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

Jonathan S. Litt
Jonah J. Sachs-Wetstone
Donald L. Simon
NASA Glenn Research Center

T. Shane Sowers
A. Karl Owen
Mark E. Bell
HX5, LLC

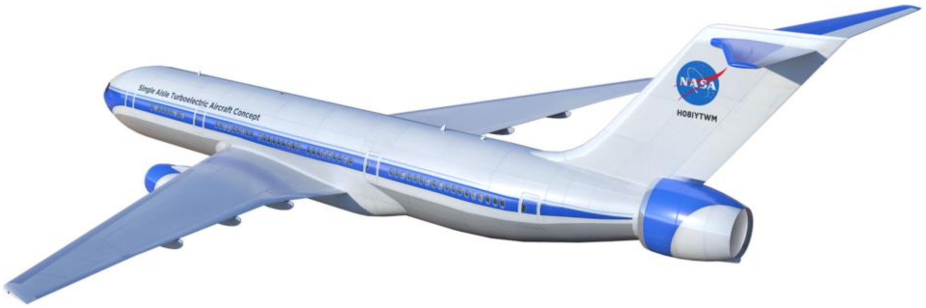
Brenden E. Guthrie[1]
Julian Lehan[1]
Amado Castro[2]
[1]LERCIP Intern
[2]USRA

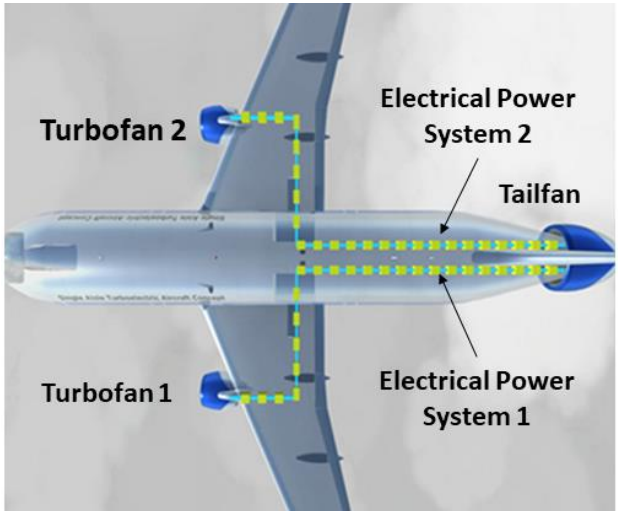
Objectives

- Test previously developed reversionary propulsion control modes for an aircraft with an electrified powertrain in a piloted flight simulator
- Investigate how current certification requirements apply to a concept aircraft with a turboelectric powertrain

Background—Aircraft Description

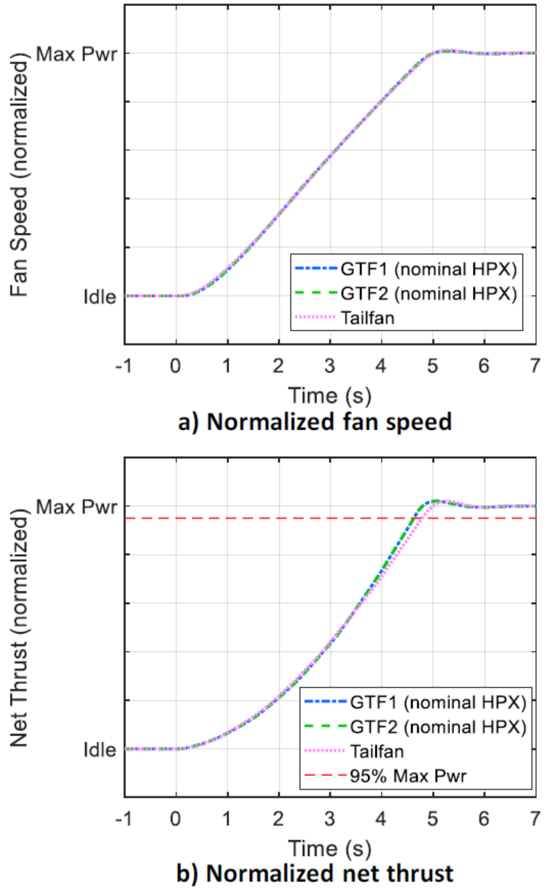
- Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsor (STARC-ABL)
  - NASA concept with 2035 entry into service
  - 150-passenger class commercial transport
  - Traditional “tube-and-wing” shape
- Partial turboelectric powertrain
  - Thrust sources are two underwing geared turbofans and an electric, boundary layer ingesting tailfan
  - Geared turbofans produce thrust and power to drive the tailfan
  - There is no energy storage



