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Flight Simulator Demonstration and Certification Implications of Powertrain Failure Mitigation in a Partial Turboelectric Aircraft

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Abstract

The Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsor (STARC-ABL) is a concept aircraft with a partial turboelectric powertrain. The complexity and integrated nature of the partial turboelectric powertrain architecture presents failure modes and hazards not found in conventional aircraft propulsion designs. Previously, various electrical and mechanical faults and associated recovery modes were demonstrated in a dynamic model of the powertrain. It was shown that certain faults were catastrophic without recovery logic, due specifically to the interaction of the subsystems. However, in each case, the logic, known as a reversionary control mode, enabled continued operation with assumed sufficient thrust to maintain safe flight. The current work evaluates the powertrain faults and recovery strategies using a full aircraft model in a piloted flight simulator, and places it in the context of current regulatory practice. Faults initiated in flight were successfully mitigated, with the accommodated aircraft subsequently evaluated against certification requirements for three-engine aircraft, which were shown to be appropriate for the STARC-ABL configuration.

Nomenclature

DC	Direct Current
EAP	Electrified Aircraft Propulsion
F_N	Net Thrust
GTF	Geared TurboFan
HPC	High Pressure Compressor
HPX	HorsePower eXtraction
LPC	Low Pressure Compressor
OEI	One Engine Inoperative
PLA	Power Lever Angle
SM	Stall Margin
STARC-ABL	Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsor
TCM	Transport Class Model

1.0 Introduction

Electrified Aircraft Propulsion (EAP) is an emerging technology that presents a number of potential benefits along with technical integration challenges. While EAP provides the possibility of more efficient flight operations with reduced noise and emissions, it introduces novel failure modes that depart from those experienced with conventional aircraft propulsion systems. EAP enables aircraft designers to employ new propulsion system architectures that tend to be distributed, redundant and integrated. These architectures add complexity and necessitate new strategies to preserve and protect propulsion system functions. One such strategy is to exploit the inherent redundancy. Here, failure in one powertrain subsystem is mitigated by adapting the behavior of the remaining subsystems, leveraging control-based failure mitigation. To facilitate this modified operation, analysis is required to properly control the remaining powertrain subsystems in a way that does not violate their limitations and place them at risk of failing themselves.

Much analysis has been done on a concept aircraft known as the Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsor (STARC-ABL) (Figure 1) (Ref. 1). Its powertrain consists of two wing-mounted geared turbofan (GTF) engines, each with its own power system. The power systems extract mechanical power from the low-pressure spool of the turbofans, which is converted to electricity and used to power an electric motor-driven fan in the tail (Figure 2). This architecture, with fuel-burning engines that produce both thrust and electricity to power electric thrust producing fans, is known generically as Partial Turboelectric. Figure 3 contains a more detailed diagram of the powertrain showing the various components. The GTFs are scaled versions of the Advanced Geared Turbofan 30,000 (AGTF30) (Ref. 2).

Previous work with the STARC-ABL powertrain demonstrated a variety of failure modes, some catastrophic when not mitigated, and associated propulsion-based reversionary control modes (Refs. 3 and 4) that were stable and recovered more than 50 percent of the maximum thrust at the flight condition (Ref. 5). The work described in this paper expands on that previous effort by integrating the powertrain model with an aircraft flight dynamics model and testing the impacts of the failures and reversionary control modes in a piloted flight simulator. It also examines more closely the implications of current certification requirements relative to electrified aircraft.

As electrified aircraft propulsion technology is commercialized and eventually put into service, regulations will need to be developed (Refs. 6 and 7). There has been some recent progress, with the Federal Aviation Administration (FAA) publishing special conditions to operate electrical technology

Figure 1.—STARC-ABL aircraft concept in flight. (Credit: NASA)

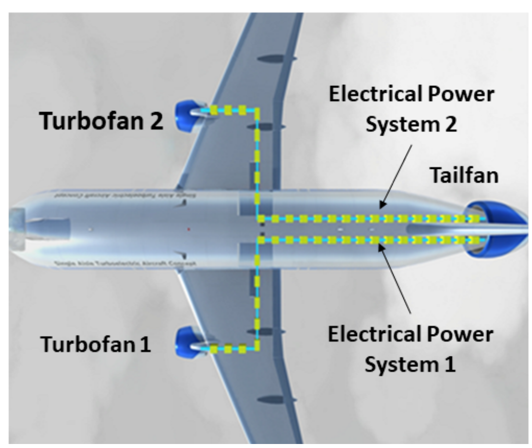

Figure 2.—STARC-ABL powertrain. (Credit: NASA)

