NASA's Magnetic Gearing Research for Electrified Aircraft Propulsion

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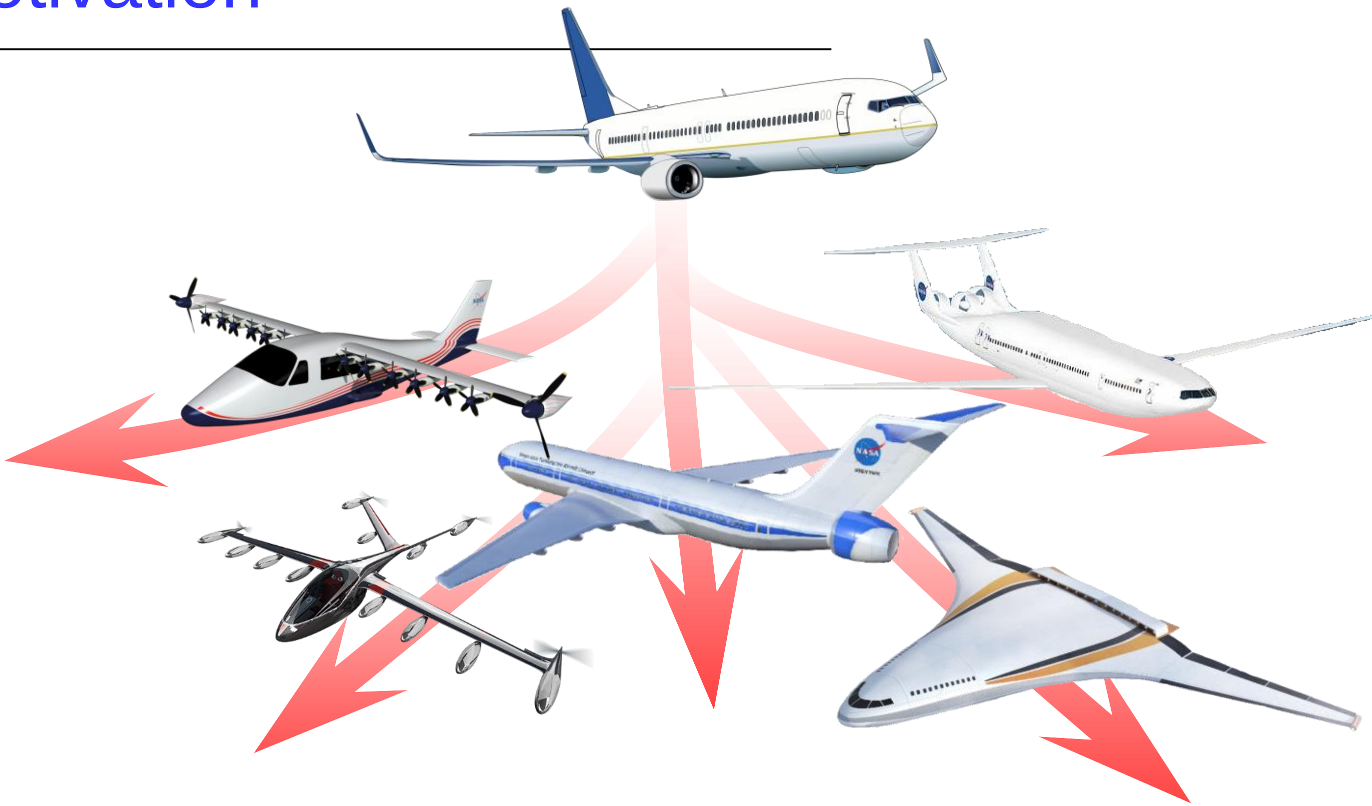
Outline

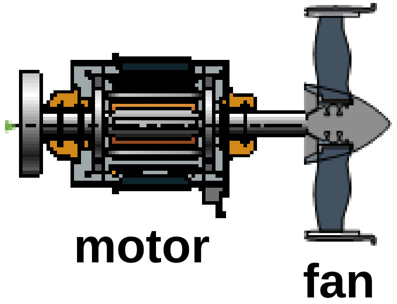
- Motivation
- Principles of operation
- Technology development at NASA
- Future work
- Conclusions

Motivation

- NASA set goals for aircraft efficiency, emissions, reliability, and noise [1]
  - Parallel large & small aircraft development
  - Economic benefit of alternative propulsion
- Electrified aircraft propulsion is a key enabler
- Most concepts use direct drive
- Geared drives are almost always mass optimal



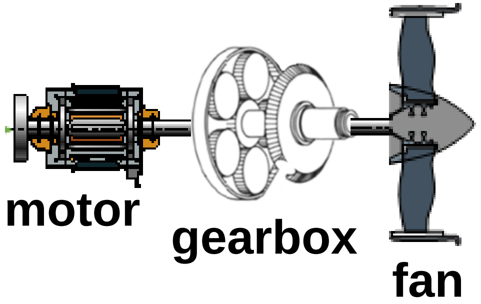
Direct drive



\+ Simpler

− Non-optimal motor and/or fan

Geared drive



\+ Optimized motor & fan

− More complex

− Potentially less reliable

Motivation

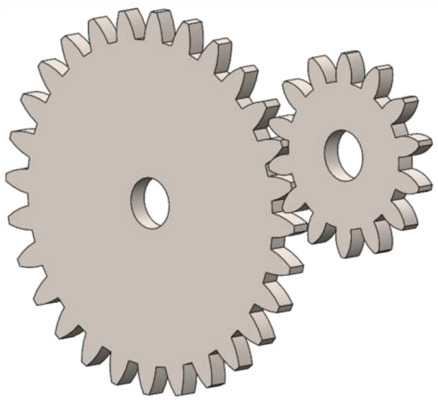
Mechanical gearing

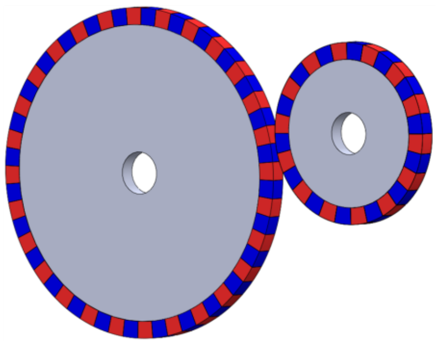
Pros

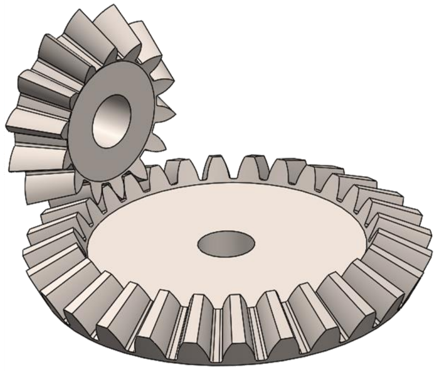
+ High / very high torque/mass (**specific torque**)
+ High / very high efficiency
+ Mature technology

