Promising Electric Aircraft Drive Systems

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Outline

• Background
• Critical Technologies for Electric Aircraft
• Power-system configuration options
• Comparing Electric Aircraft Power-systems
• Analytical approach
• Typical component subsystem performance
  – Energy Storage
  – Energy Conversion
• Power-system weight comparisons
• Electric power systems performance targets
• Summary
Background

• The idea to power aircraft with electric motors has been around a long time
  – Patents filed in 1943 for both battery and piston-engine hybrid electric airplanes
  – Progress limited by key technology barriers
    > A source of electricity with power and energy densities suitable for aircraft
    > Electric motors with high power/weight ratios

• What has changed
  – Environmental concerns are accelerating development of electric power-system technologies that have the potential to overcome the historical barriers
Worldwide Interest in Piloted Electric Aircraft

Pipistrel Taurus – 2007
Li-Polymer battery
65 mph 1.0 hr

Boeing Dimona – 2008
PEM fuel cell + Li-ion battery
62 mph for 20 min

Antares DLR-H2 – 2008
PEM fuel cell + battery
106 mph, 10 min flight, 465 mi range

DigiSky SkySpark – 2009
Li-Polymer battery
155 mph, 8 minute flight

Yuneec E430 – 2009
Li-ion battery
~1.5-2 hr with 60 mph cruise
Why Now

• Increasing public awareness of environmental and climate concerns

• Maturation and accelerated development of key enabling technologies

• Possible near term market opportunities with reasonable paths for growth
Critical Technologies for Electric Aircraft

Electric Motor

Battery/Energy Storage

Fuel-cell

Hydrogen Storage
Non-Cryogenic Electric Motors

- Power density of non-cryogenic motor will continuously increase with the growth in electric car market (> 6 kW/kg motors can be expected in future).

- > 20 kW/kg power density can be achieved for cryogenic motors

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Battery technologies in development have the potential for 10X increase in storage capacity over currently available Li-ion batteries.

Fuel-cell power-systems will require some battery storage to balance power demands.
Fuel Cell Systems - Advantages / Disadvantages

- Proton Exchange Membrane (PEM) Fuel-cell:
  - More mature, operational in cars, high power density demonstrated
  - Need pure H₂, availability and storage challenge
  - Lower operating temperature (low quality heat released) needs larger heavier heat exchanger

- Solid Oxide Fuel-Cell (SOFC)
  - Less mature, currently low power density systems
  - 30-45 minute startup warm-up
    > Battery startup operations could reduce impact
  - Can use hydrocarbon fuels
  - Efficiencies greater than 60 % for hybrid system
    > Fuel-cell with gas turbine bottoming cycle
  - Higher power density needed for mobile systems
    > Pathway exists to achieve higher power density but will require significant technology development
State of Fuel-cell Technology

- Significant opportunity exists to reduce weight of balance of plant through use of lightweight materials and composite materials (~50% weight reduction possible) – 1 kW/kg stack would correspond to 0.66 kW/kg at system level

- Effective system integration may yield further weight reductions

Technology Readiness Level (TRL)

Stack Power Density (kW/kg)

- 1.25 kW/kg at system level
- 0.5 kW/kg at system level

Proton Exchange Membrane (PEM) Fuel Cell
Solid Oxide Fuel Cell (SOFC)

Commercial PEM Fuel Cell

Developmental SOFC

Balance of Plant Contributes Significant Weight (~50%)
Hydrogen Storage

Extensive Research Underway on Solid State Hydrogen Storage

- **Low Temp Hydrides**
  - Current available: 3-6 wt%
  - Potential for > 15 wt % based on theoretical limits

- **Compressed H₂ (with container)**
  - DOE 2010 Goal: 2 kW*h/kg

- **Liquid/Cryogenic H₂ (with container)**
  - DOE 2015 Goal: 3 kW*h/kg

- **Complex hydrides**
  - H₂ content of Reformed kerosene
    - Volumetric Density: 320 kg/m³
    - Gravimetric Density: 33%

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Power-system configuration options

Energy Storage
(Chemical)

- Hydrocarbon
- Hydrogen
- Electrochemical

Energy Conversion
(Mechanical Final Output)