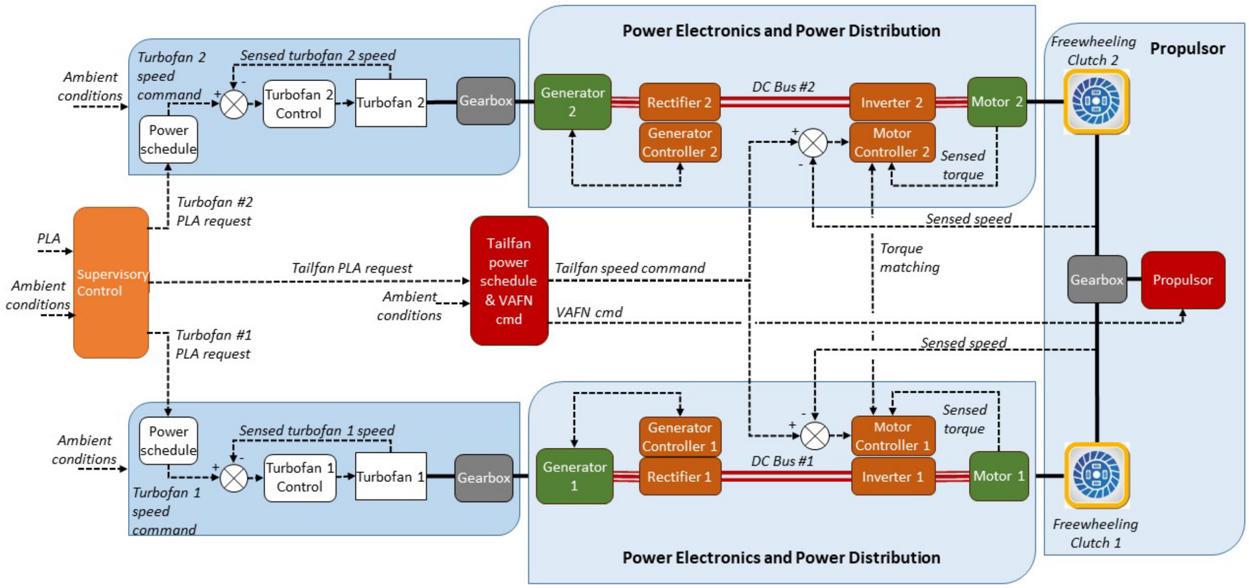

Figure 3.—STARC-ABL Propulsion System Architecture. The partial turboelectric powertrain has two parallel strings, each consisting of a fan speed controlled geared turbofan with a gearbox attached to the shaft to extract power. A generator converts this power to electricity to drive a motor connected through a freewheeling clutch to the tailfan gearbox. The two parallel strings terminate at this gearbox, which drives the tailfan. A supervisory control updates the baseline control in response to a detected fault.

installed on the aircraft for use as an aircraft engine (Refs. 8 and 9). The FAA's Title 14 of the Code of Federal Regulations (CFR) Part 25 (Ref. 10), "Airworthiness Standards: Transport Category Airplanes," is the current relevant certification standard for aircraft such as the STARC-ABL. Thus, the problem is discussed in terms of Part 25 requirements as well as Part 33, Airworthiness Standards: Aircraft Engines. Specifically, this paper focuses on powertrain failure mitigation relative to regulations concerning one engine inoperative (OEI), since failures within the powertrain can lead to loss of thrust.

The rest of this paper is organized as follows. The integrated aircraft model is described in Section 2.0. Section 3.0 proposes of how the aircraft might align with current regulatory practice. Section 4.0 contains a description of the failure modes and control mitigation in the standalone powertrain. In Section 5.0, results of the flight simulator testing are shown. This is followed by a discussion of the results and implications for certification in Section 6.0. Finally, in Section 7.0, conclusions are drawn about the use of current certification standards for this type of aircraft and the efficacy of the reversionary control modes in an installed environment.

2.0 Aircraft Model

The dynamic model of the STARC-ABL powertrain was available from past work, but no flight dynamics model currently exists. Thus, another model, the twin-engine Transport Class Model (TCM) (Ref. 11) was used as a stand-in airframe. Much previous research was conducted using the TCM integrated with two realistic engine models (Refs. 12 and 13) in a piloted flight simulator. This earlier integration consisted of replacing the default engine modules within the TCM with copies of the closed-loop Commercial Modular Aero-Propulsion System Simulation 40,000 (C-MAPSS40k) engine model (Ref. 14). The inputs to the engine models are pilot commands (throttle positions) and flight conditions (altitude, Mach number). The engine models calculate net thrust, which is transferred back to the TCM and converted into body-axis force and moment components. The TCM/C-MAPSS40k integrated simulation was validated against certification requirements to ensure that it is a reliable and meaningful testbed for the research conducted (Ref. 15).

This previous TCM/C-MAPSS40k integration effort provided a valid model and an approach that has been subsequently used to integrate flight dynamics models with dynamic powertrain models (e.g., the TCM/STARC-ABL and Reference 16). For the STARC-ABL application, an additional thrust vector was added to the TCM's empennage to account for the tailfan thrust. This way the three thrust sources act on the airframe model appropriately. However, the TCM and the STARC-ABL are not the same size and consequently have different thrust requirements (about 80,000 lb vs. 45,000 lb, respectively, at sea level static). To address this, the thrust of the TCM/C-MAPSS40k model was recorded across the flight envelope to use for scaling the thrust of the STARC-ABL powertrain model. This ensures that the scaled powertrain output is sufficient for the TCM airframe but does not otherwise impact it. Note that the TCM rudder is sized to counteract an OEI situation for a two-engine aircraft. Since about 20 percent of the STARC-ABL's thrust at takeoff comes from the tailfan, which is centrally located at the back of the fuselage, the rudder may be oversized.

