Methodology for Robust Design of Small Fuel Cell Systems: Application to Unmanned Aerial Vehicles

Thomas F. Fuller
School of Chemical and Biomolecular Engineering
Georgia Institute of Technology

Thomas H. Bradley
PhD Candidate
George Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Collaborations

- **Georgia Tech Research Institute** - Faculty (Parekh) and Staff
- **Aerospace System Design Lab** - Faculty (Mavris), Staff and Students (Moffitt)
- **GT Center for Fuel Cell Battery Technology** - Faculty (Fuller) and Students
Outline

• Complex Systems Design
• Motivation and Introduction to Fuel Cell Aircraft
• Fuel cell Unmanned Aerial Vehicle (UAV) design methodologies and demonstrations
• Conclusions
Complex systems design

- Complexity arises from
  - Constraints, Scope, Computation, Uncertainty, Decisions

- Complex systems design tools
  - Statistical Methods (RSE, Interval Analysis)
  - Operations Research
  - Decision Process Modeling
  - Decision Support
  - Multi-disciplinary Analysis/Optimization (MDO)

---

Complex systems design

- Challenges to complex system design
  - *Methods validation and realizeable problem sets*
  - “Revolutionary” designs
  - *Tradeoff between constraints and uncertainty*

Rahalbandhi and Mavris, Journal of Aircraft 43(6) 2006
Briceno et al., AIAA 2002-5808
Rowell et al., Journal of Aircraft 36(1) 1999
Fuel Cell Powered Aircraft

• Fuel cell aircraft is excellent example problem for consideration using the tools of Complex System Design
  • Academic scale
  • “Revolutionary” powerplant
  • Commercial/Academic/Government interest
Motivation for fuel cellpowered aviation

1. Environmental Compatibility

- Hydrogen – Air fuel cells
- have no regulated emissions
- can use hydrogen generated from any source, including renewables
Motivation for fuel cell powered aviation

2. Performance

- High specific energy at very long endurances (liquid H₂)
  
  \[ \frac{W_{\text{fuel}}}{\text{GTOW}} \rightarrow 1 \]
- Regenerative fuel cells
  
  > 800 Wh/kg
- On-board electricity generation
- Noise/Pollution constrained applications (General Aviation)
- High specific energy at small scales (gas, chem. and liquid H₂)
  
  < 300 W cruise, long range & endurance

Comparison of UAV Energy Storage Technologies at Small Scale (< 300W)

- Fuel Cell at 50% Hydrogen Storage Fraction
- Fuel Cell at 10% Hydrogen Storage Fraction
- Aviation Engine
- LiNiCoO₂ Modules

Engine: octane fuel, zero gasoline tank weight, tested efficiency AIAA 2003-671
Fuel cell: 0.65V/cell, tested efficiency, 10% is commercially available, 50% is representative of liquid storage
Lithium batteries: Anderman, M., California Air Resources Board, 2003
Motivating Research Questions

1. What are the design characteristics of fuel cell systems for aircraft?
   - Derive and compare fuel cell system design rules

2. How can we expand the adaptability of MDO tools to incorporate real world design complexity, experimental data and validation data?

3. How can we validate the design process?
Fuel Cell Design Characteristics

\[ \eta \text{ Fuel Cell Required} = 90\% \]

Kohout and Schmitz, AIAA 2003-2867

Fuel Cell Design Characteristics

- Conventional Design Requires Functional Design Rules

- Conventional (automotive, stationary) FC system design rules:
  - Stoichiometry $\lambda = 2$
  - BOP sized by max power
  - FC stack ($n_{\text{cells}}$, active area) sized by max power required
  - Maximize hydrogen pressure
Conventional Design

Requires Functional Design Rules

Conventional (automotive, stationary) FC system design rules:

- Stoichiometry $\lambda = 2$
- BOP sized by max power
- FC stack (n_cells, active area) sized by max power required
- Maximize hydrogen pressure
Fuel Cell Design Characteristics

- Advanced design has two effects
  
  Breaks up design rules
  
  Widens design space
Fuel Cell Design Characteristics

Results of fuel cell design rule disintegration

- Relative to conventional design rules:
  - Fuel cell active area is “oversized” by 68%
  - The fuel cell can generate more power than the aircraft uses
  - Fuel cell balance of plant is “undersized” by 38%

- Airplane fuel cells are functionally different than automotive/stationary
Fuel Cell Design Characteristics