- Baseline
- IC Engine
  - Chem - Mech
- Fuel-cell (SOFC)
  - Chem - Elect
- Reform
  - $C_nH_{2(n+1)} - H_2$
- Fuel-cell (PEM)
  - Chem - Elect
- PM/D
  - Elect - Elect
- Electric Motor
  - Elect - Mech

IC: Internal (Intermittent) Combustion
PEM: Proton Exchange Membrane
SOFC: Solid Oxide Fuel-Cell
PM/D: Power Management/Distribution

Systems boundary

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Comparing Electric Aircraft Power-systems

- Power-systems are normalized by maximum power and total available energy
- System weight is used as a figure of merit
- Two reference mission used as a basis for comparison
  - **Light Utility General Aviation (GA)**
    > 3525 lb GTOW
    > 170 Knts
    > 300 HP
    > 4.75 hr endurance
  - **Light Primary Trainer**
    > 1100 lb GTOW
    > 85 Knts
    > 67 HP
    > 1.5 hr endurance
- Electric aircraft synergistic advantages not considered
Analytical Approach

• Vehicle Power-systems are decomposed into energy storage and energy conversion subsystem components
  – Energy storage components
    > Fuel: Hydrocarbons, H₂, electrochemical…
    > Containers: tanks, pressure vessels, batteries…
  – Energy conversions components
    > Chemical to mechanical: Combustion Engines
    > Chemical to electric: Fuel-cells, Batteries
    > Electric to electric: Power Management
    > Electric to mechanical: Electric Motors

• Storage component weights scale to energy requirement

• Conversion component weights scale to power requirement

• Weight of Power-systems providing equivalent mechanical energy (Power delivered over time) is the primary figure of merit
Power-system Energy Model

• \( E_R \): Energy Requirement

\[
E_R = \sum_{n}^{m} \left( P_n \right) \left( t_n \right)
\]

Where:
- \( P_n \) is power level for interval \( n \)
- \( t_n \) is time at interval \( n \)

• \( E_S \): Total stored energy

\[
E_S = \frac{E_R}{(\eta_1)(\eta_2)(\eta_3)(\eta_4)}
\]

Where:
- \( \eta_n \) is efficiency of energy conversion component \( n \)

Reference Missions:

<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>( E_R )</th>
<th>( P_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Utility GA</td>
<td>800 kW*hr</td>
<td>225 kW</td>
</tr>
<tr>
<td>Light Trainer</td>
<td>60 kW*hr</td>
<td>50 kW</td>
</tr>
</tbody>
</table>
Power-system Weight Model

- $W_S$: Total system weight
  \[ W_S = W_{ES} + W_{EC} \]
- $W_{ES}$: Sum of energy storage component weights
  \[ W_{ES} = \sum_n (E_S)(\gamma_n) \]
- $W_{EC}$: Sum of energy conversion component weights
  \[ W_{EC} = \sum_n^m (P_{max})(\theta_n) \]

Where:
- $P_{max}$ is Maximum power
- $\gamma_n$ is the weight scaling factor for energy storage component $n$
- $\theta_n$ is weight scaling factor for energy conversion component $n$
Energy Storage
Typical and Projected Performance Parameters

Energy Storage weight factors: $\gamma$ (energy density)

• Fuels
  – Hydrogen ($\text{H}_2$) 33.5 kW*hr/kg
  – Kerosene ($\text{C}_{12}\text{H}_{26}$) 14.3 kW*hr/kg

• Batteries ($\eta = .98$)
  – Li-S (2010) 0.25 kW*hr/kg
  – Li-ion/Li-S (2015) 0.65 kW*hr/kg

• Tanks Fuel/Tank wt ratio
  – Liquid HC 10.0
  – $\text{H}_2$ (gas) (2010) 0.06
  – $\text{H}_2$ (gas) (2015) 0.10
Chemical and Electrical Energy Conversion
Typical and Projected Performance Parameters

Energy Conversion weight factors; $\theta$ (power density)

- Fuel-cells ($\eta = 50\%$)
  - Proton Exchange Membrane (PEM)
    - > 2010: Automotive systems 0.9 kW/kg
    - > 2015 1.5 kW/kg
  - Solid Oxide Fuel-Cell (SOFC)
    - > 2010 0.25 kW/kg
    - > 2015 0.50 kW/kg

