Preliminary Design of the Superconducting Rotor for NASA’s High-Efficiency Megawatt Motor

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Motivation

- Reduced energy consumption, emissions, and noise of commercial transport aircraft [1]
  - Electrified aircraft propulsion (EAP) enables system-level benefits to these metrics
- EAP concepts require advances to electric machines
- NASA’s High-Efficiency Megawatt Motor (HEMM) sized as generator for NASA’s STARC-ABL concept

<table>
<thead>
<tr>
<th>Electric machines</th>
<th>Current design</th>
<th>With HEMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific power, kW/kg</td>
<td>13.2</td>
<td>16</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>96</td>
<td>98 to 99</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance relative to STARC-ABL rev A</th>
<th>With HEMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel burn, %</td>
<td>–1 to –2</td>
</tr>
<tr>
<td>Waste heat in generator</td>
<td>$\frac{1}{2}$ to $\frac{1}{4}$ ($–30$ to $–44$ kW)</td>
</tr>
</tbody>
</table>
NASA’s High-Efficiency Megawatt Motor (HEMM)

- Sized for generator of NASA’s STARC-ABL concept
- Wound-field synchronous machine
  - Tolerant of stator fault
- Superconducting rotor
  - Negligible energy loss
  - Very strong magnetic excitation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated continuous power</td>
<td>1.4 MW</td>
</tr>
<tr>
<td>Nominal speed</td>
<td>6,800 rpm</td>
</tr>
<tr>
<td>Tip speed</td>
<td>Mach 0.31</td>
</tr>
<tr>
<td>Rated torque</td>
<td>2 kNm</td>
</tr>
<tr>
<td>Specific power goal</td>
<td>16 kW/kg</td>
</tr>
<tr>
<td>Efficiency goal</td>
<td>&gt;98 %</td>
</tr>
</tbody>
</table>
Outline

This talk

- Complete preliminary design package for rotor
  - Electromagnetic design & optimization
  - Rotor containment design & stress analysis

Talk 2 (Scheidler & Tallerico, 2018 EATS)

- Overview of current rotor design
- Fabrication & testing of sub-scale superconducting rotor coils
Outline

• Electromagnetic design & optimization
  • Thermal requirements
  • Optimization of rotor coil’s geometry
  • Optimization of back iron geometry
• Rotor containment design & stress analysis
• Conclusions
Superconductor selection & form factor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical frequency</td>
<td>DC</td>
</tr>
<tr>
<td>Number of poles</td>
<td>12</td>
</tr>
<tr>
<td>Stator configuration</td>
<td>Slotless</td>
</tr>
<tr>
<td>Rotor outer diameter</td>
<td>30 cm</td>
</tr>
<tr>
<td>Air gap</td>
<td>4 cm</td>
</tr>
<tr>
<td>Axial length</td>
<td>12.5 cm</td>
</tr>
</tbody>
</table>

- **2\textsuperscript{nd} generation high temperature superconductor (REBCO) selected**
  - Commercially available in long piece length
  - Sufficient performance at “high” temperatures in moderately strong magnetic environments

- REBCO is a composite conductor in the form of Cu-coated thin tape
- **No-insulation (NI) coils selected** [9-11]
  - Fault tolerant
  - Higher engineering current density
  - Higher mechanical strength

Self protection via no turn-to-turn insulation

Current path

Non-superconducting (“normal”) region
Superconductor current & thermal limits

- Critical current \((I_C) = I_C(T, B, \theta)\)
  - Datasheet values \(\theta = 0^\circ\) and \(90^\circ\) are insufficient
  - Datasheet specs de-rated twice: angular dependence & safety factor

\[\text{Safety factor} \pm 20\% \text{ Estimate of wire variation} + \pm 15\% \text{ Modeling inaccuracy} \pm 35\% \approx 1.5 \text{ safety factor}\]
Superconductor current & thermal limits

- Measurements at our operating condition obtained from manufacturer

<table>
<thead>
<tr>
<th>Temperature</th>
<th>High performance tape (191 A @ ~0 T)</th>
<th>Standard tape (150 A @ ~0 T), calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nominal $I_c$, A</td>
<td>min[$I_c(\theta)$], A</td>
</tr>
<tr>
<td></td>
<td>min[$I_c(\theta)$], A</td>
<td></td>
</tr>
<tr>
<td>50 K</td>
<td>249.4</td>
<td>x</td>
</tr>
<tr>
<td>65 K</td>
<td>127.1</td>
<td>x</td>
</tr>
<tr>
<td>77 K</td>
<td>28.9</td>
<td>x</td>
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<td>28.9</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Design spec
current 51.5 A
temperature $\leq 62.8$ K

Approx. max temp, K

Valid operating regime

4 mm wide tape @ 2 T
$I_c$(sf,77K) = 150 A

X: 51.51
Y: 62.76

scaled data
- cubic fit
- fit + 1.5 safety factor
Optimization of rotor coil’s geometry

