Electromagnetic Efficiency and Mass of Magnetic Gears for Electrified Aircraft

Thomas Tallerico  Justin Scheidler  Zachary Cameron

NASA Glenn Research Center
Materials and Structures Division
Rotating and Drive Systems Branch
Presentation Outline

- Background and Motivation
- Study Methodology
- Mass and Efficiency Trends:
  - Magnets per pole pair
  - Sun Gear Pole Pairs
  - Gear Ratio
  - Radius
- Summary
Background & Motivation

**Mechanical gearing**

**Pros**
+ High / very high torque/mass (specific torque)
+ High / very high efficiency
+ Mature technology

**Cons**
- Contact-related wear & failure
  - Requires lubrication system(s)
  - Routine & costly maintenance
- Strong tonal vibration & cabin noise

**Magnetic gearing**

**Pros**
+ Non-contact
  - No lubrication
  - Low maintenance
  - Easily integrated in electric machines
  - Potentially low vibration

**Cons**
- Unknown limits on specific torque & efficiency
- Magnet temperature limit
- Individual magnet interaction weaker than 1 gear tooth pair

Efficiency and Mass of Magnetic Gears For Aerospace Applications
Concentric Magnetic Gears

- Rule of thumb:
  Magnetic fields with matching spatial harmonic order can couple to transmit torque
- Modulator “modulates” the flux of each rotor so that they have matching spatial harmonic order in the airgaps

\[ \cos(\theta) \cdot \cos(\alpha) = \frac{1}{2} (\cos(\theta + \alpha) + \cos(\theta - \alpha)) \]

\[ Q = PR \pm PS \]
Concentric Magnetic Gears

Gear Ratio

<table>
<thead>
<tr>
<th>Output</th>
<th>Q Selection</th>
<th>Gear Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring Gear</td>
<td>PR-PS</td>
<td>( \frac{PR}{PS} )</td>
</tr>
<tr>
<td></td>
<td>PR+PS</td>
<td>( \frac{PR}{PS} + 1 )</td>
</tr>
<tr>
<td>Modulator</td>
<td>PR-PS</td>
<td>( \frac{Q}{PS} = \frac{PR}{PS} - 1 )</td>
</tr>
<tr>
<td></td>
<td>PR+PS</td>
<td>( \frac{Q}{PS} = \frac{PR}{PS} + 1 )</td>
</tr>
</tbody>
</table>
Motivation for This Study

- Effects of higher level variable selection:
  - Number of magnets per ring gear pole pair ($MR$)
  - Number of magnets per sun gear pole pair ($MS$)
  - Gear Ratio ($GR$)
  - Sun gear Pole Pairs ($PS$)
  - Radius ($R$)

- Previous work focused on Volume and low speed (100 rpm)
Study Methodology

• PT-4 design code
  • Only electromagnetics
  • Produce electromagnetic (EM) mass optimized designs
• Efficiency analysis on select Designs
• PT-2 used as validation point

![Study Design Diagram](image)
Study Design

Fixed Study Variables

- Based on PT-2
- 65% 2D to 3D torque reduction
- ~50 kW output power
- Gap Between Magnets
  - Tolerances/Mechanical
- High-speed Sun Magnet Retaining Hoop
  - Sets Sun-Mod Magnetic Gap

<table>
<thead>
<tr>
<th>Variable</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter</td>
<td>140 mm</td>
</tr>
<tr>
<td>2D Output Torque</td>
<td>185 Nm</td>
</tr>
<tr>
<td>3D Output Torque</td>
<td>120 Nm</td>
</tr>
<tr>
<td>Output Speed</td>
<td>4000 RPM</td>
</tr>
<tr>
<td>Mechanical Airgap Thickness</td>
<td>1 mm</td>
</tr>
<tr>
<td>Min Sun Magnet Thickness</td>
<td>5 mm</td>
</tr>
<tr>
<td>Min Pole Piece Thickness</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>Min Ring Magnet Thickness</td>
<td>3 mm</td>
</tr>
<tr>
<td>Inter-Magnet Wall Thickness</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Inner Pole Piece Span Angle (rad)</td>
<td>1.2*π/PR</td>
</tr>
<tr>
<td>Mid Pole Piece Span Angle (rad)</td>
<td>1.2*π/PR</td>
</tr>
<tr>
<td>Outer Pole Piece Span Angle (rad)</td>
<td>0.6*π/PR</td>
</tr>
<tr>
<td>Magnetic Material</td>
<td>Neodymium N52</td>
</tr>
<tr>
<td>Electrical Steel</td>
<td>Fe_{49}Co_{49}V_{2}</td>
</tr>
<tr>
<td>Allowable Stress in Carbon Fiber</td>
<td>600 MPa</td>
</tr>
</tbody>
</table>
Specific Torque Definition

