Enhancement of an Electrified Tilt-Wing Propulsion System using Turbine Electrified Energy Management

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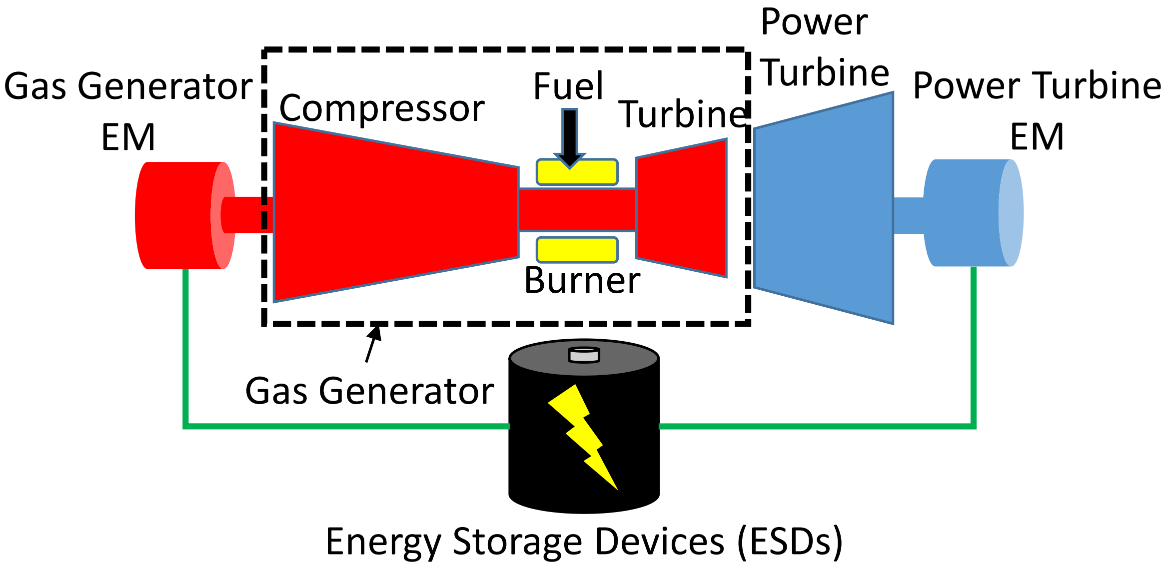
Objectives

- Investigate the applicability of Turbine Electrified Energy Management (TEEM) on a 15 passenger vertical lift concept vehicle
- Differences from prior applications of TEEM
  - Smaller turbomachinery
  - Turboshaft vs. turbofan
  - Power producing turbomachinery
  - Single spool gas generator vs. dual spool turbofans
  - Expanded propulsion system with propulsors outside of the engine
- Questions?
  - Is TEEM applicable to the smaller class vehicles?
  - Is TEEM applicable to this propulsion system architecture?

Background – TEEM

- At its broadest level, TEEM is about managing energy in an electrified turbine engine propulsion system
  - Goal: Improve operability of the turbomachinery → enable better performing engine designs and/or enhance aircraft capabilities
  - The Means: electric machines (EMs) coupled to the engine shaft(s)
    - EMs are new actuators that can alter engine operation
- Transient operability (main focus of this effort)
  - Supplement fuel flow to operate closer to steady-state design conditions



