Design, Fabrication, and Critical Current Testing of No-Insulation Superconducting Rotor Coils for NASA’s High-Efficiency Megawatt Motor

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Design & Testing of No-Insulation Superconducting Rotor Coils for NASA's HEMM
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>½ to ¼ (-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

Talk 1 (Scheidler, 2018 AIAA P&E)

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

This talk

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

• Rotor & coil design
• Coil fabrication
• Critical current testing
• Conclusions
## Rotor Design

### Design process (see 2018 AIAA P&E paper)
- Defined current & thermal limits
  - Based on manufacturer data & safety factors
- Parametric studies of back iron’s width $w$ and thickness $t$
  (2D & 3D, nonlinear FEA)
  - Optimized coil’s geometry by numerically maximizing # of turns in coil
  - Custom extrapolation of back iron’s $B$ vs $H$ response
- **Metrics:** performance • performance/mass • performance/cost
- Stress analysis of centrifugal loading (2D & 3D FEA)

### Parameter	Value
<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>Material</td>
<td>$\text{Solid Fe}<em>{49.15}\text{Co}</em>{48.75}\text{V}_2$</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>30 cm</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>18.9 to 20 cm</td>
</tr>
<tr>
<td>Axial length</td>
<td>12.5 cm</td>
</tr>
</tbody>
</table>

![Diagram of rotor design](image)

- Soft magnetic material (back iron)
- Region available for containment & clearances

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National Aeronautics and Space Administration

Design & Testing of No-Insulation Superconducting Rotor Coils for NASA's HEMM
Rotor Design

- Dovetail retainer
- Coil fixture
- Ring retainer
- Solid FeCo back iron
- High temperature superconducting coil
Rotor Design
Coil Design

- 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 thin tape
  - AC losses will be negligible
- No-insulation (NI) coils selected [9-11]
  - Fault tolerant
  - Higher \textit{engineering} current density
  - Higher mechanical strength

Self protection via no turn-to-turn insulation

No-insulation superconducting coils are very promising, but have not been studied for rotating systems
## Coil Design

### Coil characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn-to-turn insulation</td>
<td>None</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>62.8 K</td>
</tr>
<tr>
<td>Operating current</td>
<td>51.5 A</td>
</tr>
<tr>
<td># of layers per coil</td>
<td>4</td>
</tr>
<tr>
<td># of turns per layer</td>
<td>~ 230</td>
</tr>
<tr>
<td>Solder</td>
<td>52In 48Sn</td>
</tr>
</tbody>
</table>

### Superconductor characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>REBCO</td>
</tr>
<tr>
<td>Width</td>
<td>4 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>65 micron</td>
</tr>
<tr>
<td>Min. bend radius</td>
<td>15 mm</td>
</tr>
</tbody>
</table>

[Diagram of Coil's cross-section]

- Superconductor
- Separating plate
- Cryogenic epoxy
- Superconducting jumper
- Low melting temperature solder
Risk reduction testing

- Key risks of the superconducting coils
  - **Coils will fail when thermally cycled** due to thermal stresses
  - **Coils will fail when rotor is spun up** due to centrifugal stresses

- Risk reduction tests
  - **Thermal cycling**
    - **Goal**: demonstrate coils that are not degraded by thermal cycling
    - **Approach**: measure superconducting performance • subject to thermal shock • re-measure superconducting performance
    - **Proof**: negligible change in critical current & “n-value”
  - **Rotation** *(future work)*
    - **Goal**: demonstrate coils that are not degraded by high-speed rotation
    - **Approach**: measure superconducting performance • spin coils • re-measure superconducting performance
    - **Proof**: negligible change in critical current & “n-value”
Outline

• Rotor & coil design
• Coil fabrication
• Critical current testing
• Conclusions
Coil Fabrication

- Methodical development approach: simple, sub-scale realistic, full-scale
- 25-turn sub-scale coils
  - Fewer turns & shorter

dimensions in mm
Coil Fabrication

- 3D printed nylon winding fixture
  - Reduced lead time & cost
  - But, limited temperature
- Accurately establishes width of active region & height
- Fixture inverted for epoxy application
Outline

- Rotor & coil design
- Coil fabrication
- Critical current testing
- Conclusions
Critical Current Testing

• Critical current \( I_C = I_C(T, B, \theta) \)
• Coil mounted to G10 plate & suspended in liquid nitrogen
• **Measurements**: voltage & transport current

![Image of critical current testing setup]

- LN\textsubscript{2} dewar
- 6 ½ digit multimeter
- Power supply/amplifier
- Thermocouple signal conditioner
- Data acquisition
Critical Current Testing

- Voltage vs current response commonly described by
  \[ V = V_c \left( \frac{I}{I_c} \right)^n \]
  where the critical voltage \( V_c = \frac{1}{\mu V/cm} \times \text{superconductor length} \)

- "\( n \)-value" indicates combined quality of superconductor & measurement
- Detect damage via changes in \( n \) and/or \( I_c \)

For this example
\[ V_c = 0.36 \, \text{mV} \]
\[ I_c = 75.9 \, \text{A} \]
\[ n = 23.2 \]
Critical Current Testing – 1-layer coils