- 2D EM Specific Torque
  - Traditional metric for magnetic gears
  - $=\frac{185}{(\text{EM Mass})}$
- EM Specific Power
  - 50 kw
  - 1 Nm/kg @ 4000 rpm = .27 kw/kg
  - 130 Nm/kg = 35 kw/kg
  - Typical PM Motor = 5-16 kw/kg
Mass and Efficiency Trends

Magnets Per Pole Pair in Halbach Arrays (MS & MR)

- MS and MR are magnets per sun and ring pole pair
- Increasing Magnets per pole pair:
  - Improves array specific flux
  - Improves harmonic distortion
  - Reduce eddy current loss
  - It also decreases magnetic fill percentage
  - 0.5 mm wall assumption

Arrows denote magnetization direction*
Mass and Efficiency Trends

Magnets Per Pole Pair in Halbach Arrays (MS & MR)

- MS and MR are magnets per sun and ring pole pair
- Increasing Magnets per pole pair:
  - Improves array specific flux
  - Improves harmonic distortion
  - Reduce eddy current loss
  - It also decreases magnetic fill percentage
  - 0.5 mm wall assumption
Mass and Efficiency Trends

Magnets Per Pole Pair in Halbach Arrays (MS & MR)

- MS and MR are magnets per sun and ring pole pair
- Increasing Magnets per pole pair:
  - Improves array specific flux
  - Improves harmonic distortion
  - Reduce eddy current loss
  - It also decreases magnetic fill percentage
    - 0.5 mm wall assumption
Effect of Sun Gear Pole Pairs On Specific Torque

• Fixed Variables:
  • OD=140 mm
  • Gear Ratio = 4
  • MS=10, MR=6
• As PS Increases:
  1. Modulator Thickness decrease
     » Lower Reluctance Between Poles
  2. Specific Flux of Arrays increase
  3. Pole-to-Pole Ring Gear Leakage

![Specific Torque Vs PS Graph]

- Mass and Efficiency Trends
- Efficiency and Mass of Magnetic Gears For Aerospace Applications
Mass and Efficiency Trends

Pole-to-Pole Leakage Explanation

- Flux that couples between magnetic arrays provides torque
- Flux that leaks through air gap, providing no torque
- Percent of flux that leaks governed by relative reluctance
  - $R_{\text{couple}} \sim \text{airgap}$
  - $R_{\text{leak}} \sim \text{length}_{\text{pole-to-pole}}$
Pole-to-Pole Leakage Explanation

- $PR = Q - PS = (GR - 1) \times PS$
  - $PR > PS$
  - Pole-to-Pole length Smaller
- Higher percent of ring gear flux leaks than sun gear
  - Why sun gear magnets are typically thicker
- $PR$ limits optimum $PS$
  - Optimum $PS$ set by where ring gear leakage is significant
Effect of Sun Gear Pole Pairs (PS) on Specific Torque

<table>
<thead>
<tr>
<th>Gear Ratio</th>
<th>PS Optimum</th>
<th>PR Optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>11</td>
<td>33</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>35</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>36</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>35</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>36</td>
</tr>
</tbody>
</table>

At an OD of 140mm
Optimum PR value = 32-36
Mass and Efficiency Trends

Effect of Gear Ratio (GR) on Specific Torque

• Output speed = 4000 RPM
• Input speed = 4000*GR
  • At GR=10 Input Speed=40,000
• Leads to large sun gear retaining hoop
  • Large sun gear magnetic airgap
• Secondary Effect:
  • Lower Sun Gear Pole Count

