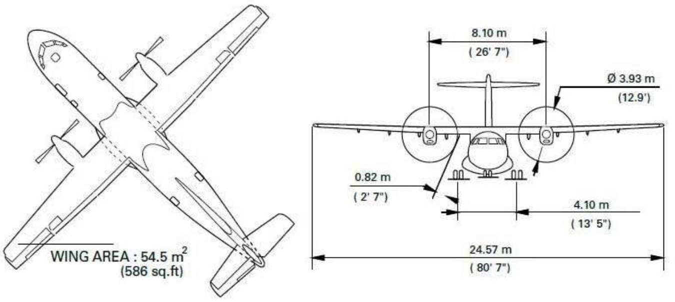

Figure 2. The ATR 42-600, a twin-turbo propeller commercial airliner, seats 48 passengers.

The ATR 42-600 seats 48 passengers and runs on the Pratt & Whitney PW127M engines (ATR, 2011).

When calibrating the baseline ATR 42-600 in FLOPS, an ERJ-190 file, an Embraer jet file, one of the closest airliner files available in FLOPS, was used to begin. The ATR 42-600 specifications were put in to calibrate the FLOPS model so it behaved as the ATR 42-600 would. A FLOPS engine deck file for the PW120 engine was readily available and was calibrated to the specifications of the PW127M. A second engine deck for the batteries was added and assigned to the taxi, takeoff, climb, and descent segments of the mission. The internal combustion engine deck was assigned to cruise and the fuel flow was increased to account for the recharging of the batteries during cruise. These modifications provided the basis on which our hybrid-electric model in FLOPS would be designed.

Method

Establishing a baseline design

The first step in the design process was establishing a baseline aircraft file for the ATR 42-600 in FLOPS and calibrating that model to the specifications released by Avions de Transport Régional (ATR), the manufacturer of the ATR 42-600. Calibration of the ATR 42-600 began with researching the dimensions of the ATR 42-600 and using those dimensions to create a 3D model in Vehicle Sketch Pad (VSP), a NASA-developed parametric geometry aircraft modeling software (Vehicle Sketch Pad, 2010). Geometric dimensions were taken from both the VSP model and the ATR specifications for use as the inputs for the geometry, weight, balance, inertia, performance controls and aerodynamic calculations variables in FLOPS.

The following model assumptions were obtained from ATR and used to calibrate the model: 48 passenger capacity, cruise altitude of 20,000-22,000 ft, Mach 0.4 cruise speed, 801 nmi design range, and 301 nmi economic range (ATR, 2011). With some modifications of design variables, low speed aerodynamic performance parameters, and weight variables, the calibrated models were completed (Lambert, 1994).

Hybrid-electric propulsion system integration

To integrate a hybrid-electric propulsion system into the ATR 42-600, we identified two engine configurations that could be feasibly integrated: a parallel and series engine architecture. Because we were testing the claim for the engine of the DA-36 E-Star to be scaled for larger aircraft, we first chose to test how the DA-36 E-Star's engine configuration, a series architecture, would perform when integrated into our ATR 42-600 model. In a series architecture, the propeller is driven by the batteries alone, with no mechanical connection to the engine, and the engine is turned off. When the batteries are not sufficient for power demands, the engine turns on and is run by a motor-generator.

In a parallel architecture, the batteries and traditional internal combustion engine can power the vehicle either individually or together, and the batteries, internal combustion engine, and motor-generator are coupled by a clutch which can engage or disengage either source of power.

The parallel architecture experiences less of an efficiency loss by design. Whereas the serial configuration has two shafts, one connecting the engine to the motor-generator and one connecting the motor-generator to the propeller, the parallel configuration has only one shaft and power travels directly from the engine to the propeller, thus we created a parallel ATR 42-600 to compare to the serial ATR 42-600.

