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
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
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
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

- **DOE 2015 Goal**
  - 3 kW·h/kg

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

- **Liquid/Cryogenic H₂ (with container)**

- **Complex hydrides**

- **Microspheres**

- **Nanotubes**

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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
  - PM/D
    - Elect - Elect
  - Electric Motor
    - Elect - Mech
- Fuel-cell (PEM)
  - Chem - Elect
  - PM/D
    - Elect - Elect
  - Electric Motor
    - Elect - Mech
- Reforming
  - C\textsubscript{n}H\textsubscript{2(n+1)} -> H\textsubscript{2}

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

$$E_R = \sum_{n}^{m} (P_n)(t_n)$$

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>Mission</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 ($H_2$) 33.5 kW*hr/kg
  - Kerosene ($C_{12}H_{26}$) 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**
  - Liquid HC 10.0
  - $H_2$(gas) (2010) 0.06
  - $H_2$(gas) (2015) 0.10
Chemical and Electrical Energy Conversion
Typical and Projected Performance Parameters

Energy Conversion weight factors; θ (power density)

• Fuel-cells (η = 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 (η = 97%)
  > 2010: Automotive systems 5.0 kW/kg
  > 2015 8.0 kW/kg
Mechanical Energy Conversion
Typical Performance Parameters

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

- **Internal Combustion Engine ($\eta = 30\%$)**
  - **Continental IO-550 (300 HP)**
    - Power = 224 kW
    - Weight = 227 kg
    - $\theta = 1.0$ kW/kg
  - **Rotax 912S (100HP)**
    - Power = 74.6 kW
    - Weight = 68 kg
    - $\theta = 1.10$ kW/kg

- **Electric Motors ($\eta = 95\%$)**
  - **Tesla Automobile (244 HP)**
    - Power = 182 kW
    - Weight = 52.2 kg
    - $\theta = 3.49$ kW/kg
  - **Honda FCX (134 HP)**
    - Power = 100 kW
    - Weight = 33.8 kg
    - $\theta = 2.96$ kW/kg

- **Gas Turbine ($\eta = 34\%$)**
  - **P&W PT6A (1500 HP)**
    - Power = 1125 kW
    - Weight = 220 kg
    - $\theta = 5.1$ kW/kg
Light Utility Aircraft
Power-systems weight comparison

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

3564 kg

Electrical Power Systems Weight (kg)

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

Light Primary Trainer
Power-systems weight comparison

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

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

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

<table>
<thead>
<tr>
<th>System</th>
<th>Current Efficiency</th>
<th>Current Power density</th>
<th>Current Battery energy density</th>
<th>Current Fuel/Tank weight ratio</th>
<th>Piston Equivalent Efficiency</th>
<th>Piston Equivalent Power density</th>
<th>Piston Equivalent Battery energy density</th>
<th>Piston Equivalent Fuel/Tank weight ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEM</td>
<td>50%</td>
<td>0.9 kW/kg</td>
<td>0.25 kW*hr/kg</td>
<td>0.06</td>
<td>60%</td>
<td>2.5 kW/kg</td>
<td>0.75 kW*hr/kg</td>
<td>0.20</td>
</tr>
<tr>
<td>SOFC</td>
<td>50%</td>
<td>0.25 kW/kg</td>
<td>0.25 kW*hr/kg</td>
<td>0.06</td>
<td>65%</td>
<td>0.90 kW/kg</td>
<td>0.75 kW*hr/kg</td>
<td>0.20</td>
</tr>
<tr>
<td>Pure Battery</td>
<td></td>
<td></td>
<td>0.25 kW*hr/kg</td>
<td></td>
<td></td>
<td>2.35 kW*hr/kg</td>
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Summary

• 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.