High Speed Testing of a High Efficiency Concentric Magnetic Gear

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Outline

• Motivation & summary of NASA’s prior work

• NASA’s high efficiency magnetic gear

• Overview of test rig – E-Drives Rig

• Measurements

• Conclusions
Motivation

• Growth of short haul market & emergence of urban air mobility market
  • Enabled by electrified propulsion systems
  • Prevalence of smaller (lower torque) propulsors
• Most concepts use direct drive
• Geared drives are almost always mass optimal

Direct drive

- + Simpler
- Non-optimal motor and/or fan

Geared drive

- + Optimized motor & fan
- More complex
- Potentially less reliable
NASA’s prior work

- Key conclusions from NASA’s Phase 1 study (understand & improve specific torque)
  - Magnetic performance limited by mechanical features & minimum gap size
  - Concentric magnetic gears are viable, at least for lower torque applications

Performance compared to aerospace gearing

<table>
<thead>
<tr>
<th>Technology</th>
<th>Specific torque, Nm/kg</th>
<th>Efficiency, % “High” output speed (900 rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerospace mechanical gears</td>
<td>55 to &gt;150</td>
<td>98.5 to 99.5</td>
</tr>
<tr>
<td>Magnetic gears</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOA</td>
<td>≤ 17</td>
<td>87.5</td>
</tr>
<tr>
<td>NASA PT-1</td>
<td>20</td>
<td>–</td>
</tr>
<tr>
<td>NASA PT-2</td>
<td>44</td>
<td>&lt; 98</td>
</tr>
</tbody>
</table>

Technology needs: High precision, dynamic data Feasibility of aerospace-grade efficiency

5.6” (141 mm) diameter

6.1” (154 mm) diameter

PT-1

PT-2
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NASA’s magnetic gear prototype 3 (PT-3)

**Goal:** Create a high efficiency version of PT-2 (high specific torque gear)

**Application**
- Loosely tailored to X-57

<table>
<thead>
<tr>
<th>Gear ratio</th>
<th>4.83 : 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>52.8 kW</td>
</tr>
<tr>
<td>Output speed</td>
<td>4,500 rpm</td>
</tr>
<tr>
<td>Output torque</td>
<td>112 Nm</td>
</tr>
<tr>
<td>Input speed</td>
<td>21,735 rpm</td>
</tr>
<tr>
<td>Input torque</td>
<td>23.2 Nm</td>
</tr>
<tr>
<td>Diameter</td>
<td>158 mm</td>
</tr>
<tr>
<td>Length (w/o shafts)</td>
<td>114 mm</td>
</tr>
</tbody>
</table>

**Design**
- 1 pole pair

**Prototype**
- 1 pole pair
NASA’s magnetic gear prototype 3 (PT-3)

Features enabling high efficiency

Laminated magnets
Tradeoff: reduced torque

Lower loss soft magnetic material (FeCo)
Tradeoff: higher cost

Ring gear
Modulator
Sun gear

~1 mm
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E-Drives Rig – Overview

### Input (controlled speed)
- 30 kW
- 40 hp
- 22,000 rpm
- 12 Nm
- 8.9 ft-lb

### Output (controlled torque)
- 30 kW
- 40 hp
- 15,000 rpm
- 100 Nm
- 73.7 ft-lb

#### Test Article
- Precision torque transducer (1 of 2)
- 6 kHz bandwidth

- Vibration isolation table
- Bearing housing (1 of 2)
- High-speed disc coupling (1 of 3)

**Measurements:** torque (in/out), speed (in/out), power (in/out), vibration, temperature

**Note:** noted specifications are for continuous operation
E-Drives Rig – Uncertainty Analysis

- Torque uncertainty depends on torque & temperature
- Efficiency uncertainty depends on input speed, output torque, & gear ratio
- At a 95% confidence level, can often measure…

<table>
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<tr>
<th>Torque to better than</th>
<th>Power to better than</th>
<th>Efficiency to better than</th>
</tr>
</thead>
<tbody>
<tr>
<td>±0.03%</td>
<td>±0.2%</td>
<td>±0.3%</td>
</tr>
</tbody>
</table>