The TCM/STARC-ABL model was implemented in a flight simulator using the procedure described in Reference 16 for testing. The STARC-ABL powertrain model is built in Simulink using the NASA-developed Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) (Refs. 17 and 18) for the AGTF30 engines and tailfan, and the Electrical Modeling and Thermal Analysis Toolbox (EMTAT) (Refs. 19 and 20) for the power systems. Use of the EMTAT physics-based blocks with a new fault injection feature enables initiation of simulated power system failures during run time. The dynamic powertrain model provides the three thrust values at each point in time to the Simulink-based TCM.

3.0 Aircraft Model Assumptions Relative to Regulations

When applying current regulations to the STARC-ABL, it is necessary to relate pre-existing definitions to features of the electrified powertrain. The STARC-ABL configuration is similar enough to current commercial aircraft that this is relatively straightforward. With the special condition for electric propulsion units that draw energy from electrical storage or generating systems (Refs. 8 and 9), the STARC-ABL can rightly be considered a three-engine aircraft. The STARC-ABL powertrain has no energy storage, so the electrical power that operates the tailfan is generated directly from the gas turbine engines. The objectives of the reversionary control modes are to (1) maintain or recover thrust, (2) prevent cascading failures, and (3) enable acceptable aircraft performance. With this in mind, the relevant regulations for this work are related to OEI, e.g., 14 CFR § 25.121 - Climb: One-engine-inoperative (Ref. 21). Here there are several requirements for three-engine aircraft, specifically when the critical engine, i.e., the engine whose failure would most adversely affect the performance or handling qualities of an aircraft (Ref. 22), is inoperative. There are several reasons to consider either of the wing-mounted gas turbine engines as the critical engine: (1) its failure will result in a thrust asymmetry, (2) it provides power to the tailfan, and (3) it provides significantly more thrust than the tailfan at low altitude, low speed conditions where a failure is most serious. The relevant requirements concern minimum climb gradients in various configurations and flight segments, controllability, handling, etc. In a traditional multi-engine jet transport aircraft, the engines are independent, so a failure in one will not impact the others. Thus, the ability to climb with OEI will simply depend on having thrust available from the remaining engines, which must be a design consideration. An OEI condition is categorized as a minor difficulty for a traditional three-engine commercial aircraft, and a safe landing is expected (Ref. 23). The STARC-ABL must also be able to meet these requirements with one gas turbine engine or tailfan inoperative. However, the complexity of the powertrain and the interdependence of its subsystems means that a seemingly minor situation presents the possibility of cascading faults that cause significant thrust reduction (see Figure 7 of Ref. 5). Modifications since the publication of Reference 5 have resulted in a more robust control system, but certain situations still have the potential for unavoidable cascading failures with the baseline control.

4.0 Failure Modes and Control Mitigation

There are three subsystem failure modes for the STARC-ABL powertrain: GTF failure, power system failure, and tailfan failure. Figure 4 contains the Failure Modes and Effects Matrix for the powertrain. Previous work showed that under baseline control, failure of a power system resulted in increased horsepower extraction (HPX) for the tailfan from the engine with the working power system (Ref. 5). This excessive load stalled the engine, resulting in a severe reduction in overall thrust. Although not shown explicitly in that work, a GTF failure would be an even worse scenario, since the increased HPX from the working engine would stall it, resulting in no thrust at all.

For each situation arising from an individual subsystem failure, however, a reversionary control mode was developed that enabled stable power increases to the highest throttle setting. These demonstrated thrust recovery of more than 50 percent of total baseline vehicle net thrust at the given flight condition (Ref. 5), presumably enough to enable continued flight. Details of the reversionary control logic for the GTFs and the tailfan are provided in Reference 5.

It was mentioned above that subsequent to the publication of Reference 5, the control system was updated based on observations of the consequences of subsystem failures, making it more robust. Some of these changes, e.g., modified or additional control limits and adjustments to the acceleration schedule, have the potential to minimize the impact of a fault and thereby help maintain operation after a powertrain subsystem failure. However, the baseline control system is still designed for nominal operation and cannot by itself mitigate all subsystem failures within the powertrain. Testing demonstrated that the stability of the baseline control with a subsystem failure is marginal at best, but at high altitude (> 15,000 ft ASL) and lower power settings (PLA < 65 in a range of 51 to 80), cascading failures are likely. The reversionary control modes are designed to modify the operation of a working subsystem (GTF or tailfan) in response to the failure of another subsystem that it interacts with, either directly or indirectly (GTF, power system, or tailfan). The reversionary control modes are enabled during flight by a set of logic gates that are activated by a change in power extraction on any turbine engine. If the level of power extraction on any turbine engine drops below a specified threshold, that engine switches over to the

