All Electric Aircraft (AEA) Mid-Air Recharging via Wireless Power Transfer: Battery Requirement Study

Shu Ting Goh, Research Fellow, ECE, NUS
S. A. (Reza) Zekavat, Professor, ECE, MTU (Visiting Prof. WPI)
Introduction

Aviation challenges:
- Lower CO2 emissions
- Lower engine noise

Two solutions:
1. More electric aircraft
   - Technology Available;
   - Jet fuel remains the source of power for take off and some for cruising;
   - e.g., Airbus/Rolls-Royce eJet application program
2. All electric aircraft
   - Fully electrical power
   - Require further development

Focus
Challenge – Flight Duration

- Dornier 328 with 3600kg of 720 Wh/kg battery
  - Flight range of 1455 km: Cannot Carry passengers
  - Typical range with Jet Fuel – 1852 km Can carry Passengers
- Shorter range (or 20% less)
- How to extend the range of all electric aircraft?
  - Higher battery energy capacity
  - Battery recharging in mid-air (or mid-air recharging, MAR)
  - Or both
Challenge – Battery Recharging

- **Inductive Power Transfer (Less than 20cm Range)**
  - Widely used application
  - High efficiency can be achieved
  - Efficiency significant drops w.r.t. charging range
  - Static power transfer only

- **Microwave Power Transfer**
  - Efficiency reduces with transmission distance
  - Efficiency improves via high gain/aperture antenna
  - Beamforming technology allows transmit energy to moving object (dynamic wireless power transfer)

- **For AEA application**
  - Inductive Power Transfer from runway
  - Microwave Power Transfer for mid-air recharging

Image credit:
Objective

- Study battery requirement of AEA application for long flight duration (e.g., duration > 4 hours)

**Energy storage**
- What type of battery is suitable for AEA?
- What is the weight requirement?
- Possible to reduce total weight?

**Mid-air Recharging (MAR)**
- Method of MAR – inductive or microwave?
- From ground or from space?
- MAR duration – always or periodic?
Battery Energy Capacity Comparison

<table>
<thead>
<tr>
<th>Type</th>
<th>Specific Energy (Wh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Theory</td>
</tr>
<tr>
<td>Li-ion</td>
<td>387</td>
</tr>
<tr>
<td>Li-S</td>
<td>2567</td>
</tr>
<tr>
<td>Li-O2</td>
<td>3582</td>
</tr>
<tr>
<td>Jet Fuel A1</td>
<td></td>
</tr>
</tbody>
</table>

Predict: About 70% of Ideal

- Assume 70% of ideal specific energy can be achieved in future (predict).
- Lithium-ion (Li-ion, used in B787) has very low energy capacity compared to Jet Fuel A1
- Lithium Sulfur (Li-S) and Lithium-air (Li-O2) are visible candidates
  - Technology maturity is required
  - In general should be combined with Mid Air Recharging (MAR)
Objective

- Study battery requirement of AEA application for long flight duration (e.g., > 4 hours)
- Energy storage
  - What type of battery is suitable for AEA?
  - What is the weight requirement?
  - Possible to reduce total weight?
- Mid-air Recharging (MAR)
  - Method of MAR – inductive or microwave?
  - From ground or from space?
  - MAR duration – always or periodic?
Battery is charged via Inductive Method from runway
MAR for All-Electric-Aircraft

No battery recharging during take-off and initial climbing phase
MAR for All-Electric-Aircraft

- Battery is charged via MAR from LEO SSP satellite once the AEA reaches certain altitude.
- MAR may not available at all time.
MAR for All-Electric-Aircraft

- MAR continues during descend phase
- MAR will be terminated once AEA reach a certain altitude
MAR for All-Electric-Aircraft

Battery is charged via Inductive Method from runway
- LEO SSP satellites may not provide full coverage (lower implementation cost)
- MAR may not be available when AEA is not within any LEO SSP satellite coverage
  - Assume fixed cycle period in this study
  - MAR unavailable for X minutes at every Y minutes interval
Purpose:
- Accumulated energy required for taxi, take-off, cruise and landing
- Maximum depth of discharge for each battery type
- Feasibility of long range AEA with MAR technology