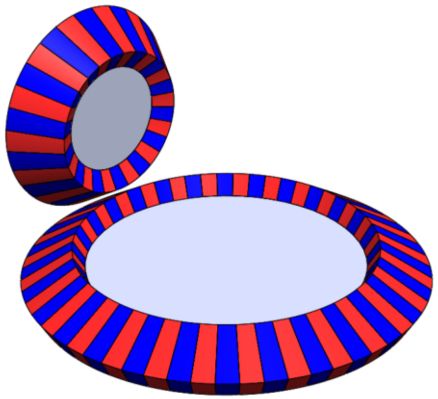
Cons

− 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

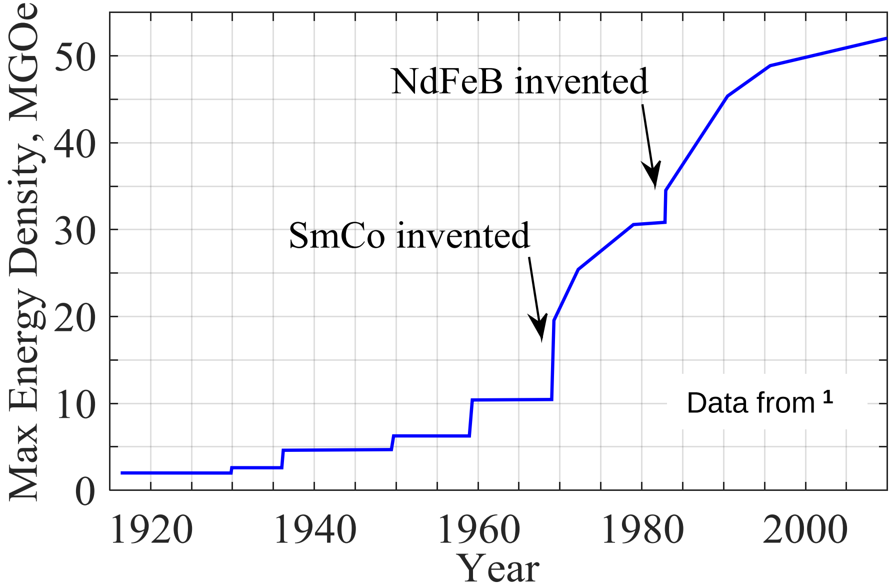
Cons

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

Background

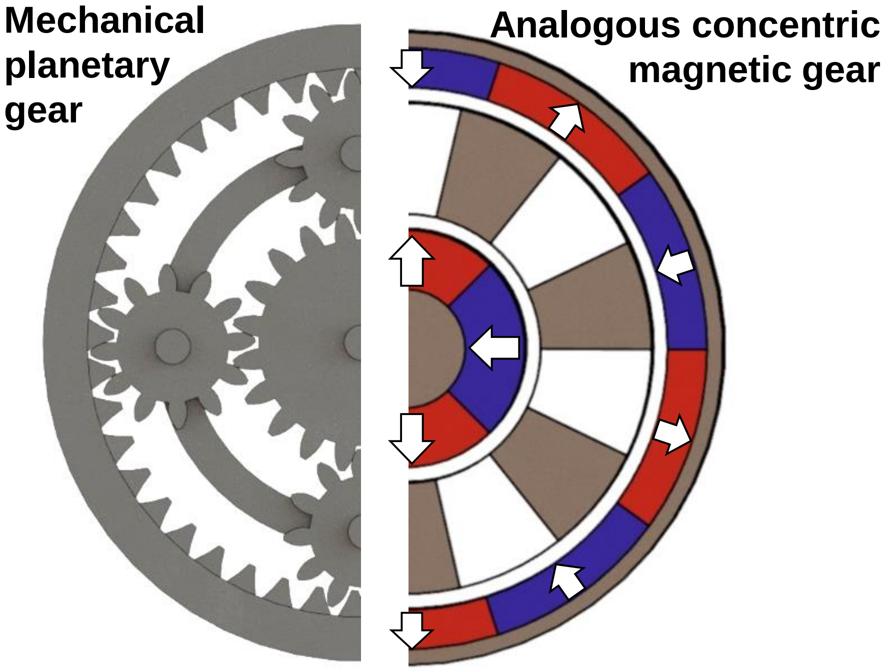
Key historical developments

- **1901** – 1st invention
- **<1960s** – primarily electromagnets
- **1966** – SmCo magnets invented
- **1983** – NdFeB magnets invented
- **2001** – Concentric magnetic gear (CMG) mathematics



