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

Application

• Loosely tailored to X-57

Design

Prototype

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gear ratio</td>
<td>4.83 : 1</td>
</tr>
<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>
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

National Aeronautics and Space Administration
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E-Drives Rig – Overview

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

Note: noted specifications are for continuous operation

<table>
<thead>
<tr>
<th>Input (controlled speed)</th>
<th>Output (controlled torque)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 kW - 22,000 rpm - 12 Nm</td>
<td>30 kW - 15,000 rpm - 100 Nm</td>
</tr>
<tr>
<td>40 hp - 8.9 ft-lb</td>
<td>40 hp - 73.7 ft-lb</td>
</tr>
</tbody>
</table>

Motor

Precision torque transducer (1 of 2)
6 kHz bandwidth

Vibration isolation table

Bearing housing (1 of 2)

High-speed disc coupling (1 of 3)

Dynamometer

Test Article

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

Efficiency uncertainty (%)
(for gear ratio 4.83 : 1, torque transducer 10 C above its calibration temperature)
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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)

100 rpm

4.83 : 1 reduction ratio

20.8 rpm
Test matrix - PT-3 testing round 2

PT-3 maximum torque = 112 Nm

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

Accessible operating space
Accessible after balancing a coupling

Design speed limit of PT-3
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

**Prediction:**

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

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

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

Power loss of prototype = $P_{in} - P_{out} - \frac{1}{2} (0.0018RPM_{in}^{1.1684}) - \frac{1}{2} (0.0018RPM_{out}^{1.1684})$

- 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
• 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
PT-3 Efficiency map – measured data & extrapolation

- 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

Maximum torque = 112 Nm
Continuous operating torque = 85% * 112 Nm
Designed speed limit of PT-3
PT-3 torque ripple

0.3% to 2% of max input torque

0.2% to 1% of max output torque
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- **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

**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
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