Modeling and Control for Turboelectric Aircraft

Aidan Dowdle
adowdle@mit.edu
NASA GRC AS&ASTAR Fellow
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Many proposed conceptual designs (e.g. STARC-ABL)

However, various electric propulsion architectures possible\(^{(1)}\)

Objective: use modeling and systems-level analysis to study the capabilities of these architectures
Modeling Research Activities

- LEARN Project - Propulsion Architecture Assessment
- S.M. Thesis - Requirements Analysis via Dynamics and Control
- Center-Based Research Experience
Modeling Research Activities

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LEARN Project

• Joint effort between MIT, USC, and Aurora Flight Sciences
  • PI: Professor Edward Greitzer

• Assessing propulsion systems using Multi-Disciplinary Optimization (MDO)

• Specific type of MDO used is Geometric Programming\(^{(2)}\)
Electrical Components Modeled

- Airframe
- Mechanical
- Electrical
  - Battery
  - Power Cables
  - PMBLDC Machines
  - Power Electronics
  - Circuit Protection
- Thermal Management System
Ex.: Cable Model

Variables

- \( A_c \) (Conductor Area)
- \( A_{di} \) (Dielectric Area)
- \( a \) (Conductor Radius)
- \( b \) (Cable Radius)
- \( d_c \) (Conductor Density)
- \( d_{di} \) (Dielectric Density)
- \( E_{\text{max}} \) (Max Field Strength)
- \( I_{\text{max}} \) (Max Current)
- \( \ell \) (Cable Length)
- \( m \) (Mass)
- \( P_{\text{max}} \) (Max Power)
- \( R \) (Resistance)
- \( V_{\text{max}} \) (Max Voltage)
- \( p_V \) (Max % Voltage Drop)
- \( \eta \) (Litz Wire Packing Factor)
- \( \rho \) (Conductor Resistivity)

Performance Model

\[
\begin{align*}
R & \quad I \\
V_{\text{source}} & \quad V_{\text{load}} \\
- & \quad +
\end{align*}
\]

Sizing Relations

- \( A_c = \pi a^2 \eta \)
- \( A_{di} \geq \pi (b^2 - a^2) \)
- \( m \geq d_c A_c \ell + d_{di} A_{di} \ell \)
- \( R = \rho \frac{\ell}{A_c} \)
- \( E_{\text{max}} \geq \frac{V_{\text{max}}}{b-a} \)
- \( I_{\text{max}} R \leq p_V V_{\text{max}} \)
- \( P_{\text{max}} = V_{\text{max}} I_{\text{max}} \)

\[ I \leq I_{\text{max}} \]
\[ Q = I^2 R \]
\[ P_{\text{load}} = IV_{\text{load}} \]
\[ P_{\text{source}} = IV_{\text{source}} \]
\[ V_{\text{load}} + IR \leq V_{\text{source}} \]
\[ V_{\text{source}} \leq V_{\text{max}} \]
Ex.: Integrated Electrical System

- 600 V vs. 7 kV system for 1 MW power delivery

\[
\begin{align*}
R_{\text{int}} & \quad \text{Battery} \\
R_{\text{cable}} & \quad \text{Cable}
\end{align*}
\]

\[P_{\text{load}} = V_{\text{cab,load}}I = 1 \text{ MW}\]

\[V_{\text{cab,load}} = 600 \text{ V}\]

\[m_{\text{batt}} = 707 \text{ kg}\]

\[m_{\text{cable}} = 11.4 \text{ kg}\]

\[m_{\text{total}} = 718.4 \text{ kg}\]

\[600 \text{ V} \rightarrow 7 \text{ kV}\]

Saves 47.1 kg

\[V_{\text{cab,load}} = 7 \text{ kV}\]

\[m_{\text{batt}} = 671 \text{ kg}\]

\[m_{\text{cable}} = 0.33 \text{ kg}\]

\[m_{\text{total}} = 671.3 \text{ kg}\]
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Requirements Analysis

Flight Path

- Current location
- Velocity
- Angle-of-Attack
- Environment (e.g. wind gusts)
- Human Pilot

\[ \sigma_x, \sigma_y, \sigma_z \]
Requirements Analysis

- Prior analysis would not account for coupling
- Can take them into account using plant model & covariance analysis
  - Thesis advised by Dr. Marija Ilic

![Diagram showing the relationships between current location, velocity, angle of attack, environment, and human pilot, with sigma_x, sigma_y, sigma_z as inputs to flight path.]
Aircraft Under Study

• Medium-sized (~150,000 lbs), tube-and-wing, turboelectric aircraft

State variables:
- \( v \) – velocity
- \( \alpha \) – angle-of-attack
- \( \theta \) – pitch angle
- \( q \) – pitch rate

Control inputs:
- \( \delta_t \) – throttle
- \( \delta_e \) – elevator

States evolve nonlinearly, e.g.

\[
\dot{v} = \frac{(T \cos(\alpha) - Q_s C_d)}{m} - g \sin(\theta - \alpha)
\]
Incorporating Electric Components

• A turbine & generator powers the propulsor

Parameters
• $J$ – motor inertia
• $\Omega$ – nominal rotor speed
• $\delta$ – rotor speed deviation
• $f$ – total motor damping
• $P_m$ - mechanical power
• $P_e$ - electrical power

$$J \ddot{\Omega} + f \dot{\delta} \Omega = P_m - P_e$$
Example Applications

- Disturbance response
  \[ \dot{\Sigma}(t) = A\Sigma(t) + \Sigma(t) A^T + B_1 W(t) B_1^T \]

- Sensor bandwidth requirements
  \[ C_2(sI - A + K_{k_f}C_2)^{-1} K_{k_f} \]

-3 dB

Bandwidth
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Center-Based Research Experience

• NASA Glenn Research Center

• Aurora Flight Sciences\(^{(4)}\)
Summary

- Research activities supported by NASA Glenn Research Center

- Geometric programming (LEARN)
  - Electrical component modeling
  - Sensitivity studies on propulsion architectures

- Requirements Analysis via Dynamics (S.M. Thesis\(^3\))
  - Take into account coupling between subsystems to perform a mission
  - Created disturbance environment and tested control design

- Center-based research experience at NASA GRC & AFS
References


