Results of NASA’s Magnetic Gear Program to Date

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Outline

• Background and Motivation
  • Concentric Magnetic Gears
• Results
  • Efficiency
  • Thermal
  • Mass
• Future Work
  • Magnetically Geared Motors
• Conclusions
Background & Motivation

- Electric motor driven fans used to enable electrified aircrafts
- Geared electric motor drives are lighter and/or more efficient than direct drive
- Direct drive common in concept vehicles:
  - Easier to design
  - Potentially more reliable

### Direct drive

- Motor
- Fan

  + Simpler
  - Non-optimal motor and/or fan

### Geared drive

- Motor
- Gearbox
- Fan

  + Optimized motor & fan
  - More complex
  - Potentially less reliable
**Mechanical vs Magnetic Gears**

**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
NASA’s Magnetic Gear Program

Phase I 2017
- How do they work? (PT-1)
- Can they be lightweight? (PT-2)

Phase II 2018-2019
- Can they be efficient? (PT-3)
- Can they be efficient and lightweight? (PT-4)

Phase III 2019-2020
- How to pair them with motors?
- Can they be reliable?
Concentric Magnetic Gears

Outer Ring Gear

Modulator

Air Gaps

Inner Sun Gear

Permanent Magnets

Soft Magnetic Material

Support Structure
Continuous Torque Transmission

Mechanical Gears Require Matching Tooth Pitch

Magnetic Gears Require Matching Field Spatial Harmonics
Spatial Harmonic

• Magnetic Filed Produced by a PM Rotor:
  • $B_r = A \times \cos(P \times \theta)$
  • $P =$ Number of Rotor Pole Pairs
  • $P =$ Spatial Harmonic Order of Flux
• In a CMG
  • PM rotor’s have different $P$
  • Modulator “modulates” flux produce by the two rotors so that the flux has matching spatial harmonic order in both airgaps
Flux Modulation

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

\[ B_{rs} = F \star \cos(PR \star (\theta + \delta)) \]

Number of Ring Gear Pole Pairs

PR=10

Surface: Magnetic flux density norm (T)
Flux Modulation

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

\[
B_{rs} = F \cdot \cos(PR \cdot (\theta + \delta))
\]

\[
u = u_{avg} + u_m \cdot \cos(Q \cdot (\theta + \varphi))
\]

Number of Pole Pieces

Pole Piece

Q=11
Flux Modulation

\[
\cos(\beta) \times \cos(\alpha) = \frac{1}{2} (\cos(\beta + \alpha) + \cos(\beta - \alpha))
\]

\[
Q - PR = 11 - 10 = 1 = PS
\]

Sun Gear Pole Pairs

**Fundamental CMG Equation**

\[
Q = PR \pm PS
\]
### 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} )</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>
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Efficient Magnetic Gears

- Main loss source = eddy currents
- Time varying magnetic fields produce electrical fields:
  \[ \nabla \times E = -\frac{\partial B}{\partial t} \]
- Electrical fields drive currents:
  \[ I = \frac{V}{R} \]
- Currents produce heat:
  \[ Q = RI^2 = \frac{V^2}{R} \]
Minimizing Eddy Currents

1. Use non-conductive (non-metallic) Structures
   - Plastics
   - Composites
   - Ceramics ($$$)

2. Laminate Electrical Components
   - Laminated Electrical Steel
   - Laminated Magnets
   - Increases effective (Bulk) resistivity
Tested Efficiency

• NASA’s PT-3
  • FeCo Pole Pieces
    • 0.1 mm laminations
  • 1 mm Magnet Lamination
    • 80 % Magnet Fill
  • Achieves >97% Efficiency
• Results discussed in Dr. Scheidler’s Presentation
Achievable Efficiency

Achievable Efficiency without Magnet Laminations

- Efficiency Vs Mass (No Magnet Laminations)

Achievable Efficiency with Magnet Laminations (Iron Loss Dominates)

- Efficiency Vs Sun gear Electrical Frequency (2mm Magnet Laminations)
Magnetic Gear Thermal Consideration