From measured torques & speeds

From measured powers

Efficiency uncertainty (%)
(for gear ratio 4.83 : 1, torque transducer 10 C above its calibration temperature)
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  • **Measurements**
• Conclusions
Measurements – PT-3 (High Efficiency)

Output side (high torque)  Input side (low torque)

Torque reaction structure (does not constrain radial or axial position)
Measurements – PT-3 (High Efficiency)

4.83 : 1 reduction ratio

100 rpm

20.8 rpm
Test matrix - PT-3 testing round 2

PT-3 maximum torque = 112 Nm

PT-3 continuous operating torque = 85% * 112 Nm

Designed speed limit of PT-3

Accessible operating space

Accessible after balancing a coupling
Tare loss correction

- Measured power loss includes contributions from the rig itself
  - E-Drives Rig’s bearing housings and 2 couplings are located between the torque transducers
- Tare loss vs. speed measured when prototype replaced by straight shaft
  - Limited to 5,000 rpm by vibration

\[
P_{\text{loss}} = \omega (0.5 \mu L d)
\]

\( P_{\text{loss}} \) = rotational speed in rad/s
\( \omega \) = coefficient of friction = 0.002 (angular contact, non-contact seal)
\( \mu \) = dynamic load rating = 7.4 kN
\( L \) = bearing bore diameter = 25 mm

\[
y = 0.0018x^{1.1684} \\
R^2 = 0.9984
\]
Tare loss correction

Power loss of prototype

\[ P_{\text{in}} - P_{\text{out}} - \frac{1}{2} (0.0018 \cdot \text{RPM}_{\text{in}}^{1.1684}) - \frac{1}{2} (0.0018 \cdot \text{RPM}_{\text{out}}^{1.1684}) \]

Tare loss, input side

Tare loss, output side

need to extrapolate measured tare loss for this

- Assume measured tare loss on input & output sides are equal
PT-3 Power loss – effect of torque

- Power loss is independent of torque
  - Important for efficiency modeling
  - Allows accurate extrapolation of data to higher torques

Note: data from PT-3 testing round 1
PT-3 Power loss – measured and predicted

- Electromagnetic losses dominate
- Predicted total loss is reasonably accurate over tested range, but will deviate as speed increases
PT-3 Power loss – extrapolation

- Power loss fit by equation commonly used to describe electromagnetic losses – used to extrapolate loss to higher speeds
- Power loss fit well, but small errors can lead to appreciable efficiency errors at lower torque

Power loss fit
(data with 95% confidence error bars)

\[
y = 0.0016x^1 + 1.1e-11x^{1.5} + 3.8e-6x^2\]

\[r^2 = 0.9543\]

Prediction vs measured
(with 95% confidence error bars)
PT-3 Efficiency map – measured data only

- Efficiency increases as torque increases & speed decreases
- Efficiency over 98.7% measured
Extrapolated efficiency exceeds 99.5% at low speeds

> 99% efficiency up to about 5,000 rpm input speed; ~97% efficiency at max operating torque & speed
PT-3 torque ripple

0.3% to 2% of max input torque

0.2% to 1% of max output torque
Motivation & summary of NASA’s prior work

NASA’s high efficiency magnetic gear

Overview of test rig – E-Drives Rig

Measurements

Conclusions
Conclusions

- **E-Drives Rig**
  - Measurements can be used to confidently calculate efficiencies up to 99.7% for most tests

- **Power loss in magnetic gears**
  - Can extrapolate power loss & efficiency to higher torque with high accuracy and to higher speed with moderate accuracy

- **PT-3 efficiency**
  - Laminated permanent magnets enable high efficiency, but reduce torque
    - > 99% up to input speeds of 5,000 rpm
    - ~97% at max operating speed

- **PT-3 torque ripple**
  - RMS ripple 0.2% to 2% of max torque

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**Future work**

- Measure efficiency, torque ripple, & dynamic response to torque overload of PT-3, PT-4, & PT-5 after reducing unbalance in the rig & installing a new dyno and new measurement hardware
- Evaluate the manufacture & benefits of *magnetically-geared motors*, with emphasis on improving drivetrain reliability
Acknowledgements

• NASA Revolutionary Vertical Lift Technology (RVLT) Project
• NASA Internal Research & Development Project
• Vivake Asnani – NASA Glenn Research Center
THANK YOU