Progress Toward the Critical Design of the Superconducting Rotor for NASA’s 1.4 MW High Efficiency Electric Machine

Dr. Justin Scheidler
Thomas Tallerico
NASA Glenn Research Center
Materials & Structures Division
Rotating & Drive Systems Branch

Wesley Miller
Vantage Partners

William Torres
Wolf Creek Federal Services

2019 AIAA/IEEE Electric Aircraft Technologies Symposium
Indianapolis, IN
August 24, 2019
Outline

• Motivation & background

• Summary of the rotor & coil design

• Refined finite element analysis
  • Coil model
  • Combined thermal, centrifugal, & electromagnetic loading

• Risk reduction testing
  • Coil fabrication
  • Thermal cycling testing

• Conclusions & future work
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

Performance impact of HEMM

(relative to STARC-ABL rev A: 96% elec. machines with 13.2 kW/kg)

<table>
<thead>
<tr>
<th></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</td>
</tr>
<tr>
<td></td>
<td>(–30 to –44 kW)</td>
</tr>
</tbody>
</table>

Refined analysis of baseline STARC-ABL (96% elec. machines with 13.2 kW/kg):
STARC-ABL uses 4% less fuel than future vehicle with assumed technology advancement
NASA’s High-Efficiency Megawatt Motor (HEMM)

<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>

- Wound-field synchronous machine
  - Tolerant of stator fault
- Superconducting rotor
  - Negligible energy loss
  - Very strong magnetic excitation

Copper stator (> 60 ºC)
Superconducting rotor coils & core (~ 60 K)
Rotating cryocooler
Rotating shaft
Slip ring
Housing
Outline

• Motivation & background

• Summary of the rotor & coil design

• Refined finite element analysis

• Risk reduction testing

• Conclusions & future work
Rotor Design

Dovetail retainer

Coil fixture

High temperature superconducting coil

Ring retainer

Solid FeCo back iron
Rotor Design
## Coils Design

### Coil characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature</td>
<td>&lt; 62.8 K</td>
</tr>
<tr>
<td>Operating current (DC)</td>
<td>51.5 A</td>
</tr>
<tr>
<td># of turns</td>
<td>~ 920</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>
Coil Design

- High temperature superconductor (ribbon-shaped)
- No electrical insulation between turns of conductor
  - Benefits:
    - Fault tolerant – Inherent protection from loss of superconductivity
    - Can fit more turns into same cross section
    - Higher mechanical strength
  - Requirement:
    - Sufficient contact between turns everywhere (for current transfer and heat transfer)

Self protection via no turn-to-turn insulation

Current path

Non-superconducting ("normal") region

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

• Motivation & background

• Summary of the rotor & coil design

• Refined finite element analysis
  • Coil model
    • Combined thermal, centrifugal, & electromagnetic loading

• Risk reduction testing

• Conclusions & future work
Refined coil model

Coil’s cross-section

Old model

Refined model

Copper
(isotropic)

Copper
(anisotropic shear modulus)

• **Ideal, but practically impossible:** explicitly model each turn with mechanical contact between adjacent turns

• **Was unable to approximate mechanical contact between turns** by including a Young’s modulus in the turn-to-turn direction that depends on strain

<table>
<thead>
<tr>
<th></th>
<th>$E_1, E_2$, GPa</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_3$, GPa</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>$\nu_{23}, \nu_{13}$</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>$G_{12}$, GPa</td>
<td>$56.8$</td>
<td></td>
</tr>
<tr>
<td>($= 0.5E_1/(1 + \nu_{12})$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G_{23}, G_{13}$, GPa</td>
<td>3.5</td>
<td></td>
</tr>
</tbody>
</table>
Combined Thermal, Centrifugal, and Electromagnetic Loading Model

- Previous simulations neglected thermal response & electromagnetic forces
- Refined model considers full combined loading & temperature-dependent material properties
  - Cool down from RT to 60 K (thermal forces),
  - Then rotation of cold rotor (centrifugal force),
  - Then rotor current (electromagnetic forces on coil)
Combined Thermal, Centrifugal, and Electromagnetic Loading Model