Background – The Tilt-Wing Vehicle

Mission Type: commercial transport

Architecture Type: Turbo-electric

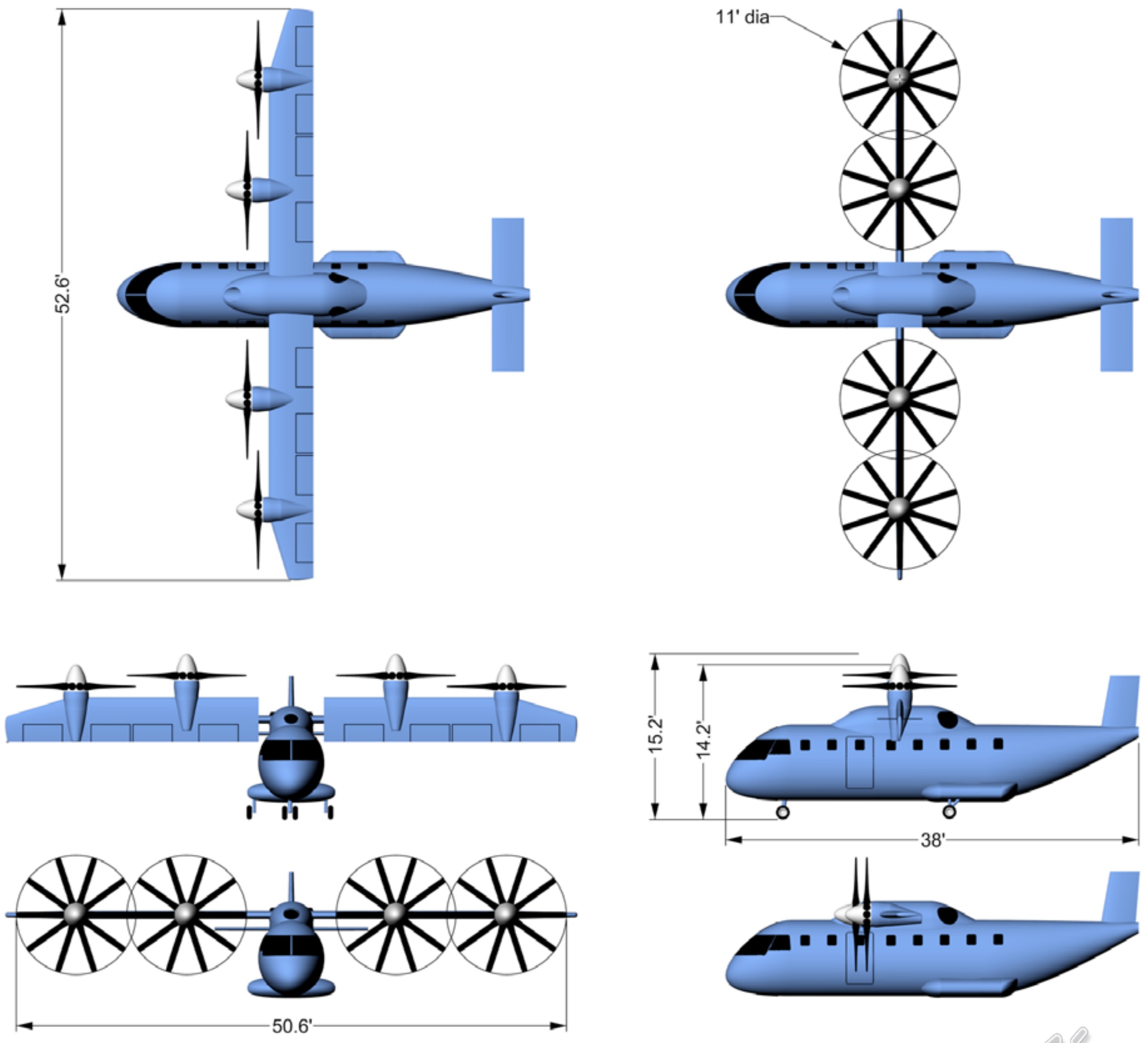
Payload: 3000 lb (15 passengers + luggage)

Max Gross Weight: 13866lb

Max range: 400nm

Cruise speed: 200kts

Key Features: performance of fixed wing aircraft with vertical take-off and landing capabilities