In order to assign an electric engine deck to the ATR 42-600 in FLOPS, we researched various state-of-the-art battery technologies for which the specifications and performance variables could be used as inputs. The most widely-used battery technologies in the market today are lithium-ion, lithium-cadmium, lithium-polymer, lithium metal hydride, and lead acid. Although various battery parameters were compared, the most attention was placed on specific energy. The energy density of a fuel per unit mass is called the specific energy of that fuel; it is measure of efficiency of that fuel and is measured in Watt-hours per kilogram (Wh/kg). Batteries high in efficiency reduce total battery weight and power requirements, thereby reducing the fuel needed to compensate for their added weight and to recharge them. Lithium-ion and lithium-polymer were the most promising options, with specific energies ranging from 44 – 194 Wh/kg and 115 – 160 Wh/kg respectively ("What's the best battery?", n.d.). Further research revealed lithium-polymer batteries as highly non-degradable, which is critical for commercial aircraft application and made them the best available option for a commercial airliner (Araki, 2000). A comparison of specific energy and volumetric energy density is shown (Figure 3).

We used lithium-polymer battery specifications from Kokam Batteries to approximate the size of the battery packs needed to generate enough thrust for the climb segment of flight. Each Kokam battery cell weighed 5 kg and produced a specific energy of 178 Wh/kg. The battery packs were sized for a thrust requirement of 6,208 lbs at top-of-climb conditions and a velocity of 335 ft/sec, determined from the

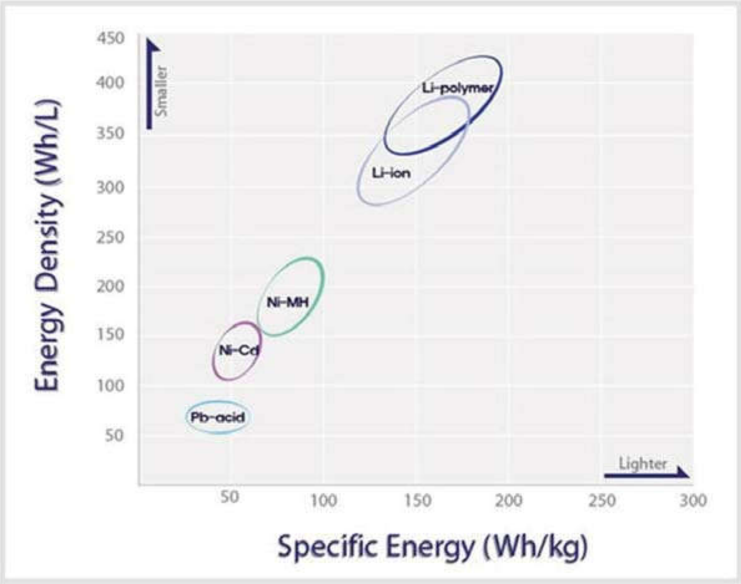

Figure 3. Specific energy as a function of volumetric energy density.

FLOPS output specifications of the calibrated baseline ATR 42-600. The required power for climb was calculated to be 1,567 kW per engine, thus, with 178 Wh/kg Kokam battery cells, approximately two sets of 587 battery cells would be required, one set attached to each nacelle. This equated a volume of 48 ft^3 per side, and a total battery weight of 12,939 lbs.

Also obtained from the output of the calibrated baseline ATR 42-600 was the 2,412-lb thrust requirement for a cruise velocity of 415 ft/sec to determine the fuel flow increase required to recharge the batteries during cruise. The power requirement to drive the propeller during cruise was calculated to be 2,022 shp (shaft horsepower), or 1,011 shp per engine. The recharge rate for cruise, as a fraction of the shp per engine, was calculated to be a 22 percent fuel flow increase per engine.

After calculating the battery power requirement and percentage of fuel flow increase, the variables for the PW120 engine decks were changed to create the hybrid-electric FLOPS input file. In the battery engine deck, the fuel flow values were changed to 1,576 kW from Mach 0 to 0.4. For the internal combustion engine deck, the fuel flow values were increased 22 percent from Mach 0.3 to 0.45.

Testing the hybrid design

The first purpose of this study was to verify that FLOPS can read a double engine deck and successfully alter between decks for different segments of flight. After determining and inputting the appropriate variables and specifications into FLOPS and troubleshooting within the program, we successfully simulated a hybrid-electric flight with the ATR 42-600 in FLOPS. FLOPS successfully allowed the use of batteries to power the ATR 42-600 for the taxi, takeoff, and climb, be recharged by the internal combustion engine during cruise, and re-engage the batteries for descent.