- As Magnet Temperature Increases
  - Remnant Flux Density Decreases
  - Torque Decreases
  - Efficiency Increases
    - At a given operating point
    - At some point magnets demagnetize
      - Ring magnets highly susceptible
      - Lower temp than catalog value

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>PT-4 2D FEA Torque (Nm)</th>
<th>PT-4 Total Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>370</td>
<td>98.50%</td>
</tr>
<tr>
<td>80</td>
<td>303</td>
<td>99%</td>
</tr>
</tbody>
</table>
Magnetic Gear Thermal Performance

- Efficiency Similar to Mechanical Gears
- Losses are distributed over gear volume (not line contact)
- Lubrication/Liquid cooling not needed
- PT-4
  - Self cooled centripetally pumped flow
  - 80 C magnet temperature predicted
Results of NASA's Magnetic Gear Program to Date

- NASA has improved SOA of magnetic gear specific torque
  - Magnetic Gear Mass
    | Prototype | Specific Torque |
    |-----------|----------------|
    | Previous SOA | ~20 Nm/kg |
    | PT-1       | 20 Nm/kg    |
    | PT-2       | 46 Nm/kg    |
    | PT-3       | 42 Nm/kg    |
    | PT-4       | 49 Nm/kg    |

- Magnetic gears are light compared to electric motor
  - Mag Gear ~ 35 kw/kg
  - Motor ~ 10 kw/kg

Specific Torque Vs Radius (No Carbon Fiber Retaining Hoop)

Magnetic Specific Torque Scales Linearly with Radius
Magnetic Gear Mass

- Heavy Compared to Mechanical Gearboxes
  - Active mass 2-3 x heavier with current capabilities for OH-58
  - Improve by
    - Reducing Modulator Thickness
    - Reducing Airgap
    - Better Magnet Materials

### OH-58 Final Planetary Stage “Active Mass”

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Gear</td>
<td>1.02 kg</td>
</tr>
<tr>
<td>Planet Gear + Roller Bearing</td>
<td>1.56 kg</td>
</tr>
<tr>
<td>Ring Gear</td>
<td>2.26 kg</td>
</tr>
<tr>
<td><strong>Total Active Mass</strong></td>
<td><strong>7.96 kg</strong></td>
</tr>
</tbody>
</table>

### OH-58 Magnetic Gear Electromagnetic Sizing Results

<table>
<thead>
<tr>
<th>Level of Tech</th>
<th>Mechanical Airgap</th>
<th>Modulator Thickness</th>
<th>EM Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA Current Prototype</td>
<td>1.00 mm</td>
<td>2.0 mm</td>
<td>21.96 kg</td>
</tr>
<tr>
<td>Improved Modulator Design</td>
<td>1.00 mm</td>
<td>1.3 mm</td>
<td>20.34 kg</td>
</tr>
<tr>
<td>Improved Manufacturing</td>
<td>0.50 mm</td>
<td>2.0 mm</td>
<td>16.43 kg</td>
</tr>
<tr>
<td>Improved Manufacturing &amp; Design</td>
<td>0.50 mm</td>
<td>1.3 mm</td>
<td>12.00 kg</td>
</tr>
<tr>
<td>Highly Improved Manufacturing</td>
<td>0.25 mm</td>
<td>1.3 mm</td>
<td>8.67 kg</td>
</tr>
</tbody>
</table>
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Magnetically Geared Motors

- Share components between motor and magnetic gear
- Potential for significant mass savings
- Topologies
  1. Outer Stator
  2. Inner Stator Coupled
  3. Inner Stator Uncoupled
  4. Topologies without HS Rotor
External Stator PDD
Coupled Inner Stator PDD
Uncoupled Inner Stator PDD
No High Speed Rotor PDD
Conclusions

• Magnetic gears can achieve
  1. Similar efficiency to mechanical gears
  2. Can be closed thermally without liquid cooling
  3. Have higher mass than mechanical gear
     » Modulator & Airgap improvements could improve mass
     » Potential to combine with motor
  4. Potentially higher reliability than mechanical gears
     » Needs to be demonstrated
Acknowledgements

• NASA Revolutionary Vertical Lift Technology (RVLT) Project
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QUESTIONS ?