Background – The Tilt-Wing Propulsion System

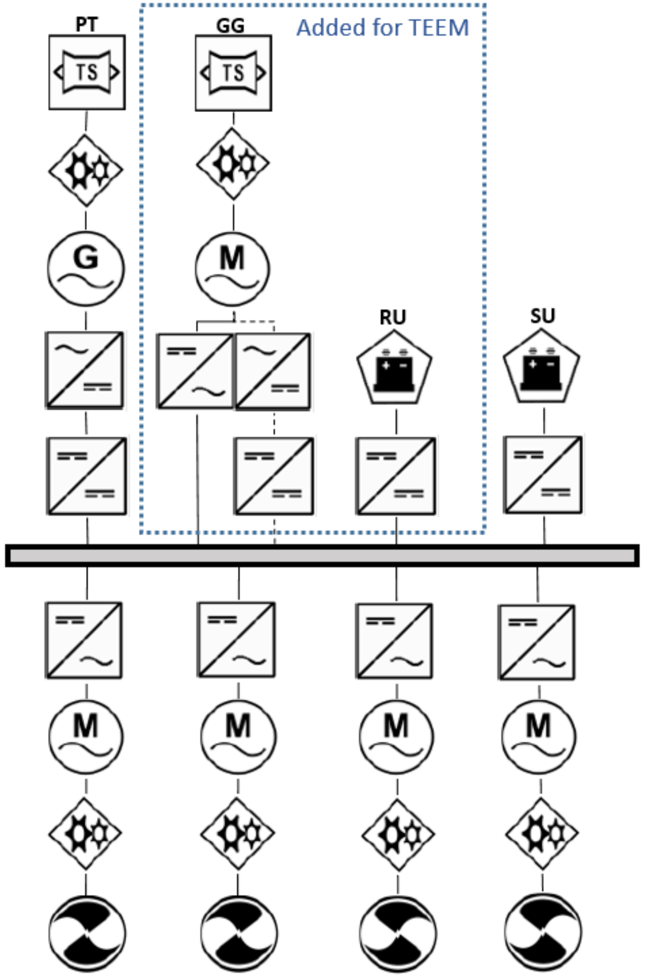
Baseline System

- Turboshaft engine (~4000 hp)
- Generator connected to power turbine (PT)
- Rectifier
- DC-DC converter
- 4 inverters
- 4 motors
- 5 gearboxes (1 for each EM)
- 4 rotors
- 1 single-use battery

TEEM additions*

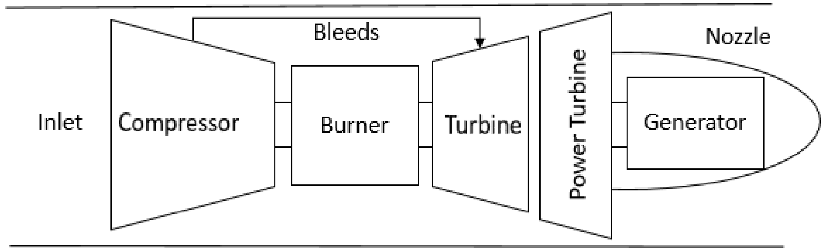
- EM connected to the gas generator (GG)
- 1 gearbox
- Re-usable energy storage
- Inverter/rectifier pair

*May already be present for the purpose of engine starting



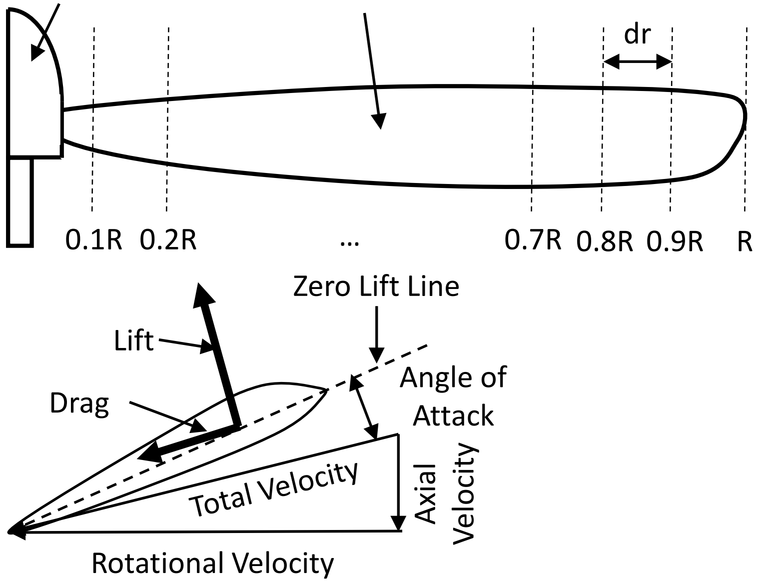
System Modeling

Turboshaft



- Utilizes the Toolbox for Modeling and Analysis of Thermodynamic Systems (T-MATS)
  - Combines bulk component level models to create an overall system model
    - Inlet
    - Compressor
    - Burner
    - Turbine
    - Power Turbine
    - Nozzle
    - Bleeds
  - Compressor and turbine performance is defined by performance maps
  - Utilizes an iterative solver to satisfy conservation equations