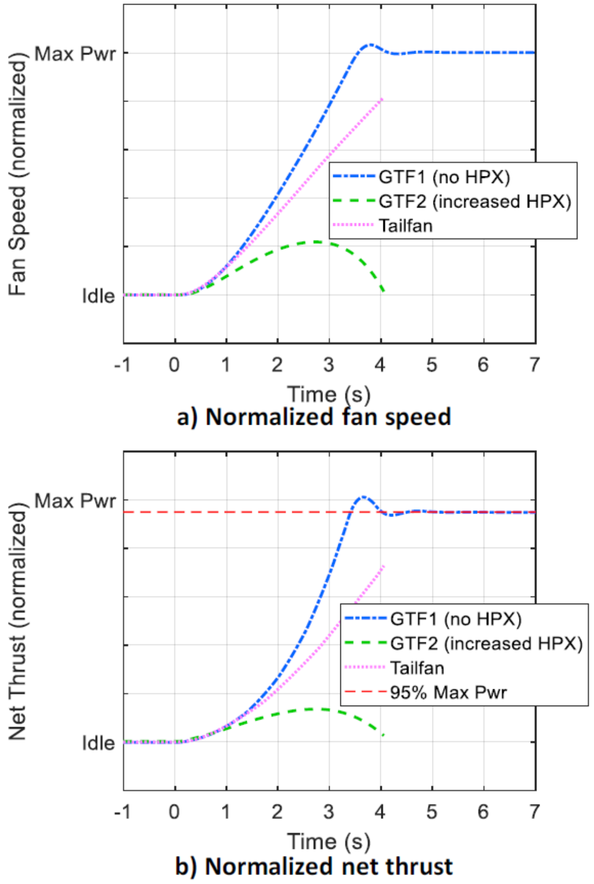


Background—Baseline Powertrain Control

- Inceptors provide the speed setpoint for each turbofan; the tailfan speed setpoint is based on the two turbofan speeds
- The baseline control design works well around the flight envelope for the nominal powertrain
- However, a powertrain subsystem failure could lead to potentially catastrophic cascading failures with the baseline control at some flight conditions



STARC-ABL Acceleration Response under Nominal Operating Conditions with Baseline Control

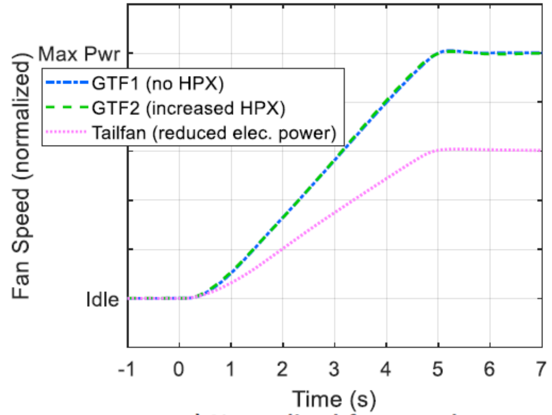


STARC-ABL Acceleration Response under Power System 1 Failure with Baseline Control

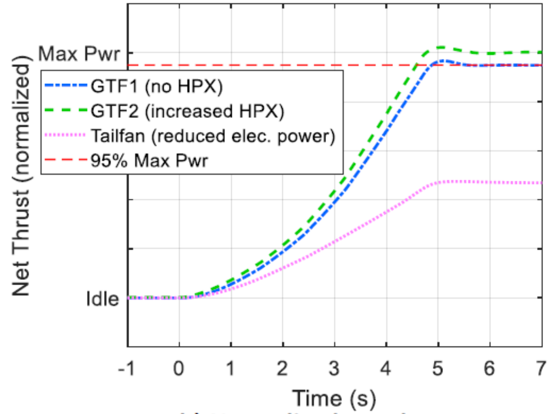
Background—Reversionary Control

- Reversionary control modes
    - Control modes designed for off-nominal cases such as sensor/actuator/subsystem failures, which the baseline control was not designed for
    - Were developed to activate in case of subsystem failures in STARC-ABL powertrain and subsequently demonstrated*
- The reversionary control modes have modified
    - Control limits
    - Schedules
- The reversionary control
    - Maintained system thrust response
    - Increased robustness to each type of subsystem failure
    - Produced less thrust than baseline

*Simon, D.L., and Connolly, J. W., "Electrified Aircraft Propulsion Systems: Gas Turbine Control Considerations for the Mitigation of Potential Failure Modes and Hazards," ASME Turbo Expo 2020, Turbomachinery Technical Conference and Exposition, GT2020-16335, September 21-25, 2020.



a) Normalized fan speed



b) Normalized net thrust

STARC-ABL Acceleration Response with Power System 1 Failure and Reversionary Control

