Optimizing Power Density and Efficiency of a Double-Halbach Array Permanent-Magnet Ironless Axial-Flux Motor

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Background

Hybrid Electric and Turboelectric Aircraft Propulsion

Boeing SUGAR

NASA STARC-ABL

NASA N3X
Background

Turboelectric Propulsion Benefits

Electric drive = motor + generator + other electrical components

Break-Even on Weight

Each aircraft configuration will yield combinations of power density and efficiency required to achieve net benefit

From Jansen et al. “Turboelectric Aircraft Drive Key Performance Parameters and Functional Requirements”
Target Application

- Example – HEIST (Hybrid-Electric Integrated Systems Testbed)
- 31-foot span wing section
- 18 fans directly driven by electric motors
- Motors powered by batteries
- Motor dimensions: 5.5” diameter, 2” length
- Target: 13 kW power at 7200 RPM

➢ Our motor design: target 13 kW/kg and 1% loss

Analysis

Double-Halbach PM Array
Ironless Axial Flux Motor

Upper Halbach Array
Rotor

Windings
Stator

Lower Halbach Array
Rotor
Analysis

Double-Halbach PM Array
Ironless Axial Flux Motor
Analysis

Double-Halbach PM Array
Ironless Axial Flux Motor

Model as 2D Pole Pair
2D magnetostatic pole pair model allows for simple equation-based analysis
Analysis

Pole Pair Analysis

\[ B_y = 2B_R e^{-ky_g} (1 - e^{-ky_m}) \frac{\sin(\epsilon \pi/n_m)}{\pi/n_m} \cos kx \cosh ky \]

\[ F_c = J \Delta r \int_{x_1}^{x_2} \int_{y_1}^{y_2} B_y \, dx \, dy \]

\[ k = \frac{2\pi}{x_p} \]
Analysis

Pole Pair Analysis

Axial Flux in Center of Gap, $B_y$ (T)

Circumferential Distance ($x/x_p$)

2D FEA
Equation
Analysis

Force/Torque/Power

\[ F_c = [2JB_R \Delta r_y g y_m] \left[ \frac{e^{-ky_g}}{ky_g} \right] \left[ \frac{1 - e^{-ky_m}}{ky_m} \right] \left[ \frac{\sin(\epsilon \pi / n_m)}{\pi / n_m} \right] \sin kx \bigg|_x^{x_2} \sinh ky \bigg|_y^{y_2} \]

\[ F_p = \sum_{c=1}^{6} F_c \quad T = pr_a F_p \quad P = T \omega_r = T \text{ RPM} \quad \pi / 30 \]
Analysis

Power Density – Based on Magnet Mass

$$\frac{P}{m_m} \propto \left[ \frac{JB_R v_{tip}}{\rho_m} \right] \left[ e^{-k y_g} \right] \left[ \frac{1 - e^{-k y_m}}{k y_m} \right] \left[ \frac{\sin(\epsilon \pi/n_m)}{\pi/n_m} \right]$$

Small gap / pole size
high power density

Large gap / pole size
low power density
Analysis

Power Density – Based on Magnet Mass

\[
\frac{P}{m_m} \propto \left[ \frac{JB_R v_{tip}}{\rho_m} \right] \left[ e^{-ky_g} \right] \left[ \frac{1 - e^{-ky_m}}{ky_m} \right] \left[ \frac{\sin(\epsilon \pi / n_m)}{\pi / n_m} \right]
\]

Small magnet thickness to pole size
high power density

Large magnet thickness to pole size
low power density

Ratio of magnet thickness to pole size
Analysis

Power Density – Based on Magnet Mass

\[
\frac{P}{m_m} \propto \left[ \frac{J B_R v_{tip}}{\rho_m} \right] [e^{-k y_g}] \left[ \frac{1 - e^{-k y_m}}{k y_m} \right] \left[ \frac{\sin(\epsilon \pi / n_m)}{\pi / n_m} \right]
\]