		Failed Subsystem				
		GTF1 Failed	**GTF2 Failed**	**Power System 1 Failed**	**Power System 2 Failed**	**Tailfan Failed**
Coupled Failure Effects on Other Subsystems	**GTF1**	*Failed*	*Increased HPX*	*No HPX*	*Increased HPX*	*No HPX*
	GTF2	*Increased HPX*	*Failed*	*Increased HPX*	*No HPX*	*No HPX*
	Power System 1	*No Electric Power*	*Increased Electric Power*	*Failed*	*Increased Electric Power*	*No Electric Power*
	Power System 2	*Increased Electric Power*	*No Electric Power*	*Increased Electric Power*	*Failed*	*No Electric Power*
	Tailfan	*Reduced Electric Power*	*Reduced Electric Power*	*Reduced Electric Power*	*Reduced Electric Power*	*Failed*

Figure 4.—TCM/STARC-ABL Failure Modes and Effects Matrix.

decreased power extraction reversionary mode (Mode 1). The opposite turbine engine then switches to the increased power extraction reversionary mode (Mode 2). If either engine is in Mode 1, the tailfan controller switches to its reversionary control mode. The tailfan only has one reversionary controller (Mode 1) wherein it draws all of its power from one engine. Conflicts between the control modes are handled by priority (i.e., Mode 1 has priority, so if the engine has decreased power extraction it will remain in Mode 1 regardless of the mode of the other engine or the tailfan). However, an engine in Mode 2 will switch to Mode 1 if it has decreased power extraction, as in the case of a tailfan failure. Bumpless control transfer is achieved by having all of the control modes track the setpoint of the active controller.

5.0 Flight Simulation Results

Testing was performed in a piloted flight simulator (Figure 5). It was previously stated that the baseline control struggles with a subsystem failure at high altitude. In fact, a failure introduced into any powertrain subsystem at cruise rapidly resulted in a catastrophic cascading failure. While it was possible for the pilot to induce cascading failures at lower altitude, it was much more difficult to do consistently. Therefore, for repeatability, the pilot flew to about 21,000 ft, Mach 0.6, to conduct the initial tests.

Figure 5.—Piloted testing of reversionary control modes in flight simulator.

The first failure case is in the power system (EPS1) associated with the port GTF (GTF1), shown in Figure 6 and Figure 7, without and with reversionary control modes enabled, respectively. The failure occurs when the blue line in the bottom plot drops to zero, indicating no power extraction from the corresponding engine. Looking at Figure 6, this is followed about three seconds later by a stall in the opposite (starboard) GTF (GTF2) due to increased power extraction, thus disabling the tailfan. About one second later, GTF1 surges, eliminating the last source of thrust. Figure 7 shows the same failure with the reversionary control modes enabled. Here the power extraction from the remaining (right) engine (GTF2) is increased, which allows the tailfan to continue operating at a slightly reduced thrust level, thus avoiding further failures. To demonstrate the robustness, the pilot executed some severe throttle maneuvers, which the control system was able to accommodate.

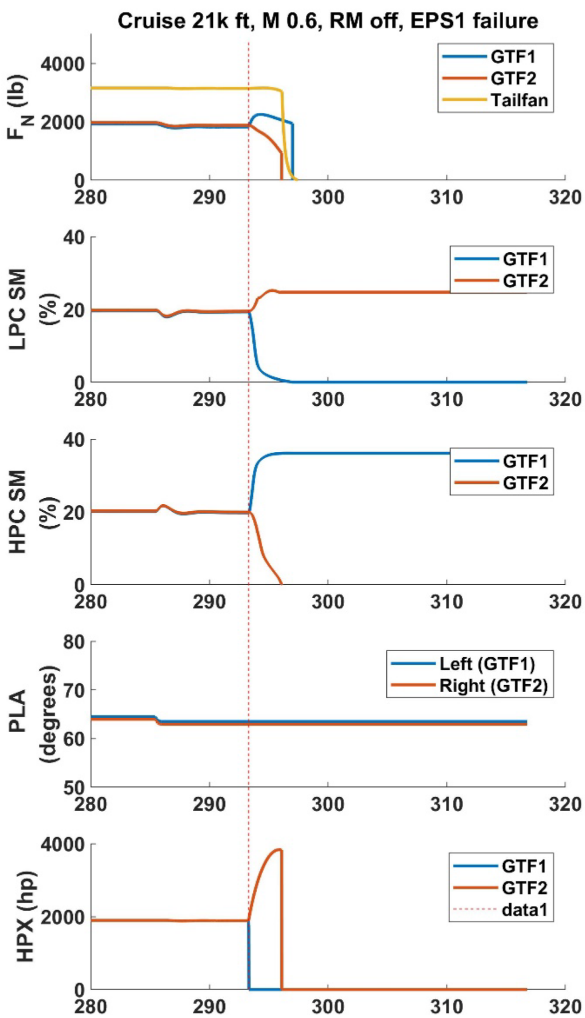

Figure 6.—Electrical Power System (EPS) failure, Reversionary Control Modes Off. Initial failure occurred at about 293 s, indicated by vertical line.