Testbed—Flight Simulator Setup

Piloted testing of the STARC-ABL with powertrain failures

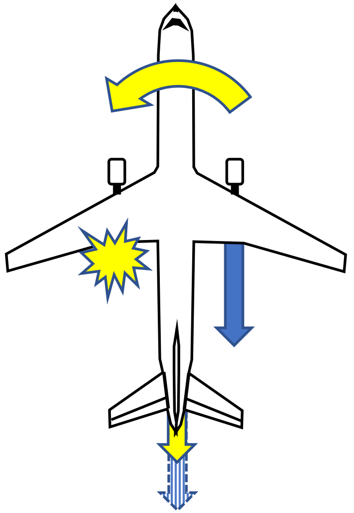
Custom STARC-ABL instrumentation

Certification Standards
Title 14 of the Code of Federal Regulations (CFR)

- Which, if any, are applicable?
  - Part 25, *Airworthiness Standards: Transport Category Airplanes*
  - Part 33, *Airworthiness Standards: Aircraft Engines*
  - magniX Special Condition—relates to electric motor, controller, and high-voltage systems installed on the aircraft for use as an aircraft engine
  - One-Engine-Inoperative (OEI) requirements
- Is the STARC-ABL a two- or three-engine aircraft?
- Which is the critical engine?
  - the engine whose failure would most adversely affect the performance or handling qualities of an aircraft

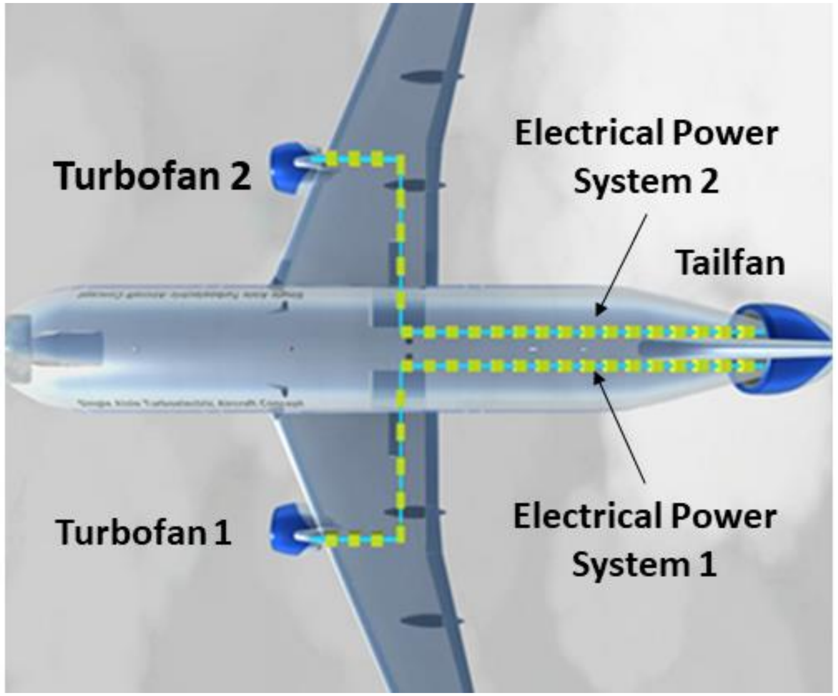
Addressing Certification Standards

- Given the magniX Special Condition, the tailfan is an engine ➔ the STARC-ABL is a three-engine aircraft
- Either wing-mounted gas turbine engine is the critical engine because
  - its failure will result in a thrust asymmetry
  - it provides power to the tailfan
  - it provides significantly more thrust than the tailfan at low altitude, low speed conditions where a failure is most serious