Battery type
- Li-ion, Li-S and Li-O2

Battery mass
- Equivalent fuel mass of A320neo, A330-900 (A339) and B777-200LR (B77L)
Requirement Study

- Case studies:
- Energy Requirement
  - Aggregated Required Energy for taxi, and take-off to cruise altitude
  - Aggregated Required Energy for descend, landing and taxi to gate
- Battery requirement with wireless power transfer (WPT)
  - MAR is always available
  - MAR is partially available
Energy Requirement

- Aggregated Required Energy at time period $k$, $P_k$ is

$$P_k = P_{k-1} + \hat{f}_{\text{fuel}} c_{A1} \Delta t_k$$

Fuel flow rate

Jet fuel A1 specific energy (11.9 kWh/kg)

Fuel Flow Rate of each aircraft type in each phase (fuel mass per sec.)

<table>
<thead>
<tr>
<th>Phase</th>
<th>A320neo</th>
<th>A330-900 (A339)</th>
<th>B777-200LR (B77L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max fuel capacity</td>
<td>21450 kg</td>
<td>109185 kg</td>
<td>145538 kg</td>
</tr>
<tr>
<td>Engine type</td>
<td>CFM LEAP-1A26</td>
<td>RR Trent 7000</td>
<td>GE90-115B</td>
</tr>
<tr>
<td>Taxi</td>
<td>0.176 kg/s</td>
<td>0.482 kg/s</td>
<td>0.760 kg/s</td>
</tr>
<tr>
<td>Take-off</td>
<td>1.710 kg/s</td>
<td>4.940 kg/s</td>
<td>9.380 kg/s</td>
</tr>
<tr>
<td>Climb Phase 1 Until 15000 ft</td>
<td>1.560 kg/s</td>
<td>4.449 kg/s</td>
<td>8.360 kg/s</td>
</tr>
<tr>
<td>Climb Phase 2 Until 37000 ft</td>
<td>1.410 kg/s</td>
<td>4.058 kg/s</td>
<td>7.340 kg/s</td>
</tr>
<tr>
<td>Cruise</td>
<td>0.726 kg/s</td>
<td>2.010 kg/s</td>
<td>2.226 kg/s</td>
</tr>
<tr>
<td>Approach</td>
<td>0.484 kg/s</td>
<td>1.340 kg/s</td>
<td>2.260 kg/s</td>
</tr>
<tr>
<td>Landing</td>
<td>1.454 kg/s</td>
<td>4.199 kg/s</td>
<td>7.973 kg/s</td>
</tr>
</tbody>
</table>
Take-off and climbing to cruise altitude requires much higher energy
- At least 4 times higher than landing process
- Battery available capacity could significantly drop for AEA
Case studies:

Energy Requirement

- Aggregated Required Energy for taxi, and take-off to cruise altitude
- Aggregated Required Energy for descend, landing and taxi to gate

Battery requirement with wireless power transfer (WPT)

- MAR is always available
- MAR is partially available
Battery requirement Case Study Assumptions

- Inductive power supply via IPT (Inductive Power Transfer)
  - Charging power at $K_{MAR} = 8 \text{ MWh}$ for Taxi to take-off and Taxi to gate

- Microwave power supply via MAR
  - Charging power at $K_{MAR} = 337.5 \text{ MWh}$ during Climb phase 2
  - Charging power at $K_{MAR} = 450 \text{ MWh}$ during Cruise and Approach

\[ \Delta t_k \text{ in } P_k = P_{k-1} + \dot{f}_{fuel} c_{A1} \Delta t_k \]

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Aircraft Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A320neo</td>
</tr>
<tr>
<td>Taxi to take-off (sec)</td>
<td>1560</td>
</tr>
<tr>
<td>Take-off (sec)</td>
<td>30</td>
</tr>
<tr>
<td>Climb phase 1 (sec) till 15000 ft</td>
<td>420</td>
</tr>
<tr>
<td>Climb phase 2 (sec) till 37000 ft</td>
<td>1166</td>
</tr>
<tr>
<td>Cruise (sec)</td>
<td>23400</td>
</tr>
<tr>
<td>Approach (sec)</td>
<td>240</td>
</tr>
<tr>
<td>Landing (sec)</td>
<td>30</td>
</tr>
<tr>
<td>Taxi to gate (sec)</td>
<td>1560</td>
</tr>
</tbody>
</table>
Case 1: MAR Always Available

