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.
Battery Energy Storage

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

Specific Energy (kW•h/kg)

Specific Density (kW•h/m$^3$)

- Li-S ~300 - ? cycles
- Li-ion ~100-15,000 cycles
- Ni-H$_2$ 50,000 cycles

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

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Extensive Research Underway on Solid State Hydrogen Storage

Volumetric Density (kg/m³)

Gravimetric Density (% weight Hydrogen)

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

Gravimetric Density (% weight Hydrogen)

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

DOE 2010 Goal
2 kW•h/kg

DOE 2015 Goal
3 kW•h/kg

Low Temp Hydrides

Compressed H₂ (with container)

Liquid/Cryogenic H₂ (with container)

Complex hydrides

Microspheres

Nanotubes
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
  - Elect - Mech
- Electric Motor

Chemical-to-Electrical Conversion:
- IC Engine: $C_nH_{2(n+1)} \rightarrow H_2$
- Fuel-cell (SOFC): $\text{Chem} \rightarrow \text{Elect}$
- PM/D: Elect - Elect
- Electric Motor: Elect - Mech

Electrical-to-Mechanical Conversion:
- Electric Motor: Elect - Mech

Systems boundary

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, $H_2$, 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>Aircraft Type</th>
<th>$E_R$</th>
<th>$P_{max}$</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\(\text{hr/kg} \)
  - Kerosene (C\(_{12}\)H\(_{26}\)): 14.3 kW\(\text{hr/kg} \)

- Batteries (\( \eta = .98 \))
  - Li-S (2010): 0.25 kW\(\text{hr/kg} \)
  - Li-ion/Li-S (2015): 0.65 kW\(\text{hr/kg} \)

- Tanks
  - Fuel/Tank wt ratio
    - 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; $\theta$ (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
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
  - **Rotax 912S (100HP)**
    > Power = 74.6 kW
    > Weight = 68 kg

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

- **Gas Turbine ($\eta = 34\%$)**
  - **P&W PT6A (1500 HP)**
    > Power = 1125 kW
    > Weight = 220 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

GTOW 3564 kg

Motor
Power Mgmt
Fuel-cell
Battery
Tank
Fuel

Electrical Power Systems Weight (kg)

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

Electrical Power Systems Weight (kg)


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

<table>
<thead>
<tr>
<th>Technology</th>
<th>Current Efficiency; $\eta$</th>
<th>Current Power density; $\theta$</th>
<th>Current Battery energy density; $\gamma$</th>
<th>Current Fuel/Tank weight ratio; $\rho$</th>
<th>Piston Equivalent Efficiency; $\eta$</th>
<th>Piston Equivalent Power density; $\theta$</th>
<th>Piston Equivalent Battery energy density; $\gamma$</th>
<th>Piston Equivalent Fuel/Tank weight ratio; $\rho$</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></td>
<td>65%</td>
<td>0.90 kW/kg</td>
<td>0.75 kW*hr/kg</td>
<td></td>
</tr>
<tr>
<td>Pure Battery</td>
<td>0.25 kW*hr/kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.35 kW*hr/kg</td>
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</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.