- Power management/distribution ($\eta = 97\%$)
  - > 2010: Automotive systems 5.0 kW/kg
  - > 2015 8.0 kW/kg
## Energy Conversion weight factors; $\theta$ (power density)

<table>
<thead>
<tr>
<th>Type</th>
<th>$\eta$ (%)</th>
<th>$\theta$ (power density)</th>
<th>Power (kW)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal Combustion Engine</strong> ($\eta = 30%$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Continental IO-550 (300 HP)</td>
<td>30</td>
<td>1.0 kW/kg</td>
<td>224 kW</td>
<td>227 kg</td>
</tr>
<tr>
<td>- Rotax 912S (100HP)</td>
<td></td>
<td>0.984 kW/kg</td>
<td>&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.10 kW/kg</td>
<td>&gt;</td>
<td></td>
</tr>
<tr>
<td><strong>Electric Motors</strong> ($\eta = 95%$)</td>
<td>95</td>
<td>3.4 kW/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Tesla Automobile (244 HP)</td>
<td></td>
<td>3.49 kW/kg</td>
<td>182 kW</td>
<td>52.2 kg</td>
</tr>
<tr>
<td>- Honda FCX (134 HP)</td>
<td></td>
<td>2.96 kW/kg</td>
<td>&gt;</td>
<td></td>
</tr>
<tr>
<td><strong>Gas Turbine</strong> ($\eta = 34%$)</td>
<td>34</td>
<td>5.1 kW/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- P&amp;W PT6A (1500 HP)</td>
<td></td>
<td></td>
<td>1125 kW</td>
<td>220 kg</td>
</tr>
</tbody>
</table>
Light Utility Aircraft
Power-systems weight comparison

1600 kg ~ 3525 lb GTOW
315 km/hr ~ 170 knts
225 kW ~ 300 HP
4.75 hr

GTOW

3564 kg
Light Primary Trainer
Power-systems weight comparison

GTOW

500 kg ~ 1100 lb
160 km/hr ~ 85 knts
50 kW ~ 67 HP
1.5 hr

Electrical Power Systems Weight (kg)

- Motor
- Power Mgmt
- Fuel-cell
- Battery
- Tank
- Fuel

Electric power-systems performance targets to match a piston engine Light Utility GA Aircraft

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Piston Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PEM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency; $\eta$</td>
<td>50%</td>
<td>60%</td>
</tr>
<tr>
<td>Power density; $\theta$</td>
<td>0.9 kW/kg</td>
<td>2.5 kW/kg</td>
</tr>
<tr>
<td>Battery energy density; $\gamma$</td>
<td>0.25 kW*hr/kg</td>
<td>0.75 kW*hr/kg</td>
</tr>
<tr>
<td>Fuel/Tank weight ratio; $\rho$</td>
<td>0.06</td>
<td>0.20</td>
</tr>
<tr>
<td><strong>SOFC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency; $\eta$</td>
<td>50%</td>
<td>65%</td>
</tr>
<tr>
<td>Power density; $\theta$</td>
<td>0.25 kW/kg</td>
<td>0.90 kW/kg</td>
</tr>
<tr>
<td>Battery energy density; $\gamma$</td>
<td>0.25 kW*hr/kg</td>
<td>0.75 kW*hr/kg</td>
</tr>
<tr>
<td><strong>Pure Battery</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery energy density; $\gamma$</td>
<td>0.25 kW*hr/kg</td>
<td>2.35 kW*hr/kg</td>
</tr>
</tbody>
</table>
Available electric motor and power-management systems are adequate, however significant technology challenges remain in the development of batteries, fuel-cells, and light weight H₂ tanks.

Battery powered aircraft will require a 10X energy density increase to match Light Utility GA piston performance, but looks like a viable option for Light Primary Trainer aircraft in the near future.

Several potentially viable approaches exist for electric propulsion-systems and targets for component performance have been identified, but significant development work remains before the best solution is known.

The rate Electric Aircraft Propulsion technologies are advancing is encouraging and holds the promise of new more capable aircraft in the near future.