• Interesting observations of this machine
  • Superconducting rotor coils are significantly stronger than copper stator coils
    • Thus, **stator current ripple has negligible effect on rotor’s magnetic response**
  • When optimizing specific power or torque, pushing FeCo back iron far into saturation is favored
    • Thus, **Lorentz forces on rotor coils are considerable**

2D simulation of $|B|$ (T)
Combined Thermal, Centrifugal, and Electromagnetic Loading Model

Radial deformation (m) results

End of cool down to 60 K

End of cold spin up to 6,800 rpm

At full power (60 K, 6,800 rpm, max current)

Outermost point’s radial deflection:
-0.25 mm

Physical radial gap**:
1.25 mm

+0.08 mm
(old model: +0.32 mm)

0.92 mm

+0.06 mm

0.94 mm

** excludes assembly & geometry errors, deflection due to unbalance
Combined Thermal, Centrifugal, and Electromagnetic Loading Model

Von Mises stress (Pa) results

End of cool down to 60 K

End of cold spin up to 6,800 rpm

At full power (60 K, 6,800 rpm, max current)

Cannot rotate to full speed before cooling down

End of cool down to 60 K

\[ \Delta 3.83 \times 10^8 \]

\[ \downarrow 5.18 \times 10^{-6} \]

End of cold spin up to 6,800 rpm

\[ \Delta 1.26 \times 10^9 \]

\[ \downarrow 3.37 \times 10^5 \]

At full power

\[ \Delta 1.23 \times 10^9 \]

\[ \downarrow 1.85 \times 10^5 \]
Old model vs. refined model
Comparison of maximum von Mises stress (MPa) in each component

<table>
<thead>
<tr>
<th>Component</th>
<th>Old FEA model (Rotation-only)</th>
<th>New FEA model (Cool down + rotation)</th>
<th>% change</th>
<th>‘Failure’ strength, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil</td>
<td>124</td>
<td>127</td>
<td>+ 2.4</td>
<td>See next slide</td>
</tr>
<tr>
<td>Back iron</td>
<td>436</td>
<td>433</td>
<td>– 0.7</td>
<td>694**</td>
</tr>
<tr>
<td>Coil fixture</td>
<td>519</td>
<td>507</td>
<td>– 2.3</td>
<td>1100</td>
</tr>
<tr>
<td>Dovetail</td>
<td>1260</td>
<td>1260</td>
<td>0</td>
<td>1100</td>
</tr>
<tr>
<td>Ring</td>
<td>349</td>
<td>368</td>
<td>+ 5.4</td>
<td>1100</td>
</tr>
</tbody>
</table>

- Here, minimal differences in peak von Mises stress between old & refined models, but...
  - Peak stress & stress distribution in end turn of coil now captured
  - Radial deformation greatly over predicted before
### Combined Thermal, Centrifugal, and Electromagnetic Loading Model

**Range of each stress component (MPa) in the superconductor**

<table>
<thead>
<tr>
<th>Stress component</th>
<th>‘Failure’ strength</th>
<th>End of cool down to 60 K</th>
<th>End of cold spin up to 6,800 rpm</th>
<th>At full power (60 K, 6,800 rpm, max current)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{11} )</td>
<td>&gt; 550</td>
<td>-86.1 to 63.5</td>
<td>-145 to 80.3</td>
<td>-137 to 90.2</td>
</tr>
<tr>
<td>( \sigma_{22} )</td>
<td>Low (?) in tension</td>
<td>-18.8 to 27.8</td>
<td>-181 to 24.8</td>
<td>-162 to 24.1</td>
</tr>
<tr>
<td>( \sigma_{33} )</td>
<td>Very low in tension</td>
<td>-37.1 to 9.8</td>
<td>-91.1 to 16.2</td>
<td>-89.8 to 15.2</td>
</tr>
<tr>
<td>( \sigma_{12}, \sigma_{21} )</td>
<td>Low (?)</td>
<td>-10.1 to 6.5</td>
<td>-19.8 to 40.6</td>
<td>-19.4 to 37.5</td>
</tr>
<tr>
<td>( \sigma_{23}, \sigma_{32} )</td>
<td>Very low</td>
<td>-5.8 to 6.8</td>
<td>-6.0 to 12.0</td>
<td>-5.8 to 11.5</td>
</tr>
<tr>
<td>( \sigma_{13}, \sigma_{31} )</td>
<td>Very low</td>
<td>-0.4 to 1.4</td>
<td>-2.1 to 2.8</td>
<td>-2.1 to 3.1</td>
</tr>
</tbody>
</table>