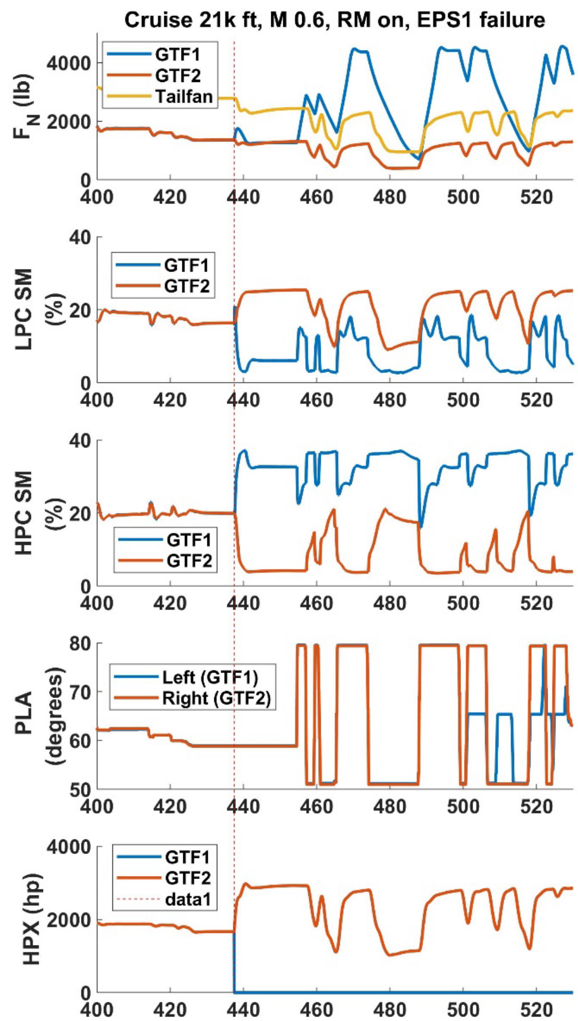

Figure 7.—Electrical Power System (EPS) failure, Reversionary Control Modes On. Failure occurred at about 437 s, indicated by vertical line.

The second failure case is the GTF1, shown in Figure 8 and Figure 9, without and with reversionary control modes enabled, respectively. The failure occurs when the blue line in the F_N plot (top) becomes negative, indicating the engine is producing drag rather than thrust. The power extraction corresponding to the failed engine immediately drops to zero; this might not be representative of the situation where the engine spins down and subsequently windmills. In Figure 8, as in the previous example, the power extraction on the remaining engine increases to run the tailfan resulting in a stall and loss of all thrust after about three seconds. With reversionary control (Figure 9), the power extraction from the working engine increases to supply the tailfan, but the thrust of both the functioning engine and the tailfan decease slightly to maintain stability. Again, the pilot successfully tested the robustness of the control system with aggressive throttle movements.

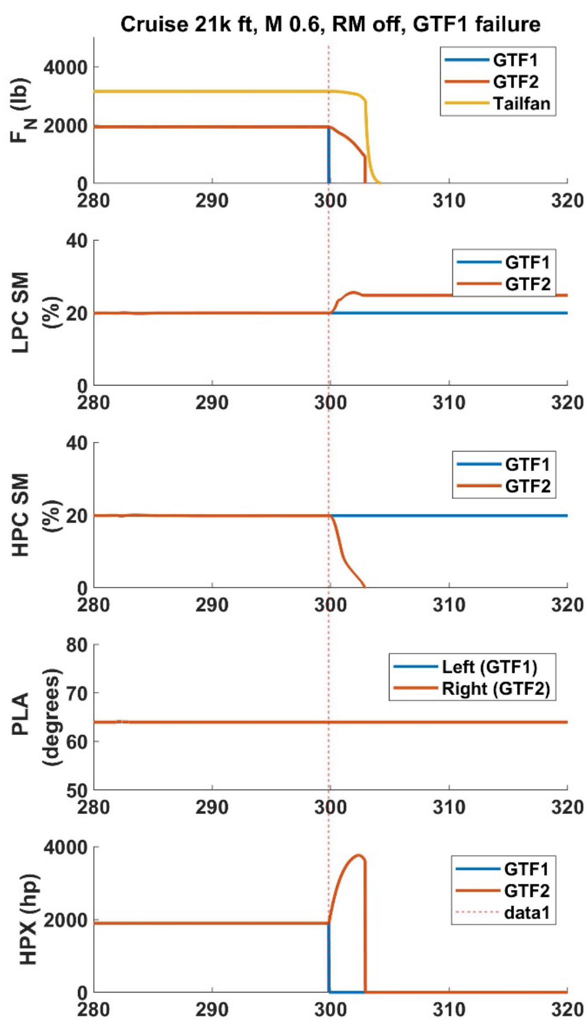

Figure 8.—GTF1 failure, Reversionary Control Modes Off. Initial failure occurred at about 300 s, indicated by vertical line.