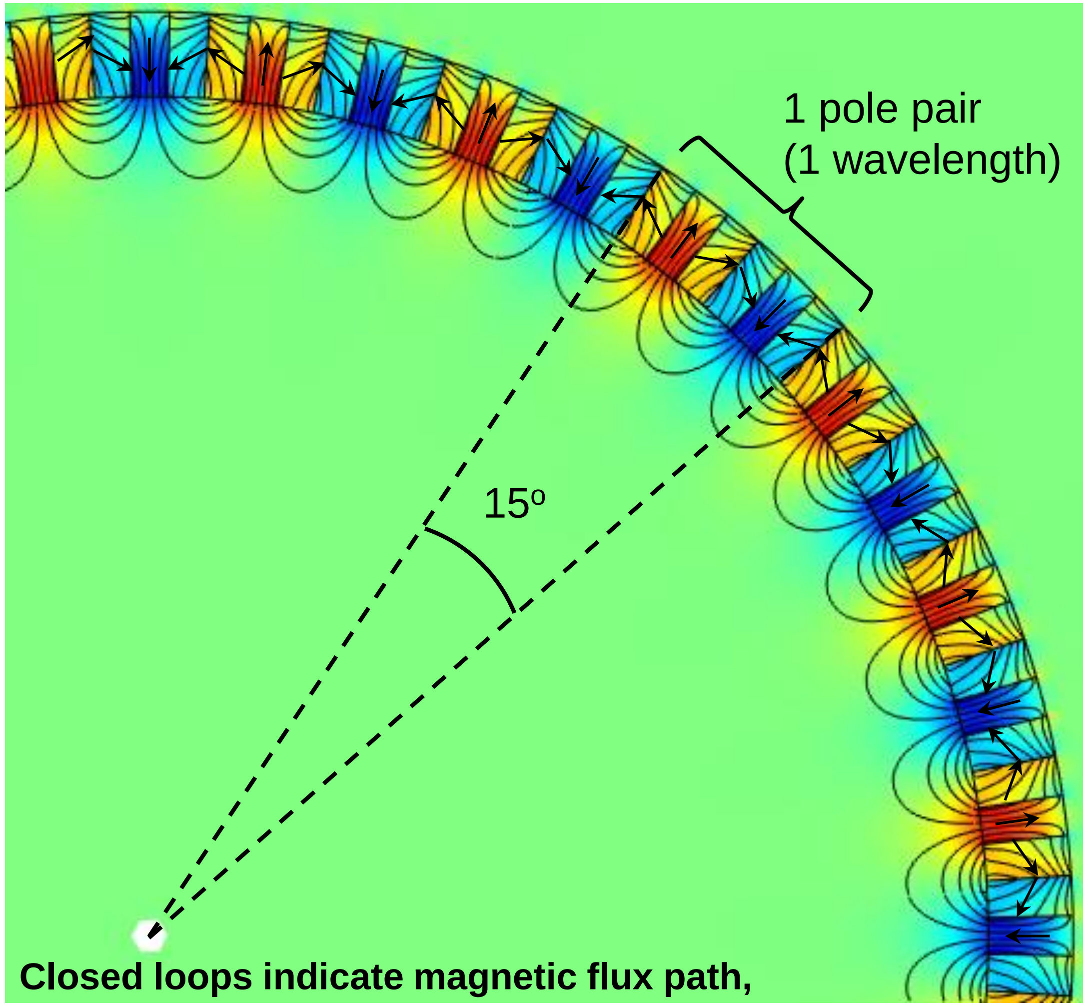
Why we selected CMG

- Concentric input & output is most logical for most concepts
- High specific torque
- Easily integrated in electric machines

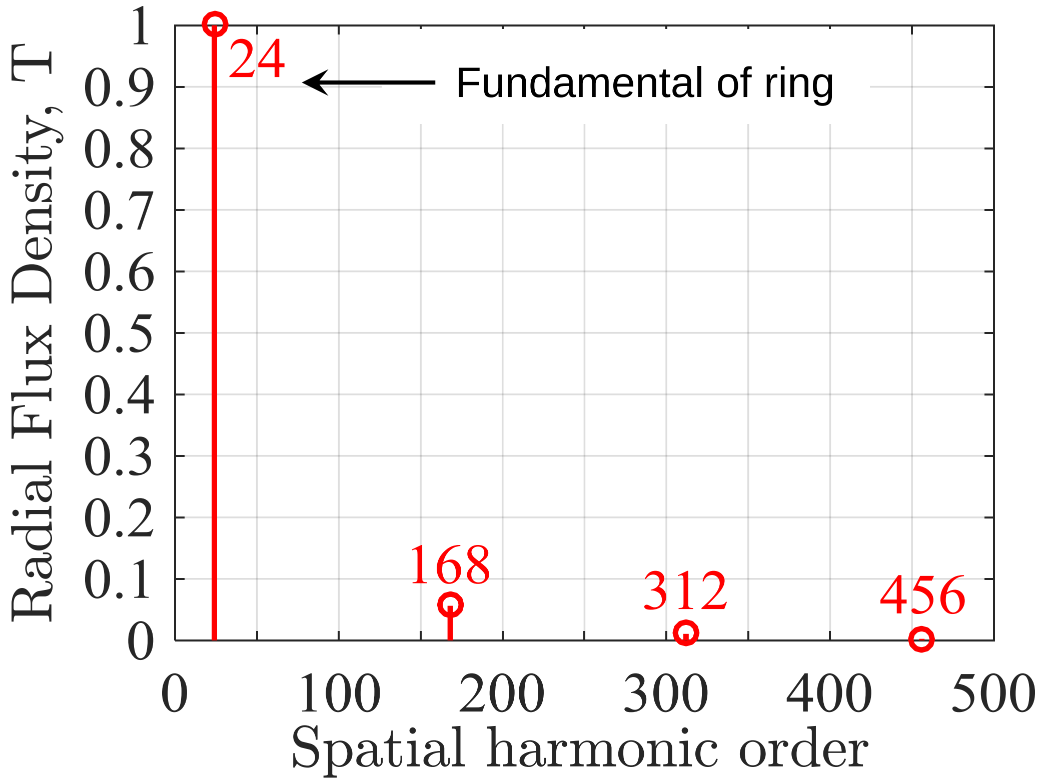


Principles of Operation

- **Example:** 4:1 gear ratio, 24 pole pairs in ring (15° wavelength), 6 magnets per pair