**Stress components in relation to conductor orientation**

1. \( \sigma_{11} \) - Normal stress in the direction of 1
2. \( \sigma_{22} \) - Normal stress in the direction of 2
3. \( \sigma_{33} \) - Normal stress in the direction of 3
4. \( \sigma_{12}, \sigma_{21} \) - Shear stress between 1 and 2
5. \( \sigma_{23}, \sigma_{32} \) - Shear stress between 2 and 3
6. \( \sigma_{13}, \sigma_{31} \) - Shear stress between 1 and 3
Outline

• Motivation & background

• Summary of the rotor & coil design

• Refined finite element analysis

• Risk reduction testing
  • Coil fabrication
  • Thermal cycling testing

• Conclusions & future work
Risk reduction testing

Questions to answer

• Can we maintain superconductivity in the operating environment?
• Are we confident enough to spend $$$ on superconductor?

Key risks of the rotor

1. Rotor heat load will be higher than expected
2. Superconducting coils will not be able to handle the centrifugal loads
3. Superconducting coils will be difficult to manufacture
4. Superconducting coils will not survive the thermal cycling

Why thermal cycling?

• **The problem:** superconductor has anisotropic thermal contraction → tensile stress
• Limited success in literature & only demonstrated for 1 to 7 thermal cycles

Addressing these risks in this talk
Coil fabrication process

1. Coil former
2. Fixture rotation direction
3. Vertical positioning stage
4. Side clamps
5. Stainless steel plate
6. Mass
7. Coil-shaped cap
8. Low CTE cryogenic epoxy
Experimental Setup

- Coil mounted to G10 plate & suspended in liquid nitrogen
- **Measurements**: DC voltage & DC current
Thermal Cycling Procedure (summarized)

1. Very slowly lower the coil into LN2
   1. Wait ~5 minutes to reach steady state
2. Measure voltage vs. current response
   1. Change DC current at a rate of < 0.05 A/s
3. Thermally cycle
   1. Remove coil from LN2 and air quench for > 5 minutes
   2. Use fan for 3 minutes to finish warming up coil to room temperature
   3. Very slowly lower coil into LN2, wait ~5 minutes
4. Repeat steps 2 & 3

1 thermal cycle = room temperature to 77 K to room temperature
Superconductor's voltage versus current response commonly described by:

\[ V = V_{\text{critical}} \left( \frac{I}{I_{\text{critical}}} \right)^n \]

- "n-value" indicates combined quality of superconductor & measurement
- Using 1 µV/cm criterion for \( V_c \)
Prediction of Experimental Critical Current

Manufacturer’s data

Finite element simulation

Critical current, A
(at 77 K & self field)

B perpendicular, T

Manufacturer’s $I_c$ vs $B_\perp$

Simulated maximum $|B|$

Simulated maximum $|B_\perp|$

Predicted range of $I_c$
Thermal Cycling – Sub-scale, 4-layer coil

- **Critical current** ($I_c$) **prediction**: 60.5 A to 67.5 A
- Coil thermally cycled 50 times
- No clear trend in critical current or $n$-value
- Linear fit has nearly flat slope
Thermal Cycling – Full-scale, 2-layer coil

- **Critical current \((I_c)\) prediction:** 32 A to 38 A
- **Coil thermally cycled 13 times**
- **No clear trend in critical current or n-value**
- **Slope of linear fits small & have opposite polarity**
Outline

• Motivation & background
• Summary of the rotor & coil design
• Refined finite element analysis
• Risk reduction testing