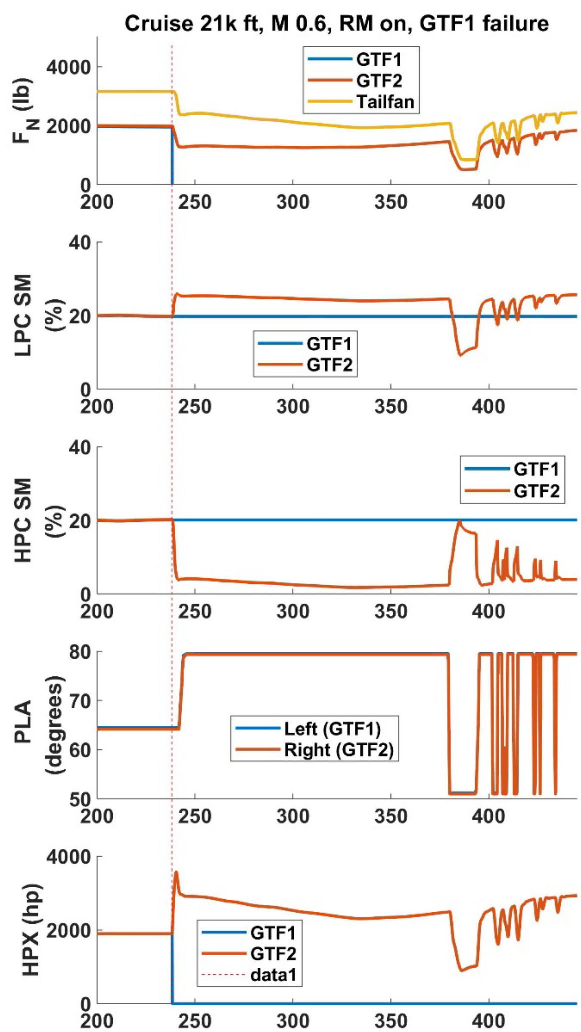

Figure 9.—GTF1 failure, Reversionary Control Modes On. Failure occurred at about 238 s, indicated by vertical line.

The third failure case is tailfan, Figure 10 and Figure 11, without and with reversionary control modes enabled, respectively. The failure occurs when the yellow line in the F_N plot drops straight down, indicating the lack of thrust production. Without a working tailfan, the power extraction for both engines immediately drops to zero. Without the reversionary control (Figure 10), both GTFs surge within about four seconds. With reversionary control (Figure 11), GTF operation is adjusted to compensate for the tailfan failure allowing the GTFs to continue running.

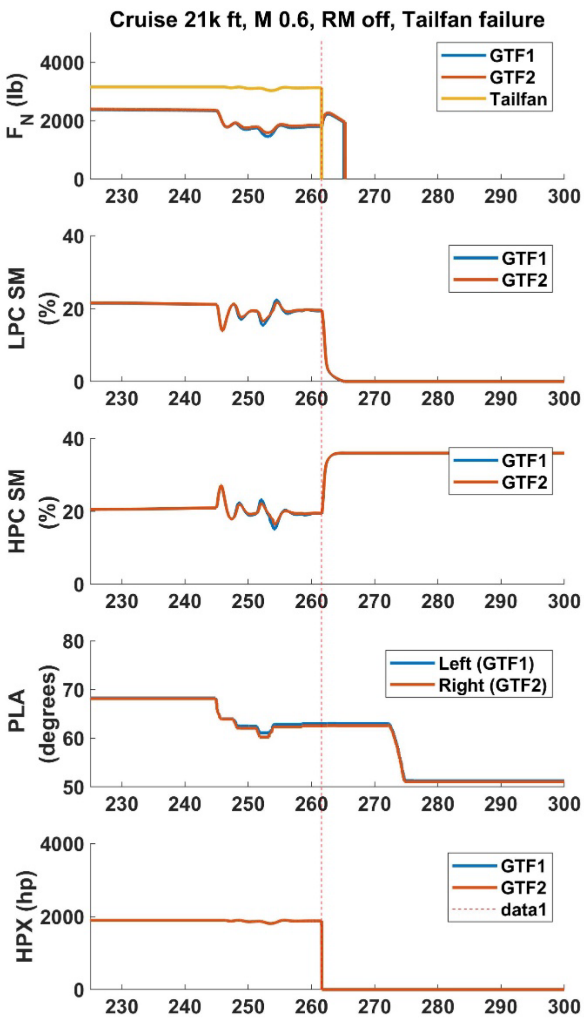

Figure 10.—Tailfan failure, Reversionary Control Modes Off. Initial failure occurred at about 262 s, indicated by vertical line.