- \( \epsilon = 1.00 \)
- \( \epsilon = 0.75 \)
- \( \epsilon = 0.50 \)

Number of magnets per pole pair, \( n_m \)

- \( \epsilon = 1.00, n_m = 2 \)
- \( \epsilon = 0.5, n_m = 2 \)
- \( \epsilon = 1.0, n_m = 8 \)

\( J B_R v_{tip} \)
## Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target power</td>
<td>13 kW</td>
</tr>
<tr>
<td>Target power density</td>
<td>13 kW/kg</td>
</tr>
<tr>
<td></td>
<td>Based on magnet and winding mass only</td>
</tr>
<tr>
<td>Target loss</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td></td>
<td>Including magnet and winding losses only</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>5.5 inches (140 mm)</td>
</tr>
<tr>
<td>Magnet remanence flux, $B_R$</td>
<td>1.4 T (NdFeB)</td>
</tr>
<tr>
<td>Current density, $J$</td>
<td>3 A/mm$^2$ (natural convection) to 30 A/mm$^2$ (liquid cooling)</td>
</tr>
<tr>
<td>Electrical frequency, $f$</td>
<td>&lt; 2000 Hz</td>
</tr>
<tr>
<td></td>
<td>≤ 16 pole pairs at 7200 RPM</td>
</tr>
</tbody>
</table>
Results

Power

\( y_c = 3 \text{ mm}, 16 \text{ pole pairs}, \text{ magnet aspect ratio } y_m/x_m = 1 \)

*16 pole pairs \( \rightarrow f = 1920 \text{ Hz} \)*
Results

Power Density

\[ y_c = 3 \text{ mm}, \text{ 16 pole pairs}, \text{ magnet aspect ratio } y_m/x_m = 1 \]

16 pole pairs \( \rightarrow f = 1920 \text{ Hz} \)
Results

\[ I^2R \text{ Loss } P_c \quad P_c \propto \frac{J_{rms}^2 V_c}{\sigma \eta} \]

\[ \text{Resistive Loss (\%)} \]

\[ \text{Ratio of Motor ID to OD} \]

- \( J = 3 \text{ A/mm}^2 \)
- \( J = 10 \text{ A/mm}^2 \)
- \( J = 20 \text{ A/mm}^2 \)
- \( J = 30 \text{ A/mm}^2 \)

Low ID/OD

High ID/OD
Results

Conductor Eddy Loss $P_e$

$$P_e \propto \sigma f^2 d^2 B_{pk}^2 V_c$$

Eddy current loss in conductors

<table>
<thead>
<tr>
<th>Ratio of Motor ID to OD</th>
<th>Eddy current loss in conductors</th>
</tr>
</thead>
<tbody>
<tr>
<td>d = 0.50 mm</td>
<td></td>
</tr>
<tr>
<td>d = 0.10 mm</td>
<td></td>
</tr>
<tr>
<td>d = 0.05 mm</td>
<td></td>
</tr>
</tbody>
</table>
Results

Effect of Magnet Aspect Ratio

Rotor ID/OD = 0.6, $y_c = 3$ mm, 16 pole pairs
Results

Effect of Coil Thickness

Rotor ID/OD = 0.6, $y_c = 3$ mm, 16 pole pairs

![Graph showing the effect of coil thickness on power density and resistive loss. The x-axis represents coil thickness (mm) ranging from 0 to 12. The y-axis for power density shows values from 0 to 16 kW/kg, and the y-axis for resistive loss shows values from 0.0% to 1.6%. The graph demonstrates a decrease in power density and an increase in resistive loss as coil thickness increases.](image-url)
Results