- Results of fuel cell design rule disintegration relative to conventional design rules

\[
\text{Endurance} = t = \left( \frac{E}{m^{3/2}} \right) \left( \frac{1}{2} \rho S_w \right)^{1/2} \frac{C_L}{g^{3/2}C_D}
\]

\[
\text{Range} = s = \left( \frac{E}{D} \right) = \left( \frac{L}{D} \right) \left( \frac{E}{L} \right) = \left( \frac{E}{m} \right) \left( \frac{C_L}{gC_D} \right)
\]

- Optimizing subsystems gives sub-optimal system results
Motivating Research Questions

1. What are the design characteristics of fuel cell systems for aircraft?
   - *Deductive design breaks design rules, improves performance*

2. How can we expand the adaptability of MDO tools to incorporate real world design complexity, experimental data and validation data?
   - *Structure design methods for sensitivity analysis and validation*

3. How can we validate the design process?
Design Structured for Validation

- Uncertainty dominates early phases of design
- Uncertainty increases with scale
- Instantaneous performance prediction for fuel cells is challenging
<table>
<thead>
<tr>
<th>CA Number</th>
<th>CA Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fuel Cell Mass and Dimensions</td>
</tr>
<tr>
<td>2</td>
<td>H2 Tank Mass and Dimensions</td>
</tr>
<tr>
<td>3</td>
<td>Redlich Kwong Equation of State</td>
</tr>
<tr>
<td>4</td>
<td>Hydrogen Mass</td>
</tr>
<tr>
<td>5</td>
<td>Hydrogen Tank Mass</td>
</tr>
<tr>
<td>6</td>
<td>Propeller Mass Relation</td>
</tr>
<tr>
<td>7</td>
<td>FC System Mass</td>
</tr>
<tr>
<td>8</td>
<td>Fuselage Mass and Dimensions</td>
</tr>
<tr>
<td>9</td>
<td>Wing and Tail Mass</td>
</tr>
<tr>
<td>10</td>
<td>Aircraft Mass</td>
</tr>
<tr>
<td>11</td>
<td>Propeller Interference</td>
</tr>
<tr>
<td>12</td>
<td>Fuselage Drag</td>
</tr>
<tr>
<td>13</td>
<td>Wing and Tail Lift Drag</td>
</tr>
<tr>
<td>14</td>
<td>Airplane Lift Drag</td>
</tr>
<tr>
<td>15</td>
<td>Steady Level Flight</td>
</tr>
<tr>
<td>16</td>
<td>Propeller Non-Dimensionalization at Climb</td>
</tr>
<tr>
<td>17</td>
<td>Propeller Coefficients at Climb</td>
</tr>
<tr>
<td>18</td>
<td>Propeller Torque at Climb</td>
</tr>
<tr>
<td>19</td>
<td>Motor Speed at Climb</td>
</tr>
<tr>
<td>20</td>
<td>FC Polarization at Climb</td>
</tr>
<tr>
<td>21</td>
<td>Aux Current at Climb</td>
</tr>
<tr>
<td>22</td>
<td>Stack Current at Climb</td>
</tr>
<tr>
<td>23</td>
<td>BOP Power at Climb</td>
</tr>
<tr>
<td>24</td>
<td>Power Summations at Climb</td>
</tr>
<tr>
<td>25</td>
<td>Efficiency Calculations at Climb</td>
</tr>
<tr>
<td>26</td>
<td>Propeller Non-Dimensionalization</td>
</tr>
<tr>
<td>27</td>
<td>Propeller Coefficients</td>
</tr>
<tr>
<td>28</td>
<td>Propeller Speed</td>
</tr>
<tr>
<td>29</td>
<td>Propeller Torque</td>
</tr>
<tr>
<td>30</td>
<td>Motor Current</td>
</tr>
<tr>
<td>31</td>
<td>FC Polarization</td>
</tr>
<tr>
<td>32</td>
<td>Aux Current</td>
</tr>
<tr>
<td>33</td>
<td>Stack Current</td>
</tr>
<tr>
<td>34</td>
<td>BOP Power</td>
</tr>
<tr>
<td>35</td>
<td>Power Summations</td>
</tr>
<tr>
<td>36</td>
<td>Efficiency Calculations</td>
</tr>
<tr>
<td>37</td>
<td>Climb Rate</td>
</tr>
<tr>
<td>38</td>
<td>Propeller Tip Mach No</td>
</tr>
<tr>
<td>39</td>
<td>Reynolds Number</td>
</tr>
<tr>
<td>40</td>
<td>Hydrogen Flow Rate</td>
</tr>
<tr>
<td>41</td>
<td>Cruise Endurance</td>
</tr>
<tr>
<td>42</td>
<td>Hydrogen Flow Rate at Climb</td>
</tr>
<tr>
<td>43</td>
<td>Cruise Range</td>
</tr>
<tr>
<td>44</td>
<td>Cruise Endurance at Climb</td>
</tr>
<tr>
<td>45</td>
<td>Optimization Cost Function</td>
</tr>
</tbody>
</table>