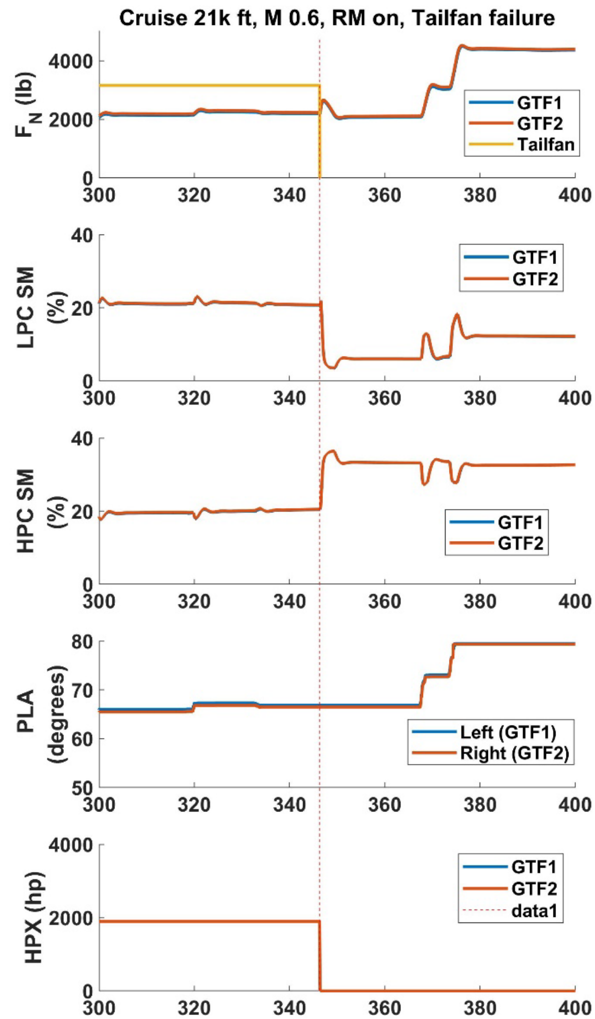

Figure 11.—Tailfan failure, Reversionary Control Modes On. Failure occurred at about 346 s, indicated by vertical line.

The final example is a missed approach in Denver, shown in Figure 12. This demonstrates the successful accommodation of a GTF1 failure on final approach. Here the pilot had the flaps and gear down in preparation for landing but raised the gear once a positive climb rate was achieved. He was also able to begin to retract the flaps over the portion of the run shown.

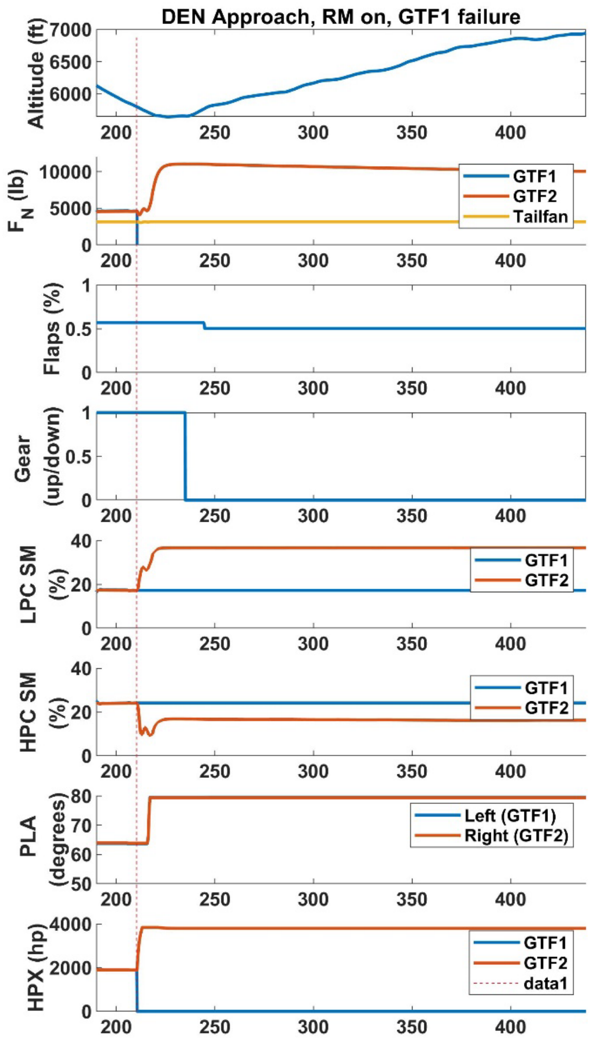

Figure 12.—GTF1 failure on approach to Denver, Reversionary Control Modes On. GTF1 failure occurred at about 210 s, indicated by vertical line.

6.0 Discussion

This work demonstrated the potential fragility of an electrified powertrain with subsystem faults and the ability of a reversionary control to stabilize it. While neither the model nor the control was based on actual developed systems and thus have not undergone the rigorous analysis and thorough testing such systems require, they are representative of the type of systems envisioned to be flying in the coming decades, and therefore exhibit some of the same characteristics. Thus, this work presents a preliminary investigation of some areas to be considered before addressing certification efforts for these aircraft with respect to current regulations.

When considering 14 CFR Part 25, there are several areas related to OEI, all of which depend on the remaining engines operating properly. Therefore, it is a prerequisite that the powertrain behaves in a stable way while producing sufficient thrust to meet the requirements. As with current commercial transports, the individual parts of the STARC-ABL's powertrain would presumably be highly reliable. The FAA states (Ref. 24) that an engine failure in which the only consequence is partial or complete loss of thrust or power (and associated engine services) from the engine will be regarded as a minor engine effect.[1] However, as was demonstrated, the loss of a subsystem, which should be a minor effect, can quickly become hazardous. The requirement states that the probability of a hazardous engine effect arising from an individual failure be not greater than 10^{-8} per engine flight hour (Ref. 25), yet this analysis showed it is likely to be much higher under baseline control given that the aircraft spends most of its time at cruise, where cascading failures are more prone to occur.