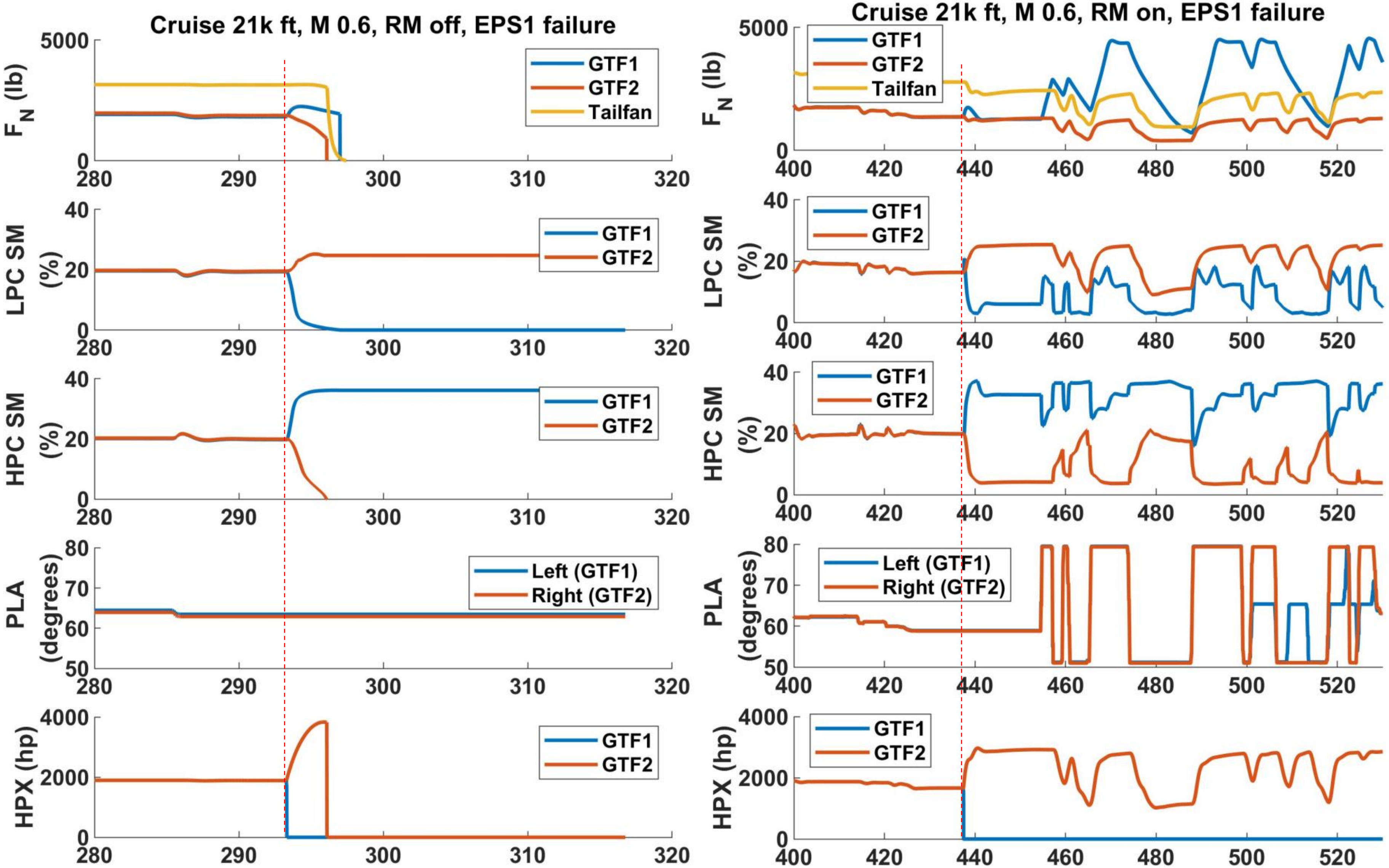
Testing Process

- Test control system robustness with reversionary control modes active to powertrain subsystem failures
  - Power system
  - Gas turbine engine
  - Tailfan
- Test specifically OEI requirements for three-engine aircraft