- Optimized coil’s geometry for a given iron thickness & width by numerically maximizing # of turns
  - Rectangular coil cross section
  - Also outputs total length & cost of conductor, mass of iron+coil
  - 4 mm is optimal width of superconductor

![Diagram showing optimization process]

- Soft magnetic material (back iron)
- Region available for containment structure & clearances
Optimization of rotor coil’s geometry

**Optimal # of turns**

**Magnetomotive force per mass**

**Superconductor length per coil**

**Total cost**
Optimization of back iron geometry

- Custom extrapolation derived for Hiperco 50A’s $B$ vs $H$ response
- Mesh refinement study completed
- Results consistent with 2D MotorSolve

<table>
<thead>
<tr>
<th></th>
<th>MotorSolve</th>
<th>COMSOL</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current, A</td>
<td>75</td>
<td>75</td>
<td>-</td>
</tr>
<tr>
<td>A-Turns in coil</td>
<td>37500</td>
<td>37500</td>
<td>-</td>
</tr>
<tr>
<td>Avg. radial flux density</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor surface, T</td>
<td>1.999</td>
<td>1.9729</td>
<td>1.31%</td>
</tr>
<tr>
<td>Stator surface, T</td>
<td>0.9028</td>
<td>0.8620</td>
<td>4.62%</td>
</tr>
<tr>
<td>Max. flux density, T</td>
<td>4.14</td>
<td>4.04</td>
<td>2.44%</td>
</tr>
</tbody>
</table>

Data from manufacturer

$$M = \frac{B}{\mu_0} - H$$

Curve fit, extrapolate

$$B = \mu_0 (H + M)$$

Calculate from extrapolation
Optimization of back iron geometry – 2D FEA

- Parametric study of iron and coil geometry
- COMSOL electromagnetic simulation
  - 2D and 3D
  - Nonlinear, static
  - No stator current
Optimization of back iron geometry – 2D FEA

- Trends nearly mirror coil’s A-turns
- Minimize rotor iron width & thickness (maximize A-Turns)
  - Diminishing returns due to magnetic saturation
- Constrained by max $B$ in coil
- Performance & performance per mass have opposite trends than performance per cost
Optimization of back iron geometry – 3D FEA

Max. flux density in rotor coil

Avg. radial flux density at stator

Rotor iron thickness, cm

Rotor iron width, cm

Iron thickness, cm

Iron width, cm

Optimal # turns

3D parametric study points

Max. flux density in rotor coil

Avg. radial flux density at stator

Rotor iron thickness, cm

Rotor iron width, cm

Iron thickness, cm

Iron width, cm

Optimal # turns

3D parametric study points
Optimization of back iron geometry – 3D FEA

- Preliminary design
  - Max rotor temp. = 62.8 K
  - HTS tape = 4 mm x 65 micron
  - Rotor thickness = ~2.6 cm
  - Rotor tooth width = ~3.3 cm
- Length of HTS wire needed
  - Each coil: ~250 m
  - Total wire length: 3150 m
- Estimated total cost of HTS wire
  - $200K = 3150 m * $60/m
    + 5% margin

<table>
<thead>
<tr>
<th></th>
<th>v1 design</th>
<th>v2 (preliminary) design</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current A</td>
<td>75 A</td>
<td>51.5 A</td>
<td>−31%</td>
</tr>
<tr>
<td>Temperature K</td>
<td>60 K</td>
<td>62.8 K</td>
<td>+5%</td>
</tr>
<tr>
<td>Magnetic Field @ gap</td>
<td>0.94 T</td>
<td>0.96 T</td>
<td>+2%</td>
</tr>
<tr>
<td>A-turns/kg</td>
<td>346</td>
<td>738</td>
<td>+113%</td>
</tr>
<tr>
<td>Induction in HTS</td>
<td>2.0 T</td>
<td>1.99 T</td>
<td>0%</td>
</tr>
</tbody>
</table>
Outline

• Electromagnetic design & optimization
  • Thermal requirements
  • Optimization of rotor coil’s geometry
  • Optimization of back iron geometry
• Rotor containment design & stress analysis
• Conclusions
Rotor containment design & stress analysis

- Only centrifugal force considered for preliminary design
  - Neglected forces: thermal, magnetostrictive, electromagnetic
- Rotor \( B \) variation minimal
  - \( \text{magnetostriction} < 6 \times 10^{-6} \text{ m/m} \)
  - Magnetostrictive forces are negligible
- Mechanical contact modeling is critical
Rotor containment design & stress analysis

- Wide range of fixture designs considered

- bolted fixtures
- ‘fir tree’ fixtures
- ‘fir tree’ teeth
Preliminary design – double dovetail rotor teeth

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>back iron</td>
<td>Hipero 50 A</td>
</tr>
<tr>
<td>Sialon (SiN + Al₂O₃)</td>
<td></td>
</tr>
<tr>
<td>SiC</td>
<td></td>
</tr>
<tr>
<td>SupremEx 640XA (Al 6061 + SiC powder)</td>
<td></td>
</tr>
<tr>
<td>Ti-6Al-6V-2Sn</td>
<td></td>
</tr>
</tbody>
</table>

double dovetail

continuous shoulder

heat extraction tab
Assembly of the rotor
## Preliminary design – stress analysis