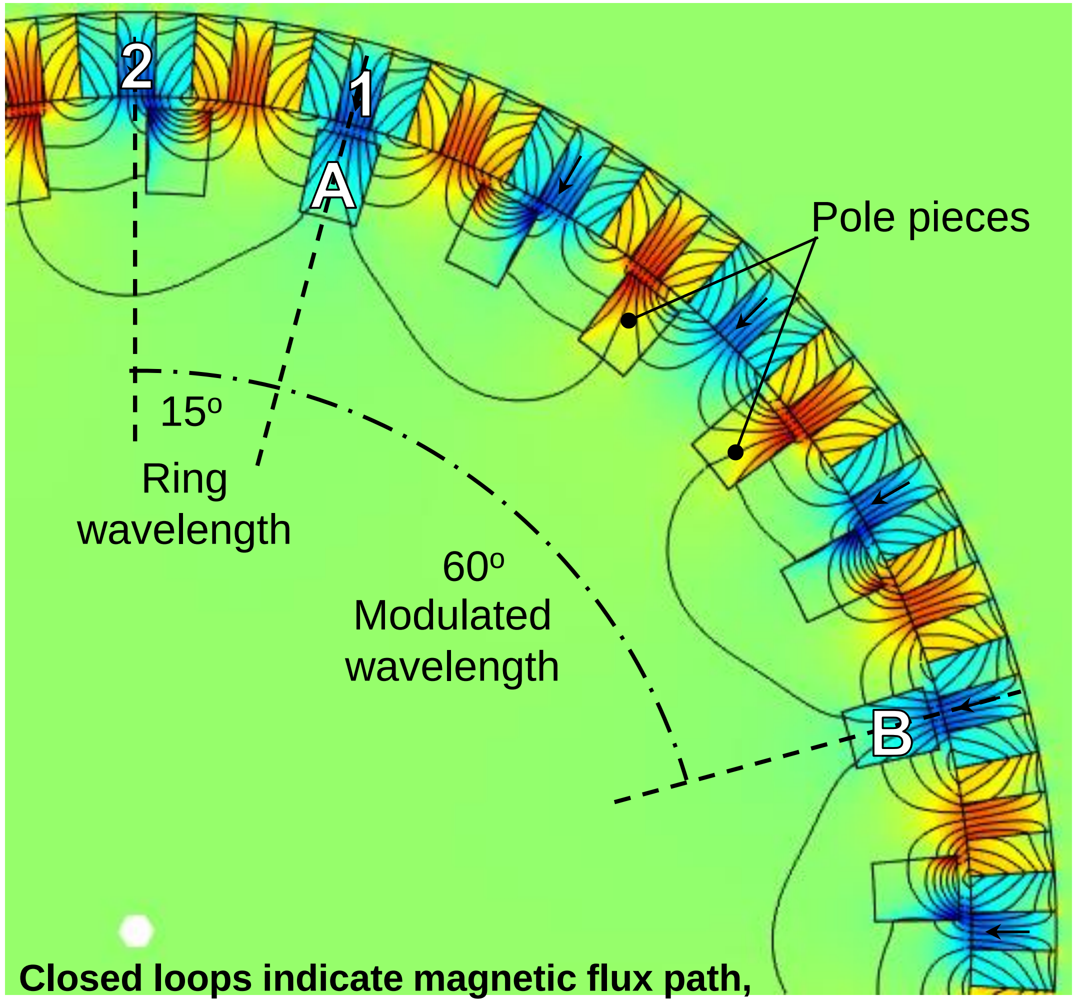


Closed loops indicate magnetic flux path, color indicates radial component of flux



Principles of Operation

- **Example:** 4:1 gear ratio, 24 pole pairs in ring (15º wavelength), 6 magnets per pair