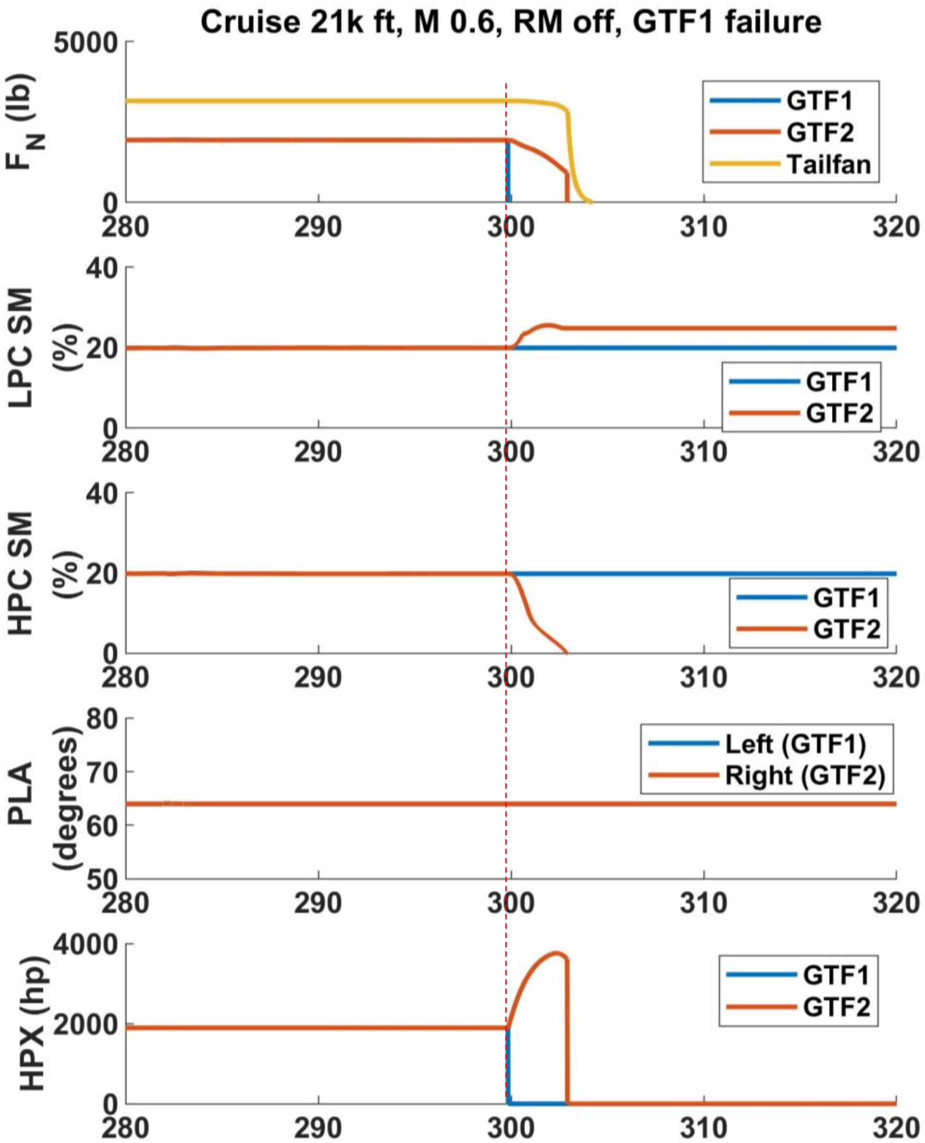
Testing—Power System Failure

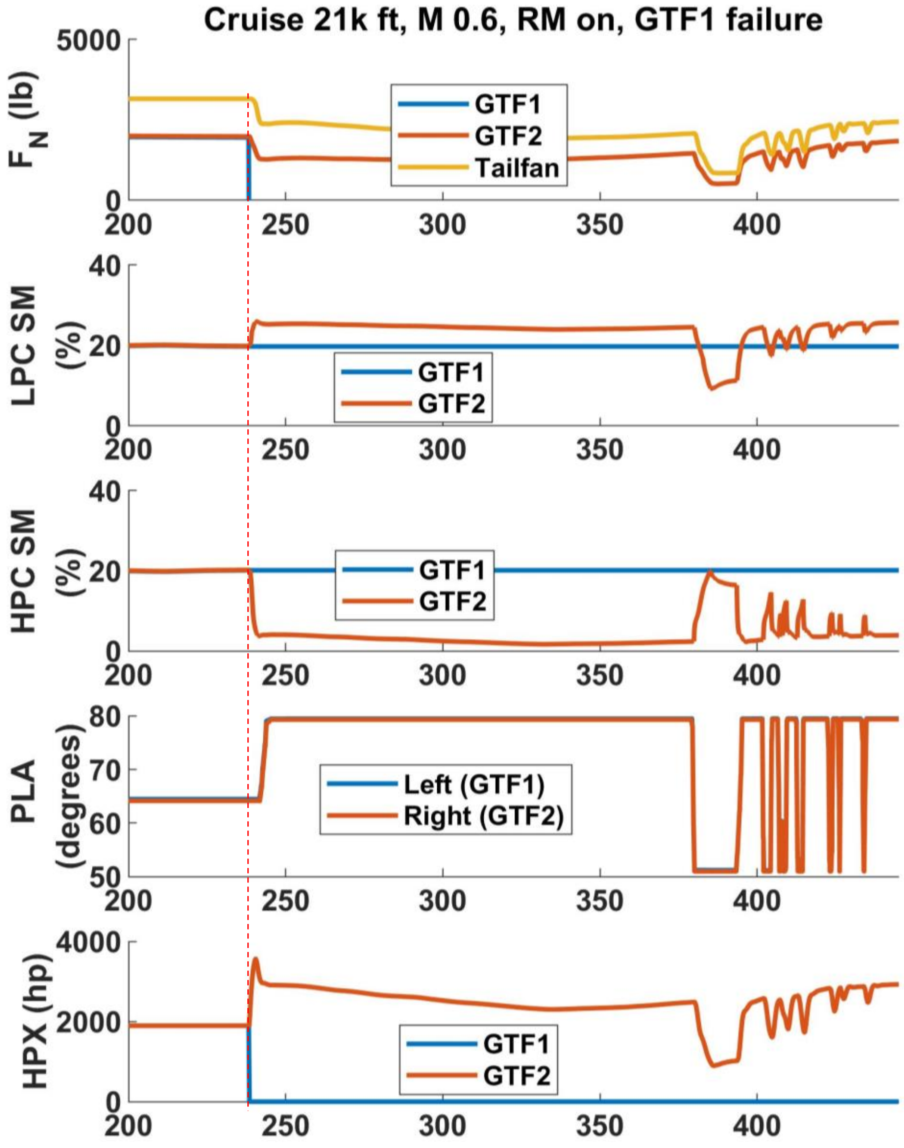
- Abrupt power system failure occurs in both cases
- With reversionary control inactive, catastrophic cascading failures occur
- With reversionary control active, failure did not propagate