• Conclusions & future work
Conclusions

Analysis

- Added fidelity to superconducting coil model
- Developed a multiphysics model that includes the thermal, centrifugal, and electromagnetic forces
  - Radial deflection calculated at each operating state → enables proper sizing or air gap
  - After fixing 1 stress concentration, structural components will have healthy margins
  - Superconductor’s stress components seem sufficiently low at each operating state

Testing

- Developed a fabrication process for no-insulation superconducting coils that can reliably survive thermal cycling
- Thermally cycled 9 superconducting coils up to 50 times from 293 K to 77 K
  - Need more repeatable solder joints between coil and copper terminals
  - Only very small and acceptable level of degradation
Future work

Analysis

• Refined optimization of geometry (2D model)
• Re-evaluate combined thermal, centrifugal, and electromagnetic loading (3D model)

Testing

• Risk reduction testing – high speed rotation of superconducting coil & structural parts
  • Measure superconductor performance metrics before & after spinning on purpose-built rotor
  • Stationary superconducting test at designed electrical, thermal, & magnetic operating point

Risk reduction test – purpose-built rotor

ICE-Box test rig at NASA GRC

Vacuum chamber

Cryocooler
Acknowledgements

• NASA’s Advanced Air Transport Technology (AATT) Project
• NASA’s Convergent Aeronautics Solutions (CAS) Project
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

Safety factor

- ±20% Estimate of wire variation
- + ±15% Modeling inaccuracy
- ±35% (≈1.5 safety factor)
Measurements at $B = 2 \, \text{T}$ obtained from manufacturer.

**Design spec**
- Current: $51.5 \, \text{A}$
- Temperature: $\leq 62.8 \, \text{K}$

**Valid operating regime**

- $I_c (\text{sf,77K}) = 150 \, \text{A}$
- $\text{min}[I_c(B,T,\theta)] = 150 \, \text{A}$
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
--- | ---
Electrical frequency | DC
Number of poles | 12
Material | Solid Fe$_{49.15}$Co$_{48.75}$V$_2$
Outer diameter | 30 cm
Inner diameter | 18.9 to 20 cm
Axial length | 12.5 cm

[Diagram showing parameters $w$ and $t$]
Thermal design

- Rotor is cooled by pulse-tube cryocooler which is connected to the backiron via a high thermal conductivity, low rigidity thermal bridge.
  - Cryocooler is designed to lift 55 W of heat with a 50 K cold end.
- Primary structural connection is high rigidity, low thermal conductivity Ti6Al4V shaft to reduce heat transfer from hot end.
- Other thermal design aspects
  - Rotor operates in vacuum to reduce convection and windage losses
  - Low emissivity coatings on rotor components and vacuum tube to reduce radiation heat transfer
  - Current lead (not shown) size and length optimized to minimize $I^2R$ losses and conductive heat transfer
Thermal design (new design, no current lead heat loads)

- Real coils have anisotropic thermal conductivity
  - $121 \text{ W/m/K}$
  - $121 \text{ W/m/K}$
  - Up to $8.9 \text{ W/m/K}$ depending on contact pressure
- Currently modeling using various isotropic thermal conductivities to determine effect on coil temperatures
- Anisotropic model in development
Thermal design (new design, no current lead heat loads)

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>0.1</th>
<th>1.0</th>
<th>5.0</th>
<th>8.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Coil Temperature (K)</td>
<td>64.0</td>
<td>60.7</td>
<td>58.8</td>
<td>58.4</td>
</tr>
</tbody>
</table>

Results depicted use 5.0 W/m/K.