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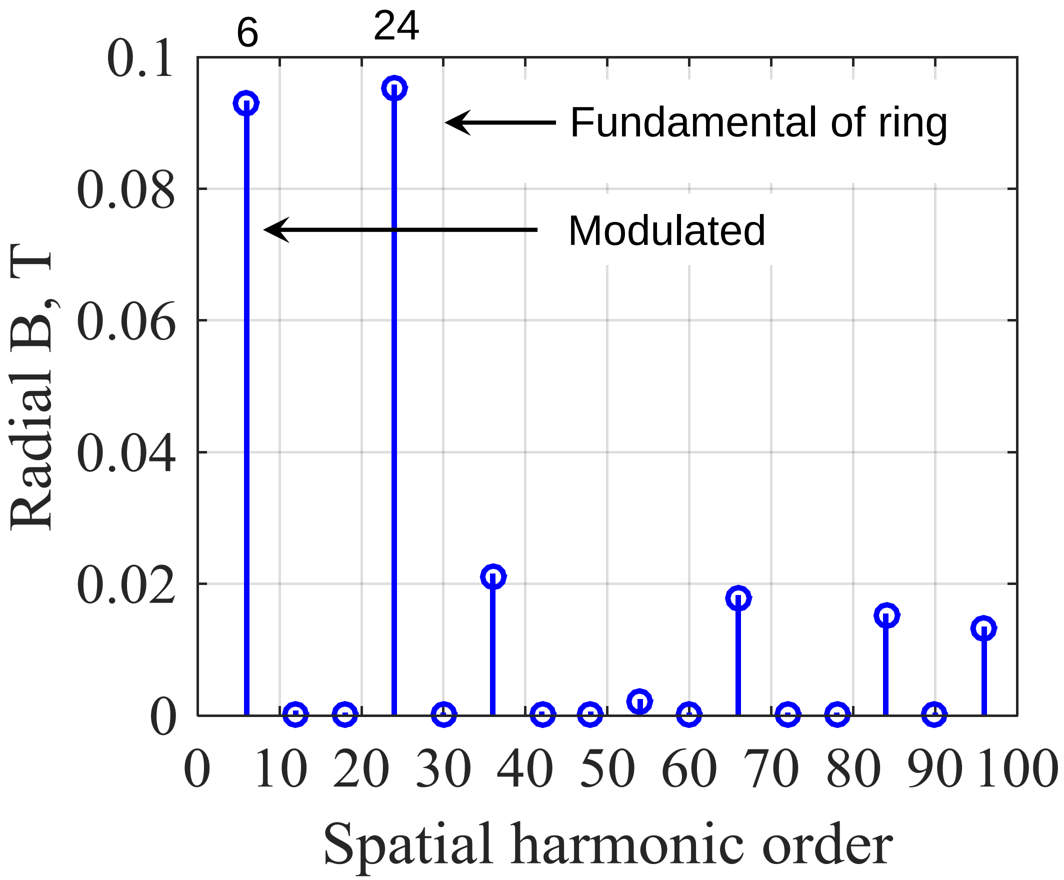
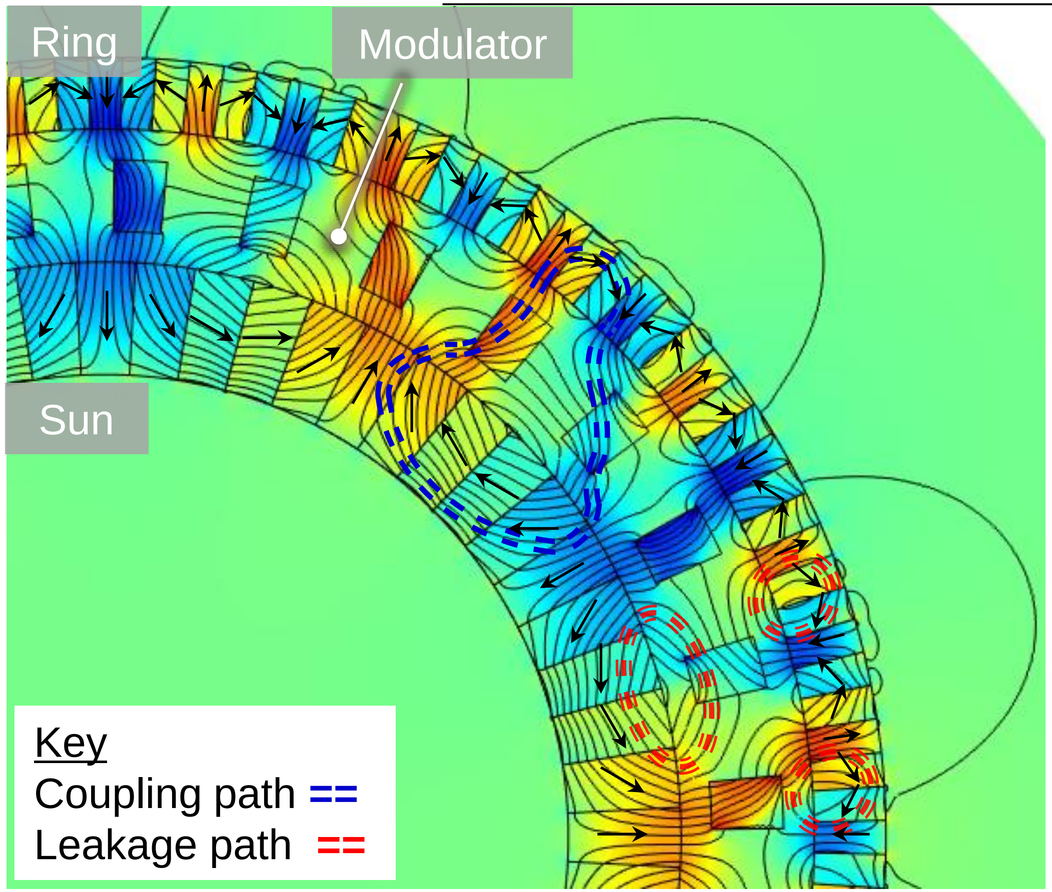
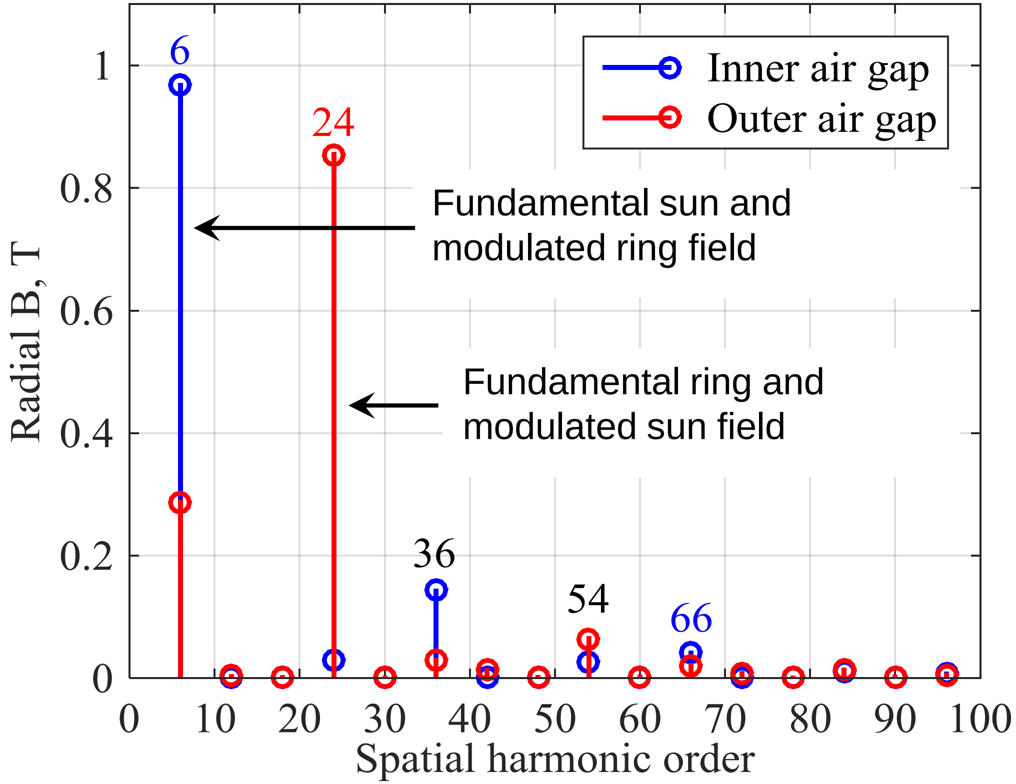


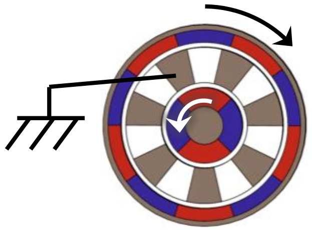
$$N_{\text{modulator}} = N_{\text{ring}} + N_{\text{sun}}$$

Principles of Operation

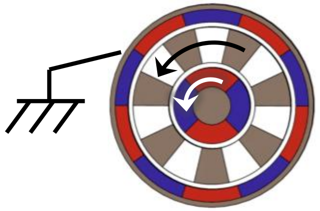




- Key design variables
  - # of magnetic pole pairs ("teeth")
  - # magnets
  - Radial thickness of components & air gaps



$$GR = \frac{N_{ring}}{N_{sun}}$$



$$GR = 1 + \frac{N_{ring}}{N_{sun}}$$

Research Needs

R&D needs in the field

- **Understand scaling**
- **Thermal management**
- Data at higher speeds – efficiency, continuous operation
- **Enhanced high-speed efficiency**
- Advancement of other configurations
  - Shaft angle change
  - Combining inputs
  - Higher ratios

