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?
At its broadest level, TEEM is about managing energy in an electrified turbine engine propulsion system.

- Goal: Improve operability of the turbomachinery to 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.
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

- 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
- 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

- 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
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Questions/Discussion

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