Rotors



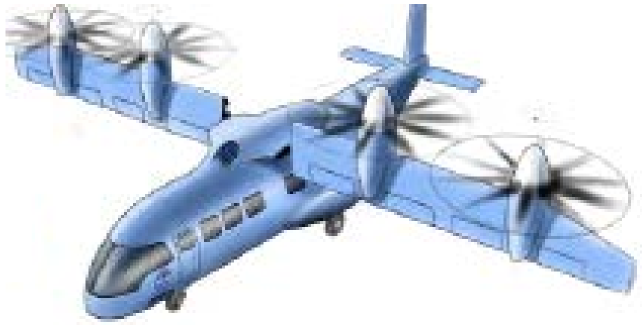
- Techniques are based on theory used by the NASA Design and Analysis of RotorCraft (NDARC) software
  - Power calculations are highly empirical
  - Rotor forces are calculated using blade element theory
  - Power and thrust calculations are coupled requiring iteration
  - A solver is utilized to satisfy thrust and rotor flapping and coning equations

System Modeling

Electric System and Gearboxes

- Simple model that applies efficiencies for each of the components
  - Electric Machines – 97%
  - Inverters/Rectifiers/Converters – 98.6%
  - Gearboxes – 98%
- 0.7 kW-hr of re-usable energy storage was included
- EM Sizes:
  - Power Turbine EM: 3600 hp
  - Rotor EMs: 800 hp
  - Gas Generator EMs: 200 hp

Flight Dynamics



*Only used to determine rotor shaft power requirements for transition

- Simple aerodynamic models for aircraft components (wing, fuselage, horizontal tail, etc.)
- Calculates forces and moments
- Solves for trim conditions (thrust, velocity, cyclic pitch or horizontal tail angle) at different tilt-wing angles

Baseline Control

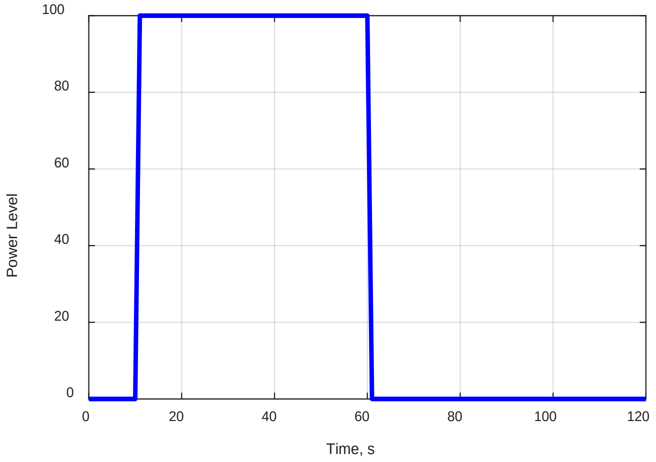
- Gain schedule Linear Quadratic Regulator (LQR) with integral action for reference tracking
- Control objectives
  - Maintain power turbine speed of 8000 rpm
  - Maintain rotors speed set-point (function of air speed)
  - Achieve a desired rotor shaft power
- Control Inputs
  - Fuel flow rate
  - Power turbine EM torque
  - Collective pitch
- Limit logic is applied to modify the shaft power set-point to prevent violation of operating limits