Testing—Geared Turbofan Failure

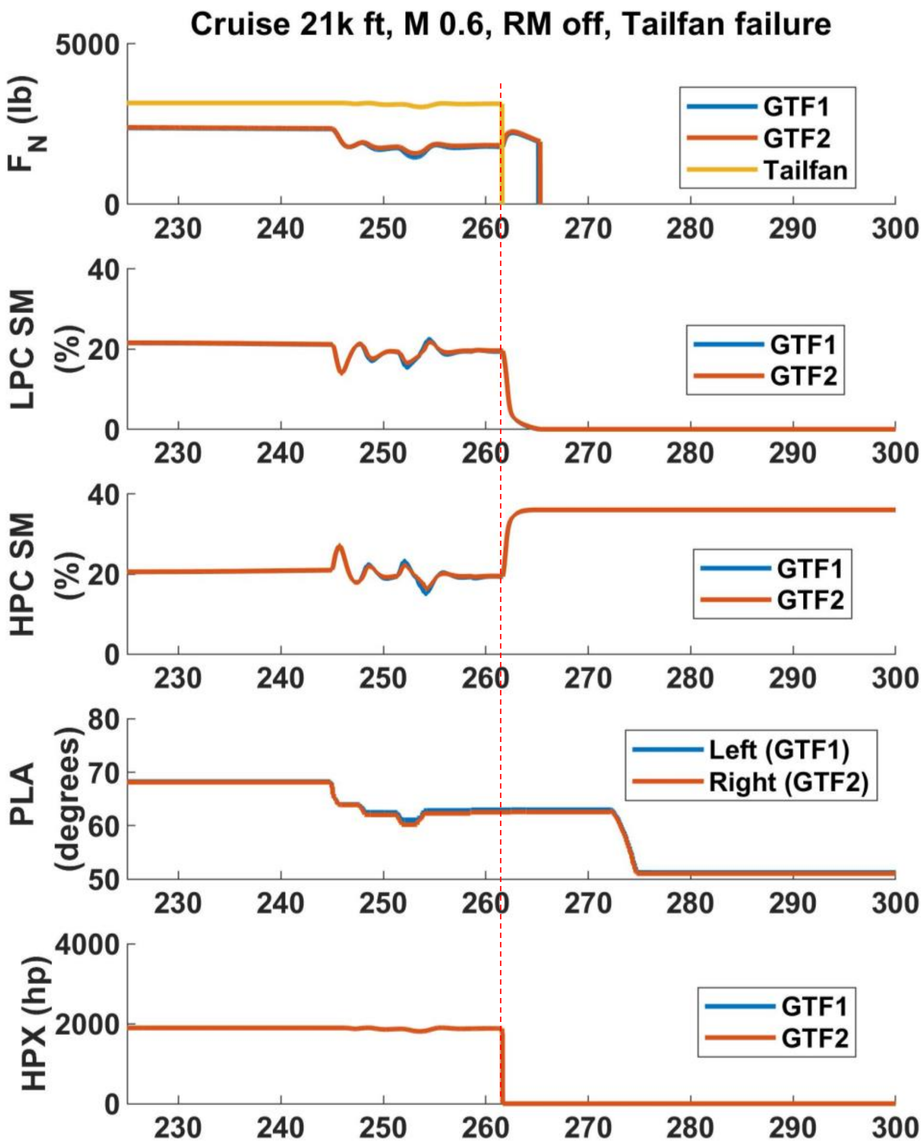
- Abrupt geared turbofan failure occurs in both cases
- With reversionary control inactive, catastrophic cascading failures occur
- With reversionary control active, failure did not propagate