- Two 1-layer coils tested: $V$ vs $I$ response at 77 K in “self field”
  - Sanity check: measure for increasing & decreasing $I$
  - Thermal cycling tolerance: measure before & after 2 or 4 thermal shock cycles

Coil 1 (2 thermal cycles)

Coil 2 (4 thermal cycles)
## Critical Current Testing – 1-layer coils

<table>
<thead>
<tr>
<th></th>
<th>Coil 1</th>
<th>Coil 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_c$, A</td>
<td>$n$, –</td>
</tr>
<tr>
<td>Before thermal cycling</td>
<td>76.8</td>
<td>19.8</td>
</tr>
<tr>
<td>After thermal cycling</td>
<td>76.9</td>
<td>19.7</td>
</tr>
</tbody>
</table>

- Averaged results for increasing & decreasing $I$
- **Coil 1** (2 thermal cycles)
  - No detectable damage
- **Coil 2** (4 thermal cycles)
  - $I_c$ increased by 1%, but $n$ decreased by 9%
  - Inconclusive, but at worst only minor degradation of $n$
Critical Current Testing – 2-layer coils

- **2-layer coil requires superconducting joint** → solder introduces finite resistance
- After subtracting the linear trend, results analyzed as before
- **Coil 3 broke while attempting to demonstrate self-protection feature**
  - Damage occurred only in unprotected current lead

![Graph showing voltage vs. current for 2-layer coils](image)

![Image of damaged coil 3](image)

Coil 3

Coil 3
Critical Current Testing – 2-layer coils

Coil 4

- Current lead damaged during coil fabrication
  - $I_c$ reduced and $n$-value significantly reduced
  - $I_c$ increased by 3%, but $n$ decreased by 13%
  - Inconclusive, but at worst only modest degradation of $n$

<table>
<thead>
<tr>
<th></th>
<th>$I_c$, A</th>
<th>$n$, –</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before thermal cycling</td>
<td>57.4</td>
<td>5.4</td>
</tr>
<tr>
<td>After 2 thermal cycles</td>
<td>58.3</td>
<td>4.7</td>
</tr>
<tr>
<td>After 6 thermal cycles</td>
<td>59.0</td>
<td>4.7</td>
</tr>
</tbody>
</table>

![Image of coil 4 with damaged lead]
Outline

• Rotor & coil design
• Coil fabrication
• Critical current testing
• Conclusions
Conclusions

• Discussed the design of the superconducting rotor of NASA’s 1.4 MW High Efficiency Megawatt Machine (HEMM)
  • Uninsulated superconducting coils selected to provide fault tolerance and significantly higher engineering current density
  • 2 key risks: resilience to thermal cycling and rotation
• 3D printed winding fixtures work well & allow short lead time
  • But, they prevent the use of some solders while the coil is fixture
• Initial thermal cycling measurements of 1-layer and 2-layer uninsulated coils
  • Tested up to $1.15I_c$ • 2 to 6 thermal shock cycles
  • After thermal cycling, $I_c$ increased but $n$-value decreased
    • Results inconclusive, but suggest little to no degradation
Acknowledgements

- Samuel Chung (summer intern)
- NASA Advanced Air Transport Technology (AATT) Project

References


Superconductor current & thermal limits

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

\[ \text{Safety factor} \]

\[ \pm 20\% \] Estimate of wire variation

\[ + \pm 15\% \] Modeling inaccuracy

\[ \pm 35\% \] (≈1.5 safety factor)
Superconductor current & thermal limits

- Measurements at $B = 2 \text{ T}$ obtained from manufacturer

Design spec
current 51.5 A
temperature $\leq 62.8 \text{ K}$

Valid operating regime
Optimization of rotor coil’s geometry

- Optimized coil’s geometry for 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
Preliminary design – double dovetail rotor teeth

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>back iron</td>
<td>Hiperco 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**: This refers to the tooth configuration that allows for continuous heat extraction.
- **Continuous shoulder**: This is a feature that ensures smooth heat flow between teeth.
- **Heat extraction tab**: This is a design element that facilitates the removal of heat from the rotor.
### Critical Current Testing – 1 layer coils

<table>
<thead>
<tr>
<th>Test</th>
<th>Coil 1</th>
<th></th>
<th>Coil 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_c$, A</td>
<td>$n$, –</td>
<td>$I_c$, A</td>
<td>$n$, –</td>
</tr>
<tr>
<td><strong>Before thermal cycling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I$ increasing</td>
<td>76.9</td>
<td>18.5</td>
<td>75.8</td>
<td>24.6</td>
</tr>
<tr>
<td>$I$ decreasing</td>
<td>76.6</td>
<td>21.0</td>
<td>75.9</td>
<td>23.2</td>
</tr>
<tr>
<td><strong>After thermal cycling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I$ increasing</td>
<td>76.8</td>
<td>19.7</td>
<td>76.2</td>
<td>21.6</td>
</tr>
<tr>
<td>$I$ decreasing</td>
<td>76.9</td>
<td>19.7</td>
<td>76.3</td>
<td>21.8</td>
</tr>
</tbody>
</table>