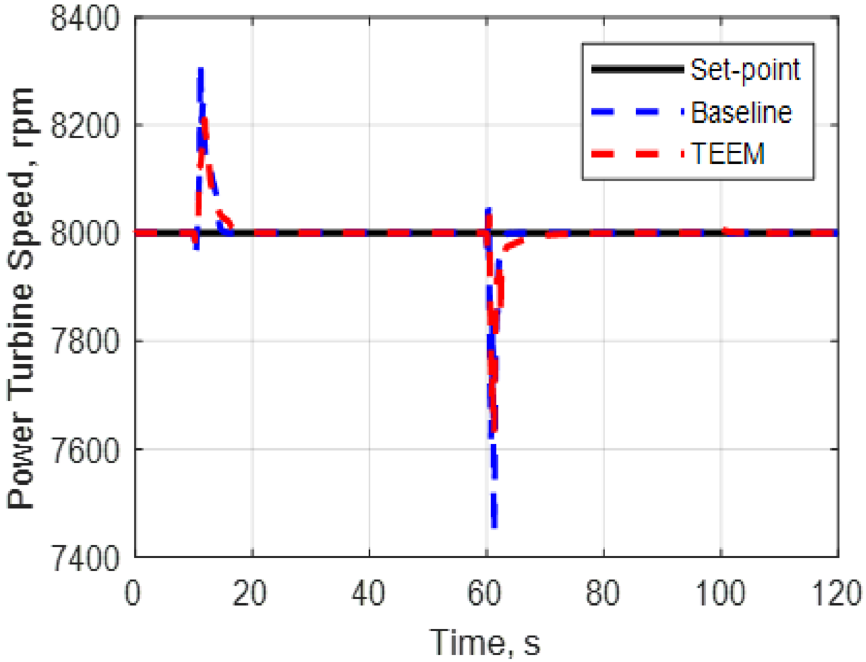
TEEM Control

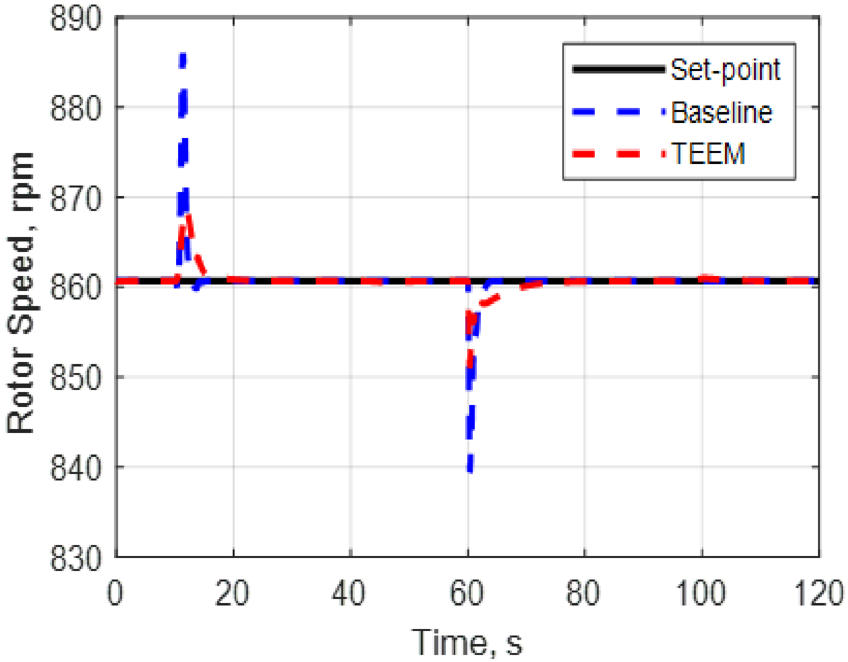
- Augments the existing baseline controller
- Transient Control Logic
  - Designed independently from the baseline controller
  - Controller commands off-nominal torques to closely match steady-state shaft speed conditions for the rotors, power turbine, and gas generator
  - Proportional integral (PI) controllers
  - Activated/de-activated based on the rotor shaft power error
- Steady-state energy management
  - Applies excess power gathered during transients to the rotors (temporarily decreases fuel consumption)
  - Charges the ESDs as needed
- Thrust augmentation
  - Allows for additional energy from ESDs to be sent to the rotors – increase maximum thrust by ~7% at sea level static conditions

Simulation Results

- Burst and chop transient at sea level static hover conditions
- More tightly regulated rotor and power turbine speeds