After verifying the capability of FLOPS to model a hybrid-electric flight, we tested Siemen's claims of scalability on the parallel, serial, and baseline ATR 42-600 models; however, we predicted that today's aircraft technology was not sufficient to compensate for the added weight of the batteries. With today's battery technology, the batteries added 12,939 lbs of weight, requiring greater power input to generate more thrust, which in turn requires burning greater amounts of fuel. Therefore, we decided to equip our models with 2025 technologies. The year 2025 was chosen as it was the furthest out projection of the advancement of aircraft technologies for which information was available by the ERA.

Both the baseline and hybrid models were fitted with 2025 technologies to compare the performance of a 2025 hybrid to that of a non-hybrid plane in 2025. The baseline and the parallel architectures were tested, and the serial design was omitted as it was less efficient than the parallel architecture. The parallel hybrid and baseline models were fitted with the 2025 technology inputs in FLOPS for advanced composites that reduce weight of the fuselage, wing and tail; natural laminar flow, riblets, and variable trailing edge camber that reduce drag; improvements for specific fuel flow; and increased aspect ratio. We then test the 2025 non-hybrid and hybrid models in FLOPS. A conceptual design of the 2025 hybrid-electric VSP model of the ATR 42-600 is shown (Figure 4).

Figure 4. Rendering of the hybrid-electric ATR 42-600 in Autodesk 3ds Max. The dark blue boxes represent the location of the battery packs attached to the exterior of the nacelles.

Analysis of data and evidence

We compared five sets of results: the baseline non-hybrid-electric ATR 42-600, a 2012 hybrid-electric ATR 42-600 with a serial architecture, a 2012 hybrid-electric ATR 42-600 with a parallel architecture, a 2025 non-hybrid-electric ATR 42-600, and a 2025 hybrid-electric ATR 42-600 with a parallel architecture. To analyze the performance of the hybrid-electric ATR 42-600 models compared to the baseline model, the fuel burn output from FLOPS was the main focus as it gave the best measure of how much emissions were reduced and thus how "green" the design was.

The hybrid-electric 2012 serial and parallel ATR 42-600 models did not burn less fuel than the baseline model in an 801 nautical mile (nmi) flight. The parallel architecture burned less fuel than the serial architecture (Figure 5). This is likely the result of the greater efficiency of a parallel configuration but the parallel architecture still burned more fuel compared to the baseline model. Therefore, for an 801 nmi mission, a 2012 hybrid-electric propulsion system did not yield savings in fuel burn. In both the serial and parallel configurations, more fuel was burned than in the baseline model to compensate for the added weight of the batteries and to recharge the batteries.

Both the 2025 non-hybrid electric and 2025 hybrid-electric parallel ATR 42-600 models produced lower fuel burn levels than the 2012 baseline model, as expected. This is because the 2025 technologies enhance the overall efficiency of the aircraft through weight and drag reductions and other enhancements, making the aircraft more "green." The 2025 non-hybrid model still burned less fuel than the 2025 hybrid-electric model for 801 nmi flights. This is likely because more fuel is needed by the hybrid-electric model to carry and recharge the added batteries. Therefore, even 2025 hybrid-electric technology did not yield savings in fuel burn for long missions.

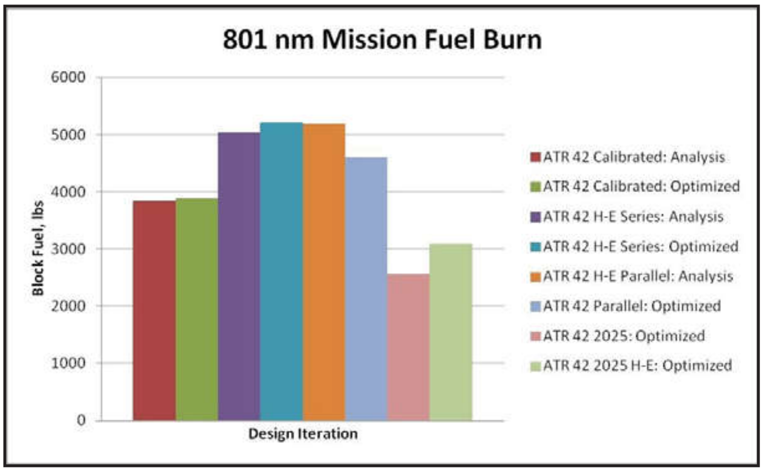

Figure 5. Amount of fuel burned for each design iteration during the cruise segment of an 801 nmi mission. In both the serial and parallel configurations, more fuel was burned than in the baseline model to compensate for the added weight of the batteries and to recharge the batteries. Therefore, for an 801 nmi mission, a 2012 hybrid-electric propulsion system did not yield savings in fuel burn.