<table>
<thead>
<tr>
<th>Fixture material</th>
<th>Superconductor</th>
<th></th>
<th></th>
<th>Hiperco 50 A</th>
<th></th>
<th></th>
<th>Fixtures</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>‘Failure’</td>
<td>Max von</td>
<td>Margin</td>
<td>‘Failure’</td>
<td>Max von</td>
<td>Margin</td>
<td>‘Failure’</td>
<td>Max von</td>
<td>Margin</td>
</tr>
<tr>
<td></td>
<td>strength, MPa</td>
<td>Mises stress, MPa</td>
<td></td>
<td>strength, MPa</td>
<td>Mises stress, MPa</td>
<td></td>
<td>strength, MPa</td>
<td>Mises stress, MPa</td>
<td></td>
</tr>
<tr>
<td>SiC</td>
<td>183</td>
<td>2.01</td>
<td></td>
<td>480</td>
<td>0.45</td>
<td></td>
<td>550</td>
<td>462</td>
<td>0.19</td>
</tr>
<tr>
<td>Sialon (SiN + Al2O3)</td>
<td>&gt;550 (approx.)</td>
<td>191</td>
<td>1.88</td>
<td>694 (@ 77 K,</td>
<td>483</td>
<td>0.44</td>
<td>760</td>
<td>391</td>
<td>0.94</td>
</tr>
<tr>
<td>SupremEX 640XA</td>
<td>209</td>
<td>1.63</td>
<td></td>
<td>467</td>
<td>0.49</td>
<td></td>
<td>560</td>
<td>236</td>
<td>1.37</td>
</tr>
<tr>
<td>(Al 6061 + SiC powder)</td>
<td>239</td>
<td>1.30</td>
<td></td>
<td>516</td>
<td>0.34</td>
<td></td>
<td>1210</td>
<td>338</td>
<td>2.58</td>
</tr>
</tbody>
</table>
Outline

• Electromagnetic design & optimization
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  • Optimization of back iron geometry
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Conclusions

- Uninsulated superconducting coils offer significant benefits, but are unproven in rotor applications

Electromagnetic design & optimization

- 2D FEA trends nearly mirror coil’s A-turns until back iron is magnetically saturated
- Performance & performance per mass have opposite trends than performance per cost
- 3D FEA performance ~7% lower than 2D, but max flux density in coil approx. the same

Rotor containment design & stress analysis

- Containment design is very challenging when pole count is relatively high & structure cannot reside in the air gap
- Double dovetail rotor teeth provide satisfactory stress margin, but may not have adequate thermal conductance

Considerable risks remain – further analysis & sub-scale testing is needed
Acknowledgements

- NASA Advanced Air Transport Technology (AATT) Project
- Hybrid Gas-Electric Propulsion Sub-project

References


Preliminary Design of the Superconducting Rotor for NASA's High-Efficiency Megawatt Motor
## Rotor coil sizing study

<table>
<thead>
<tr>
<th>Characteristic/parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconductor width, mm</td>
<td>4</td>
</tr>
<tr>
<td>Superconductor thickness, μm</td>
<td>65</td>
</tr>
<tr>
<td>Min. superconductor bend radius, mm</td>
<td>15</td>
</tr>
<tr>
<td>Max. magnetic flux density in the superconductor, T</td>
<td>2</td>
</tr>
<tr>
<td>Rotor coil gap $g_1$, mm</td>
<td>1.3</td>
</tr>
<tr>
<td>Rotor coil gap $g_2$, mm</td>
<td>1.0</td>
</tr>
<tr>
<td>Rotor coil gap $g_3$, mm</td>
<td>1.3</td>
</tr>
<tr>
<td>Rotor coil gap $g_4$, mm</td>
<td>1.3</td>
</tr>
</tbody>
</table>

- **Soft magnetic material (back iron)**
- **Region available for containment structure and clearances**
Cryogenic yield strength of Fe$_{49}$Co$_{49}$

- [1] measured yield strength of Fe$_{49}$Co$_{49}$V$_2$ (Hiperco 50) at cryo temperatures for different grain sizes
- Yield strength increases by about 90% to 110% going from room temp to 77 K
  - Material is brittle at about 150 K and lower
- Effect of trace elements (Hiperco 50A vs 50 vs 50HS) is small [2]
- Thus, ‘failure’ strength for Hiperco can be increased by 90%

<table>
<thead>
<tr>
<th>Material</th>
<th>Temp., K</th>
<th>‘Failure’ strength, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hiperco 50A</td>
<td>293</td>
<td>365</td>
</tr>
<tr>
<td>after annealing</td>
<td>77</td>
<td>694 (estimate)</td>
</tr>
</tbody>
</table>