Technology Development at NASA

2-1/2 year project

- Create fundamental understanding
- Compare to mechanical gearing for aerospace applications

Focus areas

- Phase 1 – specific torque
- Phase 2 – efficient high-speed operation
- Phase 3 – motor/gear integration

Progress

- Phase 1 was recently completed.
- Two prototypes were developed to understand specific torque

Prototype 1 (PT-1)

- **Goal:** To gain design & manufacturing experience
- Loosely tailored to X-57 high-lift propulsors
  - Ø152 mm (6 in), ~4:1 speed reduction, 4500 rpm
- Off-the-shelf magnets
- Limited design optimization
- 3D printed structures

Lessons learned

- COTS magnets lead to large gaps between magnets in the sun
- Magnetic forces can deform/damage the structures during assembly

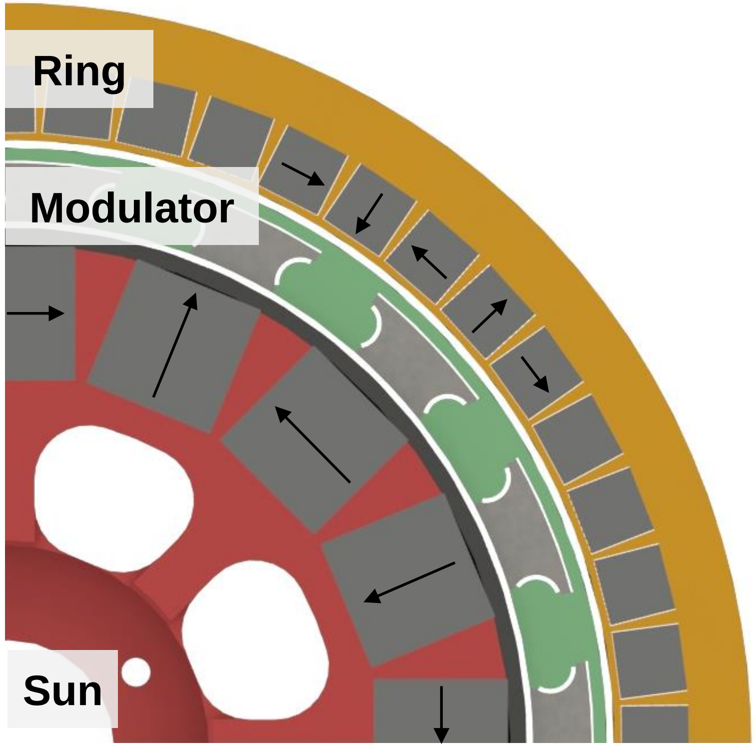
Specific torque

- 2D simulation: 31 Nm/kg

35% reduction

- Measurement: 20 Nm/kg

Design



Demonstration of gear ratio

Prototype 2 (PT-2)

- **Goal:** Maximize specific torque
- Multi-stage parametric study
- Custom-shaped magnets

Specific torque

- 2D simulation: 61 Nm/kg

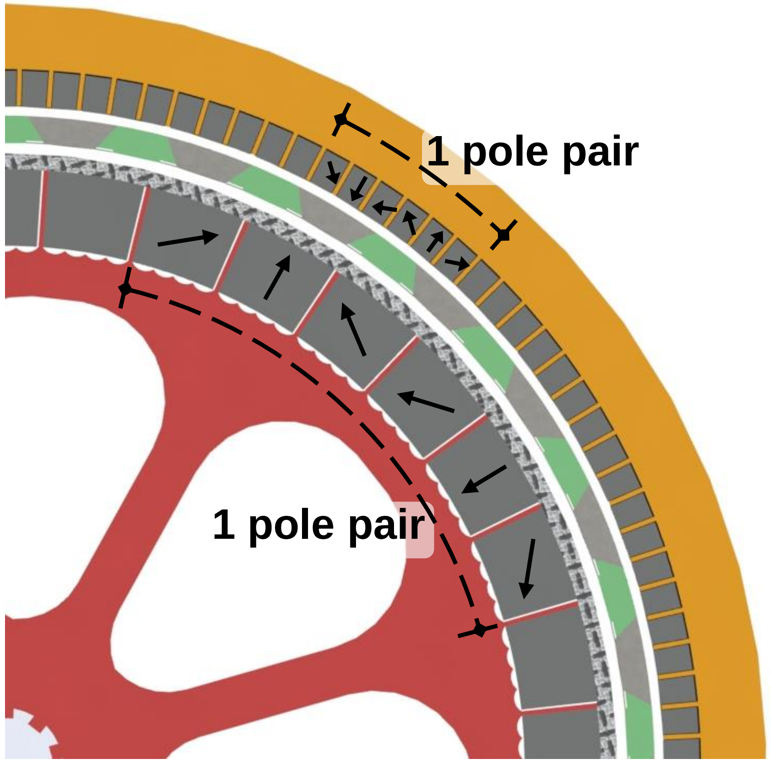
  23% reduction

- Measurement: 47 Nm/kg (>2X PT-1)

Lessons learned

- Magnetic gap thickness fundamentally limits specific torque
- Mechanical design features that enable thinner magnetic gaps can improve specific torque