We then conducted the same fuel burn analysis for an economic 301 nmi mission, which revealed both the serial and parallel 2012 hybrid models and the 2025 parallel hybrid burned less fuel than the baseline (Figure 6). Furthermore, the 2025 versions of the aircraft also resulted in lower fuel burn compared to the baseline model, and the 2025 hybrid-electric model saw significant increases in fuel efficiency compared the current baseline and 2025 non hybrid-electric models. Therefore, for shorter missions, the 2025 hybrid-electric model was more efficient than the baseline, both 2012 serial and parallel hybrid-electric models, and the 2025 non-hybrid electric model.

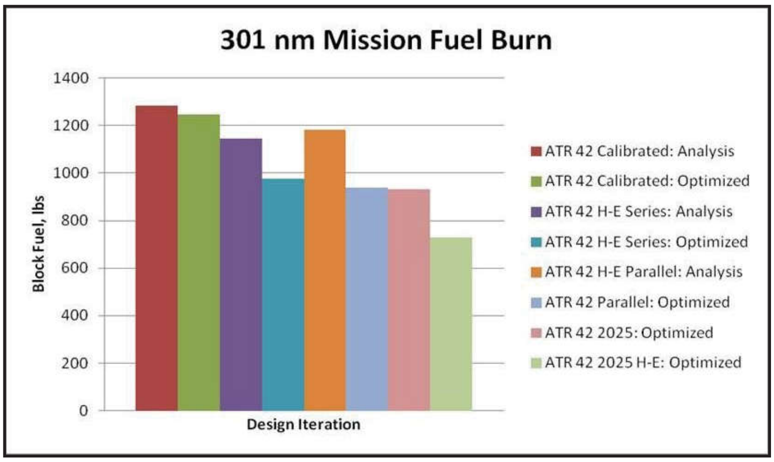

Figure 6. Amount of fuel burned for each design iteration during the cruise segment of a 301 nmi mission. The 2025 hybrid-electric models were more efficient than the baseline, both 2012 serial and parallel hybrid-electric models, and the 2025 non-hybrid electric model.

Discussion and conclusion

The two goals for this project were to test the FLOPS capability for hybrid-electric aircraft design and study the feasibility of retrofitting current hybrid-electric engine designs to existing mid-sized commercial airliners. We were successfully able to have FLOPS read two separate engine decks and correctly alternate between them for the different segments of the flight, but our findings also revealed that retrofitting existing hybrid designs to aircraft that were not designed to be hybrids was not the best way to optimize fuel efficiency, and therefore not the best approach to greener skies.

FLOPS did show that for a 301 nmi mission, a 2025-technology-enhanced hybrid electric ATR 42-600 could perform slightly more efficient than a non-hybrid electric 2025-technology-enhanced ATR 42-600. A 301 nautical mile mission is about the distance from Washington D.C. to Myrtle Beach, South Carolina. The design range for the ATR 42-600, at 801 nautical miles, is about the distance from Washington D.C. to Miami, Florida. As even the 2025 hybrid-electric aircraft did not perform more efficiently than the range for which the ATR 42-600 was designed, we could see that retrofitting existing airliners to existing—or even 2025—battery and aircraft technologies would not result in the most efficient hybrid-electric designs.

Our findings paved the way for the future of green aviation as they proved FLOPS could be used in future hybrid-electric aircraft design, allowing the analysis of an aircraft powered by different engine decks at different times. This performance analysis provided by FLOPS suggests the design of completely new aircraft that are optimized to work with a hybrid-electric engine, as opposed to retrofitting existing aircraft.

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