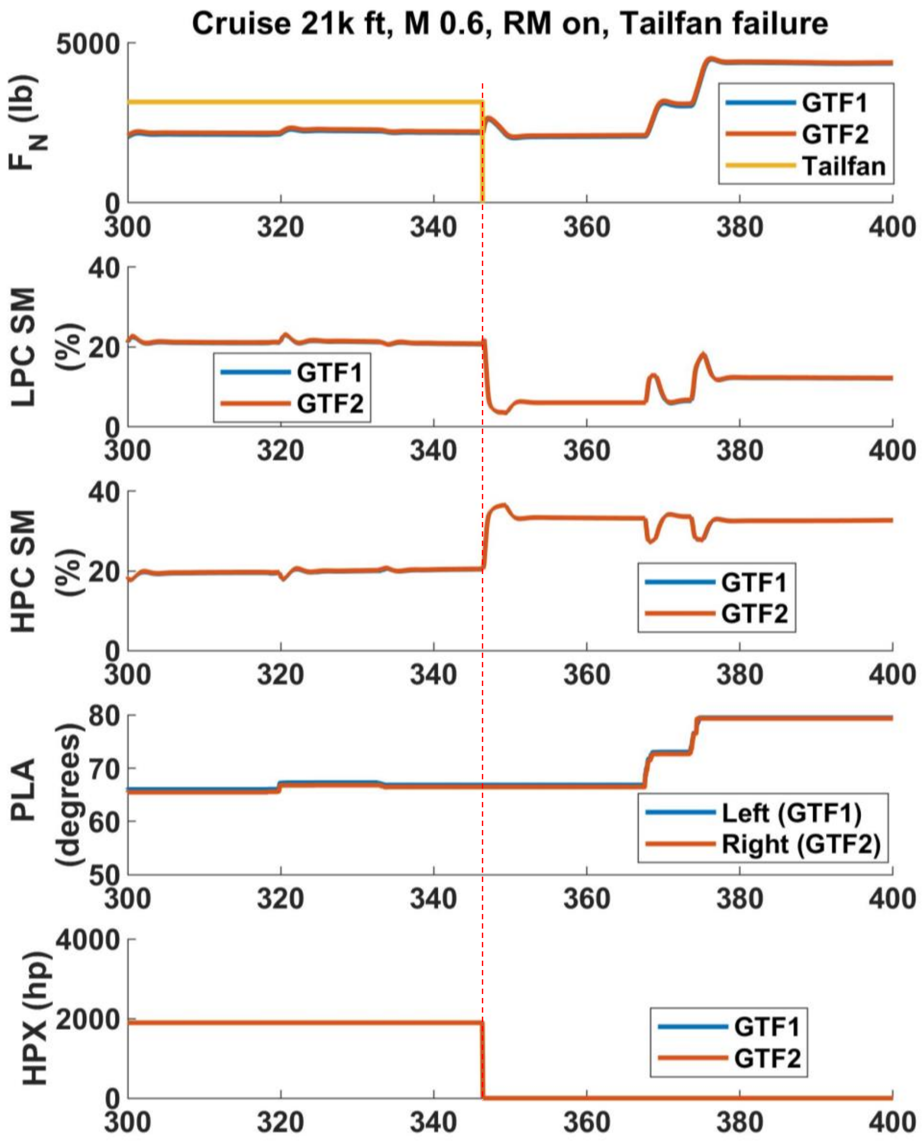




Testing—Tailfan Failure

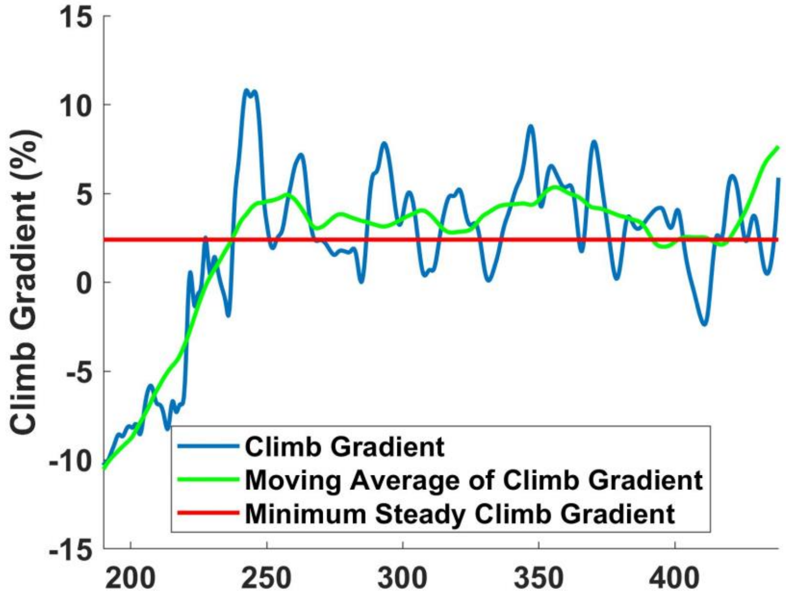
- Abrupt tailfan failure occurs in both cases
- With reversionary control inactive, catastrophic cascading failures occur
- With reversionary control active, failure did not propagate