24 hr Endurance FCUAV
108 Variables Passed within 45 CA’s
28 Input Variables and/or Constants
Design Structured for Validation

• Endurance = 20.7 ± 8.6 hrs
Define Design Problem
- Baseline Configuration
- Design Variables
- Performance metrics and Cost Function

Decompose into CA’s

Design System Matrix
Powerplant Parametric Design CA

Aircraft Parametric Design CA

[Image]

Propagate Uncertainty

Estimate Uncertainty

σTj

Actual Fuel Cell Voltage (V)

Predicted Fuel Cell Voltage (V)

Design Structured for Validation

Moffitt, Bradley, Parekh, Mavris AIAA 2007-7793
Design Structured for Validation

- Endurance = 22.5 ± 2 hrs
Motivating Research Questions

1. What are the design characteristics of fuel cell systems for aircraft?
   - *Deductive design breaks design rules, improves performance*

2. How can we expand the adaptability of MDO tools to incorporate real world design complexity, experimental data and validation data?
   - *Integrated design methods allow for MDO to be carried into later stages of design*

3. How can we validate the design process?
   - *Flight testing vs. Hardware in the Loop simulation*
Hardware in the Loop Simulation

- **Powertrain dynamometer**
  - measures torque ($Q$) and speed ($\omega$)
- **Signal generator**
  - Translates commands into TTL signals
Integrated Design and Demonstration

- 24 Hour Endurance Aircraft
  - $22.5 \pm 2$ hrs endurance FCUAV Designed
  - $22.75 \pm 0.64$ hrs endurance FCUAV HiL Tested
Validated Cross-technology Comparison

<table>
<thead>
<tr>
<th>Powerplant Type</th>
<th>Energy Storage Subsystem Specifications</th>
<th>( \frac{E}{m} )</th>
<th>( \frac{E}{m^{3/2}} )</th>
<th>Calculated Range (s) using (11)</th>
<th>Calculated Endurance (t) using (15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HiL Hydrogen PEM Fuel Cell</td>
<td>448 DC Wh kg(^{-1})</td>
<td>124.9 Wh kg(^{-1})</td>
<td>35.3 Wh kg(^{-3/2})</td>
<td>1100 km</td>
<td>24.1 hr</td>
</tr>
<tr>
<td>Zinc Air Battery</td>
<td>350 DC Wh kg(^{-1}) [4]</td>
<td>101.4 Wh kg(^{-1})</td>
<td>28.7 Wh kg(^{-3/2})</td>
<td>894 km</td>
<td>19.6 hr</td>
</tr>
<tr>
<td>Lithium Polymer Battery</td>
<td>166 DC Wh kg(^{-1}) [23]</td>
<td>48.1 Wh kg(^{-1})</td>
<td>13.6 Wh kg(^{-3/2})</td>
<td>423 km</td>
<td>9.3 hr</td>
</tr>
<tr>
<td>Small Internal Combustion Engine</td>
<td>0.3 kg hr(^{-1}) @105W [24]</td>
<td>124.7 Wh kg(^{-1})</td>
<td>35.2 Wh kg(^{-3/2})</td>
<td>1083 km</td>
<td>23.8 hr</td>
</tr>
</tbody>
</table>

- Performance comparison is at equal takeoff weight & airspeed
- PEM fuel cell UAVs with compressed hydrogen storage can yield performance competitive tactical UAVs

Summary

This research effort has accomplished:

- Definition of design methods for fuel cell systems for aircraft
- New DSM decomposition rules to enable MDO information to be carried forward in design process
- Design and experimental validation of fuel cell aircraft
- Seminal results in FCUAV design/testing/applications

FCUAVs are a growing and commercially viable application
Thomas F. Fuller
School of Chemical and Biomolecular Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0100

Thomas H. Bradley
Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0405

bradley@gatech.edu
www.fcbt.gatech.edu/fuelcellairplane