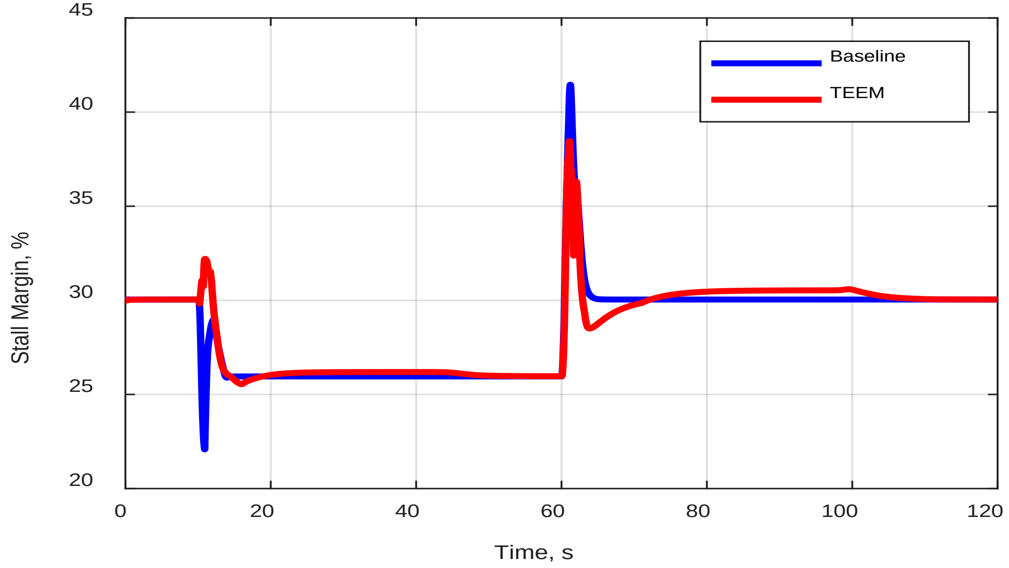


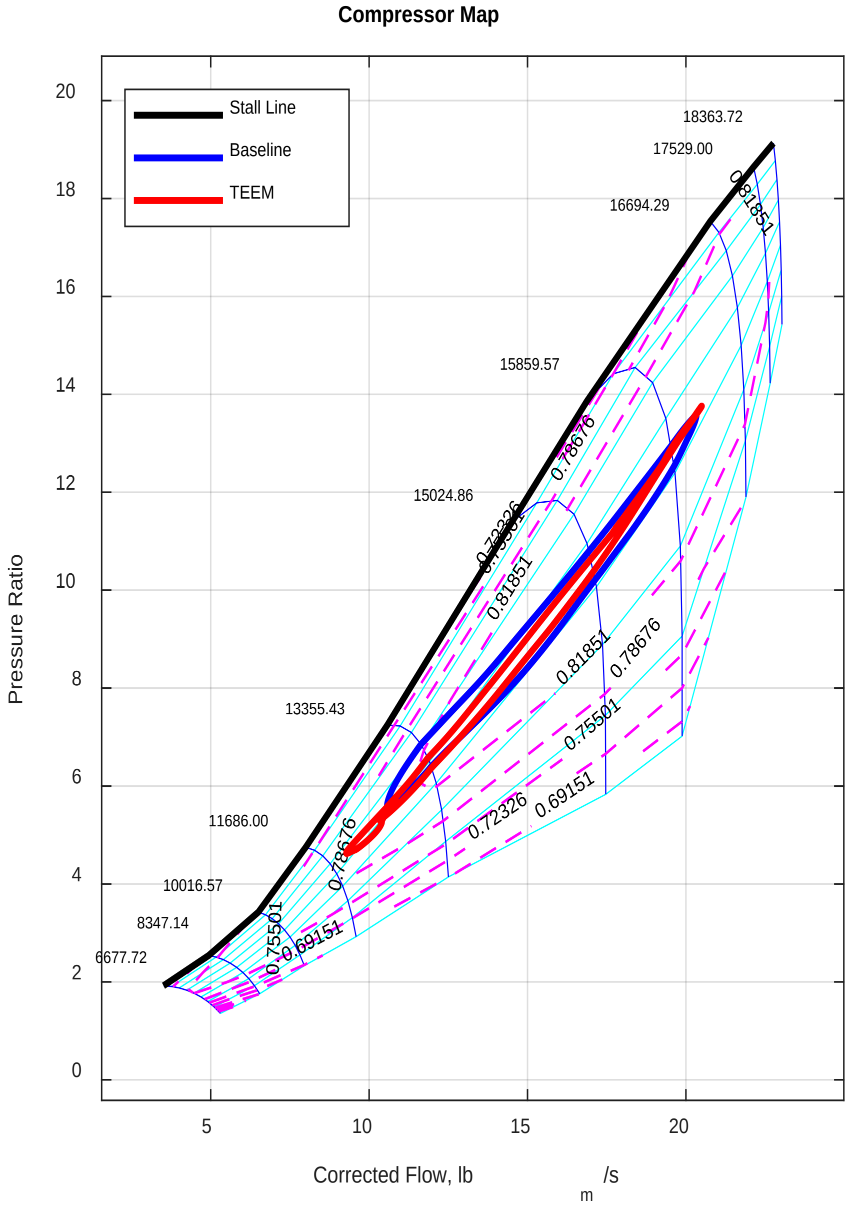




Simulation Results

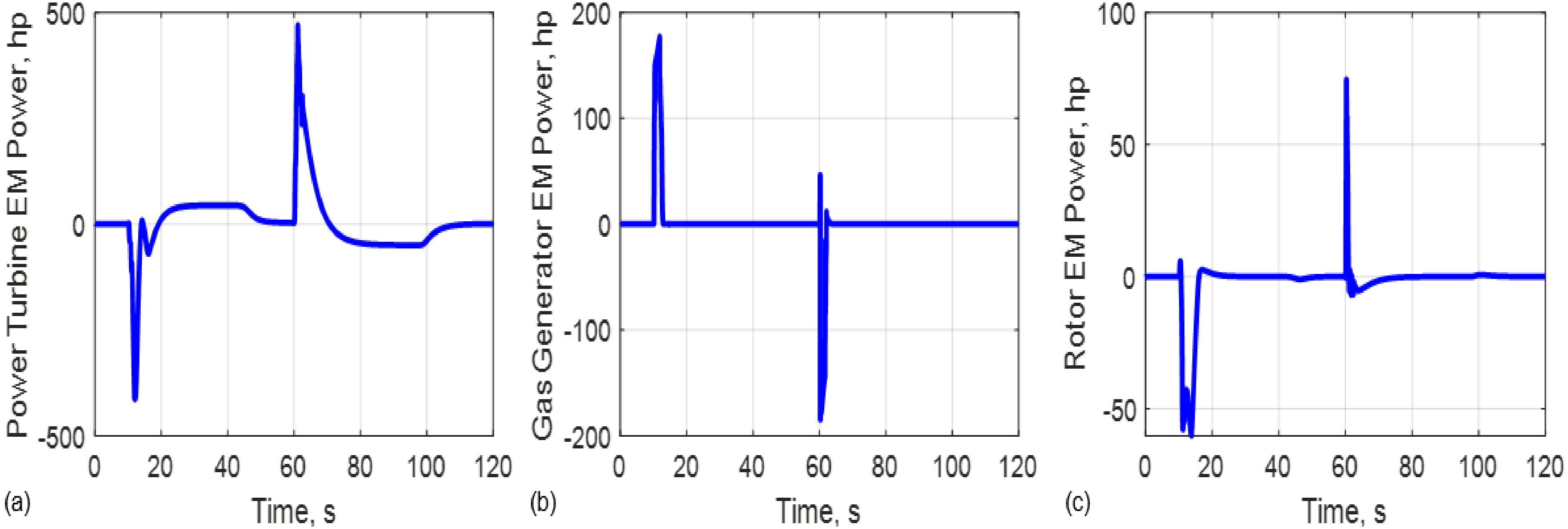
- Superior transient operability
  - Improved minimum stall margin during acceleration
  - Tighter control of operating point on the map