Effect of Number of Pole Pairs

$B_{max} = 1.0 \, T$
Results

Effect of Number of Pole Pairs

- Resistive Loss
- Conductor Eddy Loss
- Resistive + Eddy Loss

$B_{max} = 1.0$ T

Small area of < 1% loss

Eddy current loss for 0.05mm diameter wire
Results

Final Motor Performance
Verified with Maxwell 3D FEA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>13 kW at 7200 RPM</td>
</tr>
<tr>
<td>Power density</td>
<td>12.8 kW/kg</td>
</tr>
<tr>
<td></td>
<td>Based on magnet and winding mass only</td>
</tr>
<tr>
<td>Loss</td>
<td>0.85% - conductor resistive loss</td>
</tr>
<tr>
<td></td>
<td>0.11% - conductor eddy current loss</td>
</tr>
<tr>
<td></td>
<td>0.02% - magnet eddy current loss (3D FEA)</td>
</tr>
<tr>
<td>ID/OD = 0.6</td>
<td>Coil thickness = 3 mm, 16 pole pairs, 20 A/mm² current density, and magnet aspect ratio = 1</td>
</tr>
</tbody>
</table>

- Difficult to achieve goal of 13 kW/kg and 1% loss in this configuration
- Required 20 A/mm² which will require cooling
Conclusions/Future Work

• Continue to investigate configurations that will improve efficiency as well as power density
• Design, build and test
• Targets:
  • > 1 MW motor
  • 13 kW/kg
  • 96% efficiency
  ➢ 99% efficiency
Acknowledgments

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Amy Jankovsky subproject manager

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• Yaritza de Jesus-Arce – team leader
• Cheryl Bowman
• Ryan Edwards
• Ralph Jansen
• Peter Kascak
• Andrew Provenza
Results – Increasing Speed

- **13 kW**
- **26 kW**
- **52 kW**

Added weight of gearbox

- **53 m/s**
- **106 m/s**
- **212 m/s**

Power (kW) vs. Rotor Speed (RPM)

- **Power (kW)**
- **Power Density (kW/kg)**
- **Resistive Loss (%)**
Results – Increasing Speed

Redesigned for 13 kW with Gearbox

- Increasing Speed
- Redesigned for 13 kW with Gearbox

- Power Density (kW/kg)
- Resistive Loss (%)

- Rotor Speed (RPM)

- 53 m/s
- 106 m/s
- 212 m/s
3D Transient vs 2D Static Results

Power Density (kW/kg)

<table>
<thead>
<tr>
<th>Method</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation-based magnetostatic - optimal design</td>
<td>12.5</td>
</tr>
<tr>
<td>Equation-based magnetostatic - compact coils</td>
<td>12.0</td>
</tr>
<tr>
<td>Maxwell 3D transient - compact coils</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Resistive Loss (%)

<table>
<thead>
<tr>
<th>Method</th>
<th>Resistive Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation-based magnetostatic - optimal design</td>
<td>0.5</td>
</tr>
<tr>
<td>Equation-based magnetostatic - compact coils</td>
<td>0.2</td>
</tr>
<tr>
<td>Maxwell 3D transient - compact coils</td>
<td>0.5</td>
</tr>
</tbody>
</table>
### 3D Transient vs 2D Static Results

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Torque (N-m)</th>
<th>Resistive Loss (%)</th>
<th>Eddy Current Loss Conductors (%)</th>
<th>Eddy Current Loss Magnets (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation-based magnetostatic large coils/optimal</td>
<td>17.3</td>
<td>0.85%</td>
<td>0.11%</td>
<td>-</td>
</tr>
<tr>
<td>Equation-based magnetostatic compact coils/high J</td>
<td>16.3</td>
<td>7.6%</td>
<td>0.06%</td>
<td>-</td>
</tr>
<tr>
<td>Maxwell 3D magnetostatic compact coils/high J</td>
<td>16.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Maxwell 3D transient compact coils/high J</td>
<td>16.9</td>
<td>8.1%</td>
<td>-</td>
<td>0.02%</td>
</tr>
</tbody>
</table>