Design



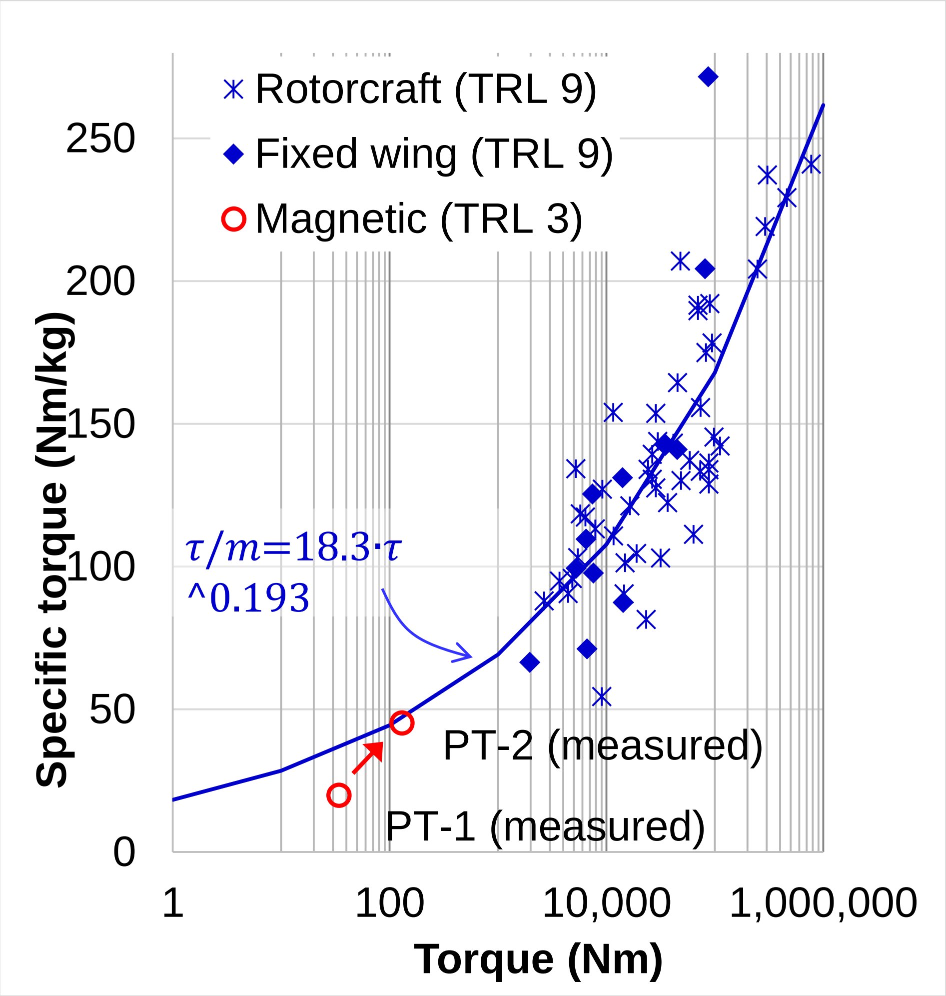
Prototype

Prototype Performance

	PT-1	PT-2
Torque (Nm)		
2D simulation	53.0	178
Measurement	34.0	134.8
Mass (kg)		
Active	1.0 (59 %)	1.7 (59 %)
Structural	0.7 (41 %)	1.2 (41 %)
Total	1.7	2.868
Specific torque (Nm/kg)		
2D simulation	31	61
Measured	20	47

- Specific torque is only 3% less than an aircraft gearbox
- Conclusive comparison requires more data & higher TRL
  - Thermal & dynamic considerations neglected so far
  - Can reduce mass with smaller air gaps & better structural integration
  - Simultaneously need high specific torque & high efficiency
- Scaling to other torque levels is unknown at this point

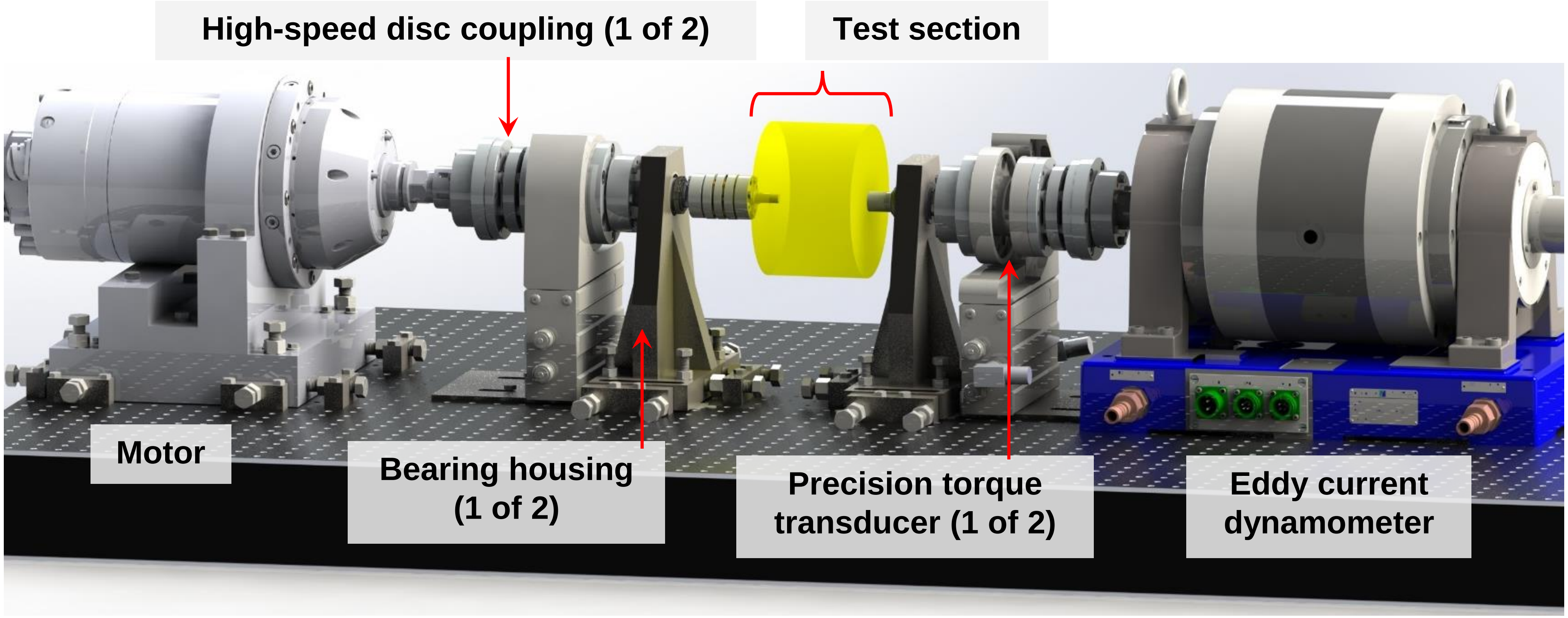
Performance compared to aircraft transmissions



Data courtesy of Dr. Tim Krantz (NASA GRC)