Simulation Results

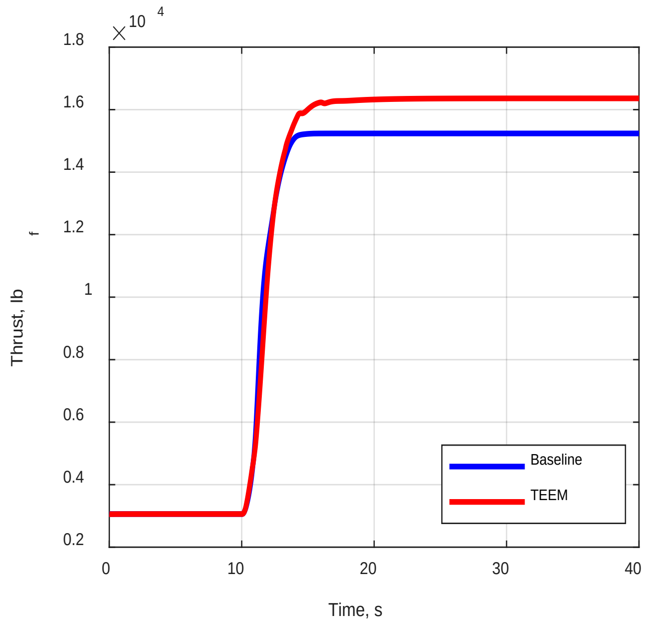
Off-Nominal EM Power Inputs



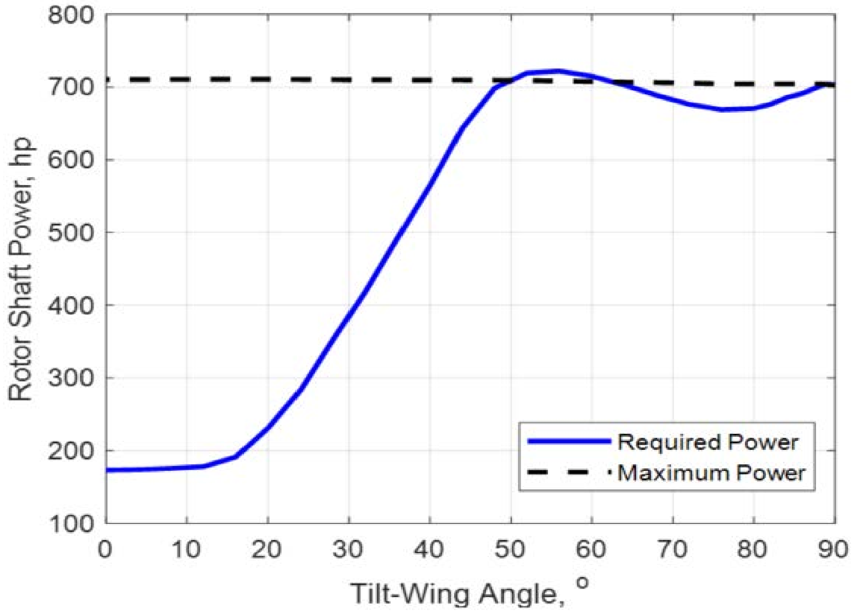
- Baseline Power turbine EM and rotor EMs should be sufficient to implement TEEM control
- Need a gas generator EM with a peak power capability of ~175 hp
- Off-nominal power inputs tend to offset each other → reduces energy storage needs
- A 0.7 kW-hr energy storage device was sufficient
- Brief periods of dissipating excess energy and charging
  - Resulted in a net decrease in bulk fuel consumption (0.3%)

Simulation Results

- Increased maximum thrust by ~7% while retaining operability benefits
- Could be used to …
  - Increase thrust during an emergency
  - Increase take-off/landing weight and or altitude
  - Address certain mission segments



Thrust Enhancement



Required Rotor Shaft Power

Conclusions

- Questions?
  - Is TEEM applicable to the smaller class vehicles?
    - Yes
  - Is TEEM applicable to this propulsion system architecture?
    - Yes

Acknowledgements

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Questions/Discussion

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