- Analysis includes temperature-dependent properties, contact pressure results from stress analysis, and the following heat loads:

<table>
<thead>
<tr>
<th>Heat Source</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation</td>
<td></td>
</tr>
<tr>
<td>Stator to Rotor Radiation</td>
<td>7.6 W</td>
</tr>
<tr>
<td>Convection</td>
<td></td>
</tr>
<tr>
<td>Windage Losses</td>
<td>1 W</td>
</tr>
<tr>
<td>Stator to Rotor Convection</td>
<td>4 W</td>
</tr>
<tr>
<td>Conduction</td>
<td></td>
</tr>
<tr>
<td>Shaft Conduction</td>
<td>8.3 W</td>
</tr>
<tr>
<td>Current Lead Conduction</td>
<td>0 W</td>
</tr>
<tr>
<td>I²R Losses</td>
<td>0 W</td>
</tr>
</tbody>
</table>
Thermal design (older design, all heat loads)

Max coil temp = 57.6 K

- Analysis includes temperature-dependent properties, contact pressure results from stress analysis, and the following heat loads:

<table>
<thead>
<tr>
<th>Heat Source</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation Stator to Rotor</td>
<td>7.6 W</td>
</tr>
<tr>
<td>Convection Windage Losses</td>
<td>1 W</td>
</tr>
<tr>
<td>Convection Stator to Rotor</td>
<td>4 W</td>
</tr>
<tr>
<td>Conduction Shaft Conduction</td>
<td>8.3 W</td>
</tr>
<tr>
<td>Current Lead Conduction</td>
<td>6.2 W</td>
</tr>
<tr>
<td>I²R Losses</td>
<td>2.0 W</td>
</tr>
<tr>
<td></td>
<td>29.2 W</td>
</tr>
</tbody>
</table>
Combined Thermal, Centrifugal, and Electromagnetic Loading Model

Von Mises stress (Pa) results

End of cold spin up to 6,800 rpm

Cannot rotate to full speed before cooling down

Stress concentration in dovetail part

Cannot rotate to full speed before cooling down
Superconductors produce much stronger magnetic fields, but they are...

- **Strongly temperature sensitive** -- superconductors must be kept below a critical temperature during their entire operation
- **Relatively fragile** – particularly to shear & transverse tensile loads
- **Difficult to accurately model** -- superconductors are anisotropic composite materials with stress/strain limits that are not well characterized
- **Significantly more expensive** -- $40 to $60 per meter
## Thermal cycling

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>HEMM coils</th>
<th>PTR-1 coils</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Superconductor</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>ReBCO (2nd gen high temperature superconductor)</td>
<td>Same</td>
</tr>
<tr>
<td>Width, mm</td>
<td>4 mm</td>
<td>Same</td>
</tr>
<tr>
<td>Thickness, micron</td>
<td>65 micron</td>
<td>Same</td>
</tr>
<tr>
<td>Min. bend radius, mm</td>
<td>15 mm</td>
<td>Same</td>
</tr>
<tr>
<td><strong>Coil</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turn-to-turn insulation</td>
<td>None</td>
<td>Same</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>62.8 K</td>
<td>77 K</td>
</tr>
<tr>
<td>Cooling</td>
<td>Cryocooler (conductive)</td>
<td>LN2 (nucleate boiling)</td>
</tr>
<tr>
<td>Operating current</td>
<td>51.5 A</td>
<td>Varies</td>
</tr>
<tr>
<td># of layers per coil</td>
<td>4</td>
<td>Up to 4</td>
</tr>
<tr>
<td># of turns per layer</td>
<td>about 230</td>
<td>Up to 221</td>
</tr>
<tr>
<td>Magnetic excitation</td>
<td>Up to 2 T</td>
<td>Up to about 0.9 T</td>
</tr>
<tr>
<td>Cryogenic epoxy</td>
<td>Stycast 2850 FT black</td>
<td>Same</td>
</tr>
</tbody>
</table>
Thermal Cycling – Performance Metrics

- Performance metrics: critical current ($I_c$) and $n$
- Detect damage via changes in $n$ and/or $I_c$
- Lesson learned: data more easily evaluated with logarithmic y-axis scale
  - Equation only fit to data above a current threshold

$$V = V_c \left( \frac{I}{I_c} \right)^n$$
Thermal Cycling – Sub-scale, 2-layer coil

- Coil thermally cycled 11 times
- No clear trend in critical current or n-value
- n-value close but lower than that of as-delivered superconductor (about n = 32)
  - No-insulation coil type
  - Appreciable uncertainty in n-value

No detectable degradation