Test Rig Development

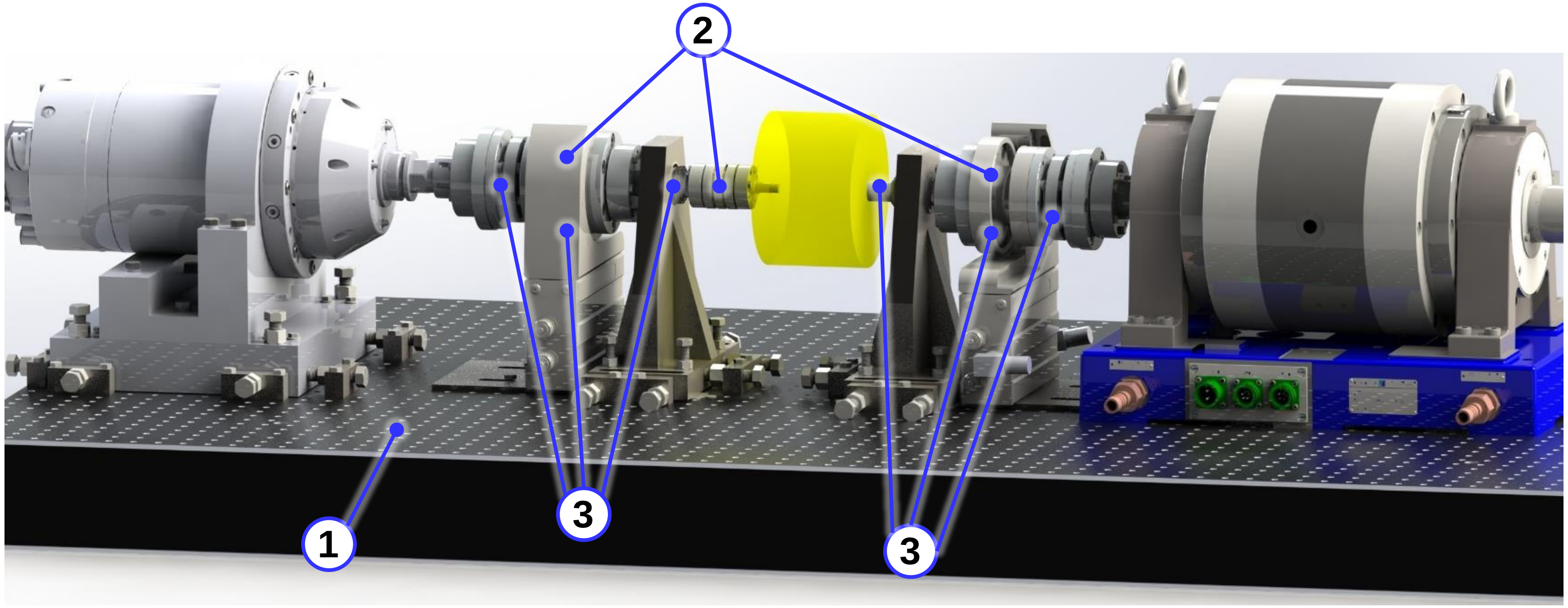
- Motivation**:** comprehensive characterization of CMG needed & very sparse description of experiments in literature
- **Purpose:** study components of electrified drivetrain
- Rotating system driven by 30 kW motor



Test Rig Development

Specialized features

1. Adaptability – support table permits wide variety of test articles (including those with parallel offset between input & output shafts)
2. Very high precision – efficiency calculated from output/input mechanical power • < ±0.02% uncertainty in measured torque & speed • couplings that impose low forces when misaligned
3. Dynamic measurement – sensors with 6 kHz bandwidth • couplings with zero backlash • lightweight & stiff components • vibration isolation table



Test Rig Development

- Controlled parameters**:** motor's speed & dynamometer's torque
- Eddy current dynamometer
  - Suitable for emulating moderate to high speed propellers (~1,000 to 4,000 rpm)
- **Disc couplings:** several benefits, but low misalignment capability
- Measurements
  - Torque (capacity, ripple, & response to overload)
  - Speed
  - Transverse vibration
  - Temperature (bearings & prototype)
- **Bearing loss vs speed measured & subtracted**

Key specifications

Input	Max torque (continuous)	16 Nm
	Max speed	22,000 rpm
	Max power (continuous)	30 kW
Output	Max torque (continuous)	100 Nm
	Max speed	15,000 rpm *
	Max power (continuous)	30 kW
Measurement uncertainty at nominal state**	Torque	±0.02%
	Average efficiency	±0.11%
	Instantaneous efficiency	±0.13%
	Measurement bandwidth	6 kHz

* with minor balancing
** not including parasitic losses or the effect of misalignment

Future Work

Phase 2 – enable high efficiency at high speeds

- **Data**
  - Speed dependence of torque, efficiency, vibration, & temperature
- **Design**
  - Reduce driving mechanism for eddy currents
  - Unconventional solutions for magnet & pole piece containment
- **Materials**
  - Alternative or laminated magnetic materials
  - Electrically-insulating, thermally-conductive structural materials

Phase 3 – integration in electric motors

- Focus**:** motor-to-rotor stages of the quadrotor and tiltwing
- Explore several topologies from literature

Conclusions

- Studied torque-to-mass ratio of concentric magnetic gear
- Designed, built, and statically tested 2 prototypes
  - **PT-1** – rapid build, understand design & fabrication issues
  - **PT-2** – nearly optimized torque-to-mass ratio
- Key conclusions from NASA's Phase 1 (understand & improve specific torque)
  - **Strong coupling between mechanical & magnetic designs**
    - Magnetic performance limited by mechanical features & min. gap size
  - **Concentric magnetic gears are viable, at least for lower torque applications** (e.g., emerging electrified short haul aircraft)
  - Improvement relies on reducing air gaps, better integration, lighter structures
- Developed a new 30 kW (40 hp) rotating test rig to study components of electrified drivetrains
  - Test a wide variety of test articles
  - Directly measure mechanical efficiency with very high precision
  - Measure dynamic responses and vibration

Acknowledgements

- NASA Revolutionary Vertical Lift Technology (RVLT) Project
- NASA Internal Research & Development Project

References

1. Constantinides, S., “The demand for rare Earth materials in permanent magnets,” Proc. of 51st Conf. of Metallurgists, Niagra Falls, Canada, 2012.

QUESTIONS ?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