Evaluate battery performance in terms of State-of-charge (SOC):

\[ \text{SOC} = \frac{c_k}{c_{\text{max}}} \times 100\% \]

Max battery capacity \(c_{\text{max}} = q \times m\)

Battery capacity, \(c_k\) is

\[ c_k = c_{k-1} - \left( f_{\text{fuel}} c_{A1} \frac{\beta k_{\text{MAR}}}{3600} \right) \Delta t \]

Assumptions:
- MAR is always available
- Battery mass is equal to maximum fuel capacity
- Battery charging efficiency at 90%
- Li-ion with predicted specific energy of 271 Wh/kg

Findings:
- Depth of discharge during take off exceeds 100%
- Conclusion, Li-ion is not suitable for AEA application
- Higher battery specific energy is needed
Case 1: MAR Always Available

Assumptions:
- MAR always available
- Equivalent mass to maximum fuel capacity
- Battery charging efficiency at 90%
- Li-S with predicted specific energy of 1791 Wh/kg
- Li-O2 with predicted specific energy of 2507 Wh/kg

Findings:
- Maximum depth of discharge is 25% or less
- Both Li-S and Li-O2 are suitable candidates for AEA

BETTER OPTION Because its $C_{max}$ is higher
Case studies:

Energy Requirement

- Accumulated energy required for taxi, and take-off to cruise altitude
- Accumulated energy required for descend, landing and taxi to gate

Battery requirement with wireless power transfer (WPT)

- MAR is always available
- MAR is partially available
Case 2: MAR Partially Available – 15 minutes of MAR outage for every 60 minutes

**Assumptions:**
- MAR is unavailable for 15 minutes, for every 60 minutes of MAR availability
- **Battery mass is equal to 75% of max fuel capacity**
- Battery charging efficiency at 90%
- Li-S with predicted specific energy of 1791 Wh/kg
- Li-O2 with predicted specific energy of 2507 Wh/kg

**Findings:**
- Maximum depth of discharge is 25% or lesser
- Both Li-S and Li-O2 are suitable candidates for AEA
Case 3: MAR Partially Available – 20 minutes of MAR outage for every 45 minutes

Assumptions:
• MAR is unavailable for 20 minutes, for every 45 minutes of MAR availability
• Battery mass is equal to 50% of max fuel capacity
• Battery charging efficiency at 90%
• Li-S with predicted specific energy of 1791 Wh/kg
• Li-O2 with predicted specific energy of 2507 Wh/kg

Findings:
• Maximum depth of discharge is 80%+ for Li-S
• Maximum depth of discharge is 60%+ for Li-O2
• Li-O2 is a better candidate for much lesser LEO SSP constellation coverage
High capacity batteries are the key technology for all-electric aircraft application
  ◦ Lithium-Sulphur, Lithium-Air

Mid-air recharging strategy is required for long flight duration
  ◦ MAR begins at climb phase 2
  ◦ Partial MAR coverage by LEO SSP satellite

Possible to reduce total batteries weight
  ◦ Up to 50% if use Lithium-Air
Future Work

- Optimal Design of the Orbit:
  - Launch Cost;
  - Weight Constraint (Power Amount to Airplane, Antenna Size);
  - Path Loss;
  - Antenna Size;

- Localization accuracy requirement of AEA

- Satellite pointing accuracy requirement
  - For microwave power beam steering to AEA rectenna
Thank you

Question?

rezaz@mtu.edu
rezaz@wpi.edu
Appendix: MAR WPT energy selection

Lithium-Sulfur Battery Scenario

Case 2

Maintain maximum battery discharge < 50%
➢ Require at least 350MWh of MAR WPT
➢ 450MWh is considered after includes margin
➢ Lower depth of discharge % is better
Appendix: MAR WPT energy selection

Lithium-Air Battery Scenario

Maintain maximum battery discharge < 50%
- Require at least 350MWh of MAR WPT
- 400MWh or higher is considered after includes margin
  - 450MWh is chosen for consistency with Li-S study
- Lower depth of discharge % is better