The discussion so far has focused on engine (GTF and tailfan) failures, but the testing showed that power system failures had the same cascading effect. Inferring the appropriate regulations based on the previously mentioned FAA special condition for electric engines (Refs. 8 and 9), power system failures are covered by 14 CFR § 33.28 (d)(3), *Engine control system failures*, which states that single failures of engine control system components do not result in a hazardous engine effect, and § 33.28(i)(1)(i), *Aircraft-supplied electrical power*, which states that loss, malfunction, or interruption of electrical power supplied from the aircraft to the engine control system will not result in a hazardous engine effect. Therefore, taking the powertrain as a whole, control logic that can limit the impact of a failure to a minor engine effect will be acceptable from a regulatory point of view.

Before moving on to a discussion of 14 CFR Part 25, it is necessary to mention fault detection. The TCM/STARC-ABL model's control system incorporated the algorithm that was described in a previous section to initiate the reversionary control modes. In other words, the faults were detected and accommodated in the simulation, the switchover was not directly initiated by the injection of the fault. For the catastrophic cases shown, total failure occurred about three to four seconds after fault injection, easily enough time for the fault detection system to react, as demonstrated by the other examples. This simple algorithm, and the reversionary control modes themselves, proved highly effective at preventing hazardous situations in the flight simulator, but their safety-critical nature implies a Design Assurance Level (DAL) of A, *Catastrophic*, because their failure may result in deaths and loss of the aircraft (DO-178C (Ref. 26)). This is a separate certification issue that will simply be acknowledged here.

With the reversionary control in place after an initial failure, the powertrain operation remained robust to cascading failures, even under severe throttle maneuvers. The reversionary control modes provide confidence in the stability of the powertrain, albeit with reduced thrust. This implies that the relevant Part 25 certification regulations correspond to those with OEI.

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[1]While the FAA does not specify the allowable probability range of a minor engine effect, it classifies a major engine effect as one that falls between minor and hazardous, with an allowable probability range of 10^{-5} to 10^{-7} per engine flight hour (14 CFR 33.75(g)(3)).

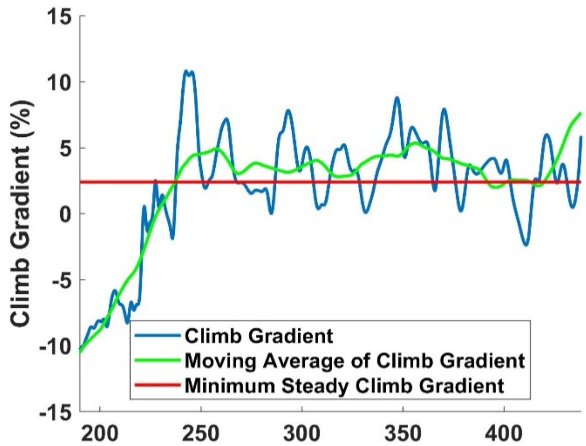

Figure 13.—Climb Gradient (actual and smoothed) for missed approach shown in Figure 12. Also shown is a line at 2.4 percent corresponding to 14 CFR 25.121(d)(1). GTF failure occurred at about 210 s and landing gear retraction initiated at about 235 s.

There are multiple mentions of OEI, specifically the critical engine, in 14 CFR Part 25. Testing focused on those regulations having to do with in-flight handling/controllability and maneuvering as a way to draw general conclusions. Specifically, select requirements for § 25.121 *Climb: One-engine-inoperative*, § 25.143 *General*, § 25.147 *Directional and lateral control*, and § 25.161 *Trim* were considered. The pilot was able to maneuver without difficulty in all cases, change flight conditions, bank and turn, and for the missed approach (Figure 12), exceeded the required steady climb gradient (Figure 13), even in the challenging environment of Denver. This implies that the 14 CFR Part 25 requirements for OEI are appropriate for a partial turboelectric STARC-ABL type configuration.

7.0 Conclusion

This work demonstrated that, for a relatively traditional looking aircraft like the STARC-ABL, despite having an electrified powertrain, the current 14 CFR Parts 25 and 33 can reasonably be applied. The inference here is that if Part 33 conditions can be satisfied, Part 25 requirements will be appropriate. It is also important to realize that this instantiation of the partial turboelectric powertrain lends itself well to the traditional airplane concept; other embodiments, potentially with multiple distributed electric fans, would give rise to new airframe concepts that might require updated certification standards. Practically speaking, these standards must be relevant to future types of transport aircraft in general, including their propulsion systems, so they will need to encompass a variety of other powertrain architectures as well, such as those with energy storage. Given the amount of interpretation of existing regulations required for this analysis of the STARC-ABL, it is obvious that, as the diversity of aircraft designs increases, current certification standards will be insufficient. This work also dramatically demonstrated the successful application of reversionary control modes in flight. Through this demonstration, it reiterated that unlike current multi-engine aircraft with independent engines, the electrified powertrain has interacting subsystems, which can produce cascading failures requiring special mitigation strategies. A clear implication of this is that control and health management schemes will be enabling for electrified aircraft propulsion technology to progress. Electrified powertrains hold the promise of cleaner, quieter, and less expensive air travel, but at the cost of much more complex integration and new, potentially catastrophic failure modes. New certification standards will ensure that future air travel is as safe as it is today but achieving this level of safety will require holistic approaches to fault mitigation.

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