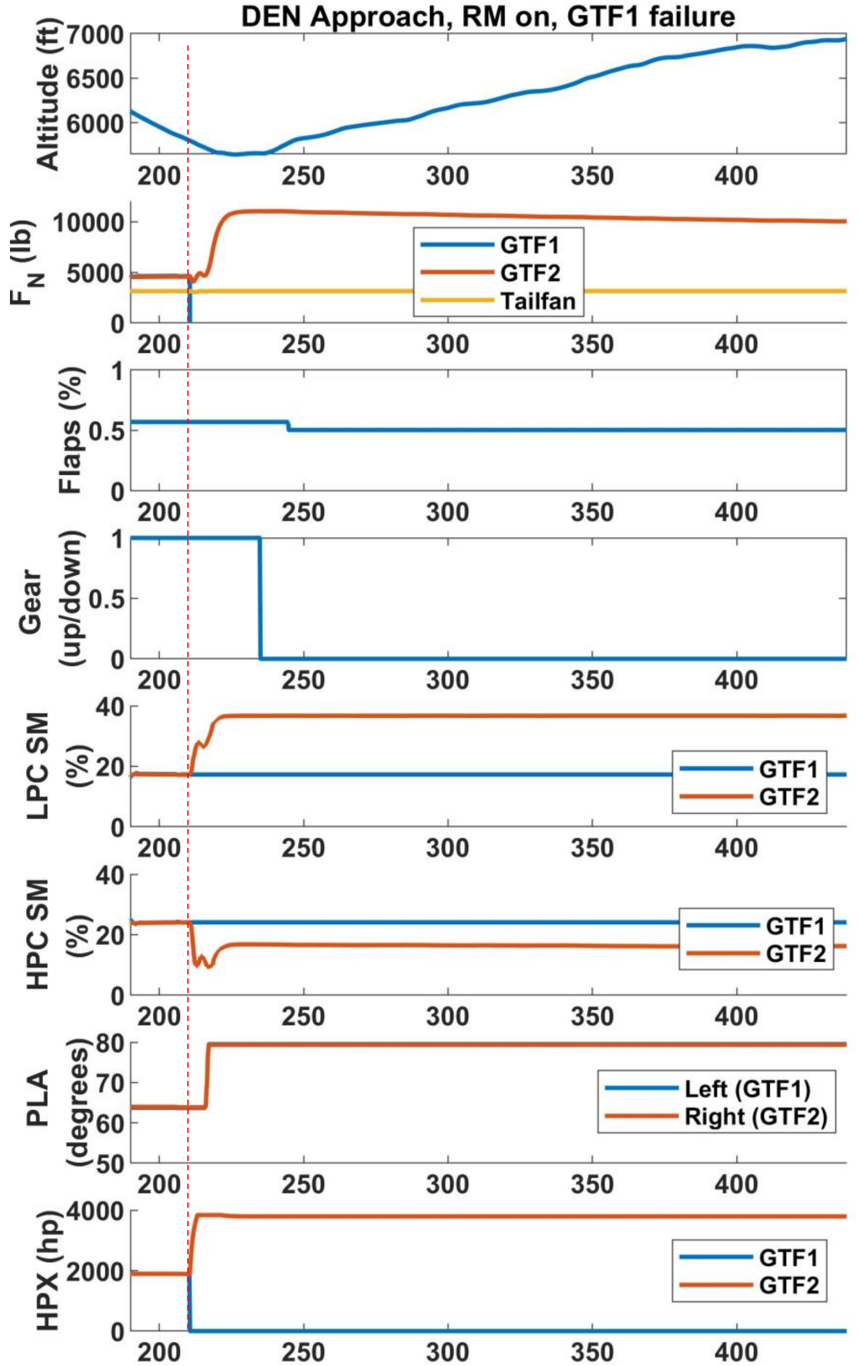




Testing—Missed Approach at Denver

- Although Denver is a high altitude airport, the baseline control system is pretty robust to subsystem failures
- However, meeting the missed approach climb requirement is harder than at lower altitudes
- Abrupt geared turbofan failure occurred
- With reversionary control active, failure did not propagate
- Aircraft was able to climb and successfully exceed minimum steady climb gradient for one engine inoperative





Other Testing

- Additional testing focused on those 14 CFR Part 25 regulations having to do with in-flight handling/controllability and maneuvering with OEI, especially the critical engine
- The pilot was able to maneuver without difficulty in all cases
  - change flight conditions
  - bank and turn

Conclusions

- The reversionary control modes worked properly under all conditions tested and were robust to cascading failures
- Cascading failures demonstrate that control and health management schemes will be enabling for electrified aircraft propulsion technology to progress
- For the relatively traditional looking STARC-ABL, despite having an electrified powertrain, the current 14 CFR Parts 25 and 33 can reasonably be applied, but require interpretation
- The STARC-ABL met all tested requirements for one engine inoperative with reversionary control modes active
- Current certification standards will be insufficient as the diversity of aircraft designs increases

Acknowledgments

- NASA Aeronautics Research Mission Directorate (ARMD)/Transformative Aeronautics Concepts Program (TACP)/Transformational Tools and Technologies (TTT) Project
- NASA ARMD/TACP/Convergent Aeronautics Solutions (CAS) Project
- NASA Minority University Research and Education Project (MUREP)
- The original hazard mitigation schemes utilized here were developed under funding from the NASA ARMD Advanced Air Vehicles Program (AAVP), Advanced Air Transport Technology (AATT) Project, Power and Propulsion Subproject

NASA