![Specific Torque Vs Gear Ratio](image)
Effect of PS and GR on Efficiency Without Magnet Laminations

- Without Laminations Sun Gear Losses Dominate
- Sun gear losses go with the size of the sun gear magnets
  
  \[ P_c = \frac{1}{16} \frac{V}{\rho} \frac{w^2l^2}{w^2+l^2} \frac{1}{T} \int_0^T \left( \frac{dB}{dt} \right)^2 dt \]
- Overall Efficiency goes with mass
Mass and Efficiency Trends

Effect of PS and GR on Efficiency Without Magnet Laminations

Specific Torque Vs PS

<table>
<thead>
<tr>
<th>PS</th>
<th>GR=4</th>
<th>GR=6</th>
<th>GR=8</th>
<th>GR=10</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>140</td>
<td>120</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>6</td>
<td>120</td>
<td>100</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>8</td>
<td>100</td>
<td>80</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>80</td>
<td>60</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>60</td>
<td>40</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>40</td>
<td>20</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Efficiency Vs PS

No Magnet Laminations

<table>
<thead>
<tr>
<th>PS</th>
<th>GR=4</th>
<th>GR=6</th>
<th>GR=8</th>
<th>GR=10</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>98</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>8</td>
<td>96</td>
<td>96</td>
<td>96</td>
<td>96</td>
</tr>
<tr>
<td>10</td>
<td>94</td>
<td>94</td>
<td>94</td>
<td>94</td>
</tr>
<tr>
<td>12</td>
<td>92</td>
<td>92</td>
<td>92</td>
<td>92</td>
</tr>
<tr>
<td>14</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>
Effect of PS and Gear Ratio on Efficiency With 2mm Laminations

- Magnet Losses reduced with laminations
- Modulator Losses are dominant
- Efficiency goes with electrical frequency of the sun and ring gears on the modulator
Radius Effects on Specific Torque

- Fixed Variables
  - MS=10
  - MR=6
- Airgap=(.0047*OD + .27)[mm]
- Swept PS, GR, and Radius
  - Select optimum PS
- 4000 RPM Output Speed
  - leads to large sun magnet retaining hoop
Radius Effects on Specific torque

- Rerun with Output Speed = 0
  - No Carbon Fiber Hoop
- Specific Torque increased significantly
- Gear Ratio Effect Reduced
- Specific torque increase linear if constant airgap
Efficiency and Mass of Magnetic Gears For Aerospace Applications

Efficiency Vs Mass

Efficiency Vs Mass (No Magnet Laminations)

Efficiency Vs Mass (2mm Magnet Laminations)
Efficiency and Mass Vs Sun Gear Electrical Frequency

Efficiency Vs Sun gear Electrical Frequency (2mm Magnet Laminations)

- GR=4
- GR=6
- GR=8
- GR=10

Mass Vs Sun gear Electrical Frequency (2mm Magnet Laminations)

- GR=4
- GR=6
- GR=8
- GR=10

Mass and Efficiency Trends
Efficiency and Mass Vs Sun Gear Electrical Frequency

**Graphs:**
- Efficiency Vs Sun gear Electrical Frequency (2mm Magnet Laminations)
- Magnetic Gear Mass Vs Ring Gear Pole Count

**Tables:**
- Efficiency: 96%, 97%, 98%, 99%, 100%
- Sun Gear Electrical Frequency (Hz): 0, 2000, 4000, 6000, 8000
- Mass: 0, 20, 40, 60, 80
- Ring Gear Pole Count: 0, 20, 40, 60, 80

**Legend:**
- GR=4
- GR=6
- GR=8
- GR=10
Summary

• Magnets per pole pair in a Halbach array
  • Increase Specific torque
    • Unless significant magnet fill percentage loss
    • Diminishing marginal returns past a value of 6
  • Increase Efficiency
• At a given Gear Ratio and Radius, there is an optimum Sun Gear Pole Pair Count
  • Set by ring gear pole count (pole-to-pole distance)
• Without laminations sun gear losses dominate
  • Efficiency goes with mass
Summary

• With magnet laminations modulator losses dominate
  • Efficiency goes with electrical Frequency
  • >99% electromagnetic Efficiency can be achieved

• Sun gear speed significantly affects achievable specific torque
  • Sets sun gear to modulator airgap size
  • Can cause significant specific torque decay with gear ratio
  • Can limit specific torque increases with radius

• Specific torque scales linearly with radius if magnetic gaps constant
Future work

- Similar study on component thickness
- Fold this work into design code
  - Create a more complete design code
- Optimized magnetically geared drivelines
Acknowledgements

• NASA Revolutionary Vertical Lift Technology (RVLT) Project

• NASA Internal Research & Development (IRAD) Project
QUESTIONS ?
Specific Torque Effects of MS

- **Fixed Variables**
  - GR=4
  - OD=140 mm
  - MR=6

- **Specific Flux of Halbach Arrays**
  - Diminishing marginal returns

- **0.5 mm wall leads to loss of fill at high Total sun magnets (TSM)**
  - \( TSM = PS \times MS \)
Specific Torque Effects of MR

- Loss of Fill more prominent:
  - $TRM = PR \times MR$
  - $= (GR - 1) \times PS \times MR$

- At low PS Halbach Array Specific Flux increase dominate
- At high PS loss of fill dominate
  - 0.5 mm wall
  - Different gear ratio
  - Different radius

- Mass and Efficiency Trends

  - Loss of Fill more prominent:
    - $TRM = PR \times MR$
    - $= (GR - 1) \times PS \times MR$
  
  - At low PS Halbach Array Specific Flux increase dominate
  - At high PS loss of fill dominate
    - 0.5 mm wall
    - Different gear ratio
    - Different radius
Effect of Increase Magnet Count on Losses

- **Eddy Current Power Loss in a magnet:**
  
  \[ P_c = \frac{1}{16} \frac{V}{\rho} \frac{w^2 l^2}{l^2 + w^2} \frac{1}{T} \int_0^T \left( \frac{dB}{dt} \right)^2 dt \]

- \( w \ll l \):
  
  \[ P_c = \frac{1}{16} \frac{V}{\rho} \frac{w^2 l^2}{l^2} \frac{1}{T} \int_0^T \left( \frac{dB}{dt} \right)^2 dt \]

- \( P_c \sim w^2 \)

- Higher PS = lower losses
  
  \[ TRM = PR \times MR = (GR - 1) \times PS \times MR \]
Mass and Efficiency Trends

Effect of Magnets Per Pole On Sun Gear Losses

• Similar to MR
  • $w < l$ not $w \ll l$
• Losses higher in sun gear
  • Larger width
  • Overall Larger Volume
  • Frequency of Ring Flux on Sun
• Higher PS decreases losses
  • $TSM = PS \times MS$
Mass and Efficiency Trends

Efficiency Effects of Magnets Per Pole Pair

**MR Effect at MS of 10**

![Graph showing efficiency vs MR (No Magnetic Laminations)]

- PS=4
- PS=6
- PS=8
- PS=10
- PS=12

**MS Effect at MR of 6**

![Graph showing efficiency vs Ms (No Magnet Laminations)]

- PS=4
- PS=6
- PS=8
- PS=10
Magnet Losses with 2 mm Laminations

- \( P_c = \frac{1}{16 \rho} \frac{V}{w^2 + l^2} \frac{1}{T} \int_0^T \left( \frac{dB}{dt} \right)^2 dt \)
- \( l = 0.002 \text{ m} \)
  - Losses lower
  - \( w > l \)
- Increase PS Increase Losses

![Ring Gear Loss Vs MR](2 mm Magnet Laminations)
Efficiency and Mass of Magnetic Gears For Aerospace Applications

Mass and Efficiency Trends

Efficiency Effects of Magnets Per Pole Pair with 2 mm magnet laminations

**MR Effect at MS of 10**

![Graph showing Efficiency Vs MR for 2 mm Magnet Laminations with various PS values](image)

**MS Effect at MR of 6**

![Graph showing Efficiency Vs Ms for 2 mm Magnet Laminations with various PS values](image)