High Speed Testing of a High Efficiency Concentric Magnetic Gear

Justin Scheidler **Zachary Cameron** Thomas Tallerico

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

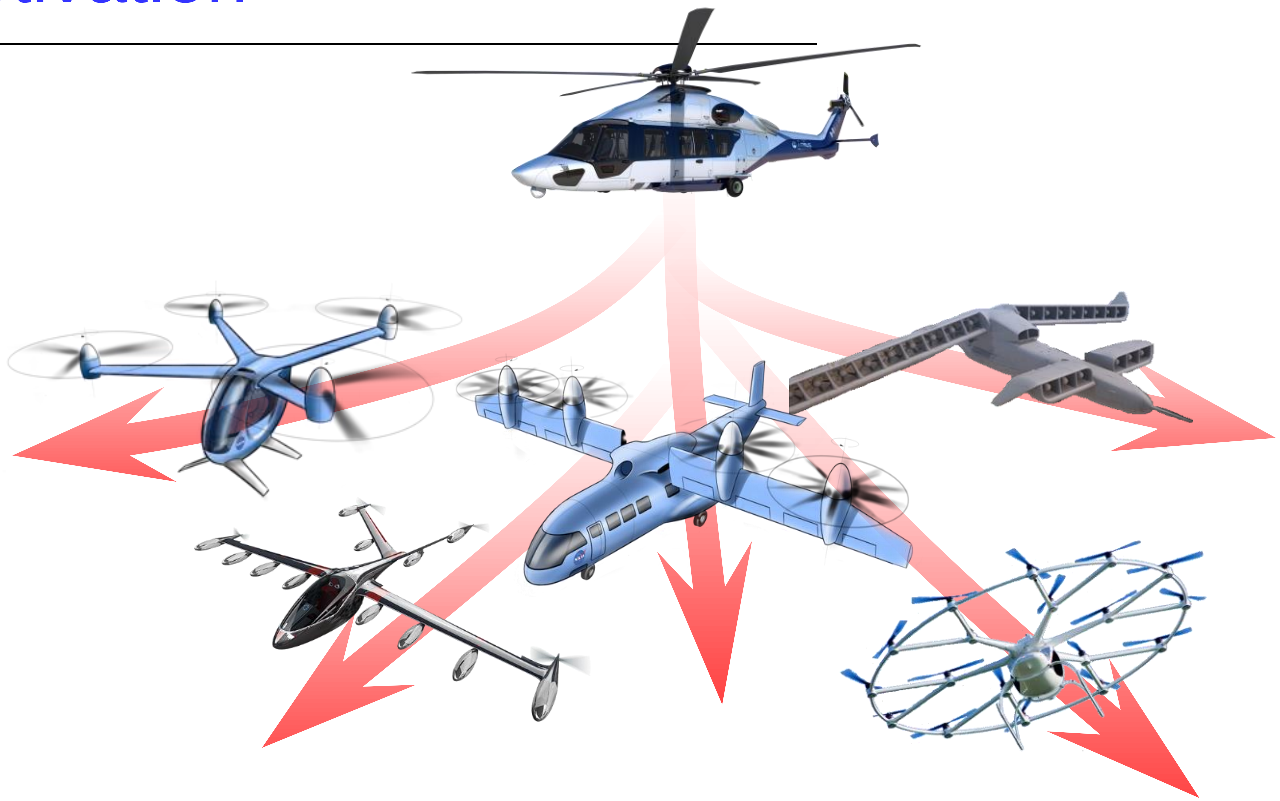
Propulsion & Power Technical Meeting
Hampton, VA
Oct 29-30, 2019

Outline

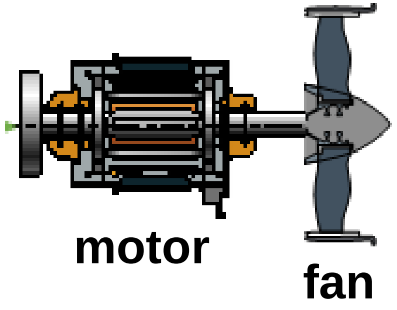
- Motivation & summary of NASA's prior work
- NASA's high efficiency magnetic gear
- Overview of test rig – E-Drives Rig
- Measurements
- Conclusions

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

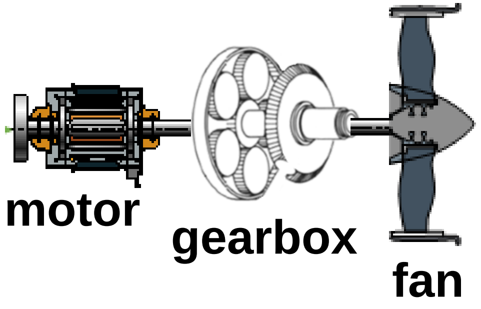


Direct drive



+ 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

PT-1

5.6" (141 mm) diameter

PT-2

6.1" (154 mm) diameter

Performance compared to aerospace gearing

Technology			Specific torque, Nm/kg	Efficiency, % "High" output speed (900 rpm)
Aerospace mechanical gears			55 to >150	98.5 to 99.5
Magnetic gears	SOA		≤ 17	87.5
	NASA	PT-1	20	–
		PT-2	44	< 98

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

Outline

- Motivation & summary of NASA's prior work
- **NASA's high efficiency magnetic gear**
- Overview of test rig – E-Drives Rig
- Measurements
- Conclusions

NASA's magnetic gear prototype 3 (PT-3)

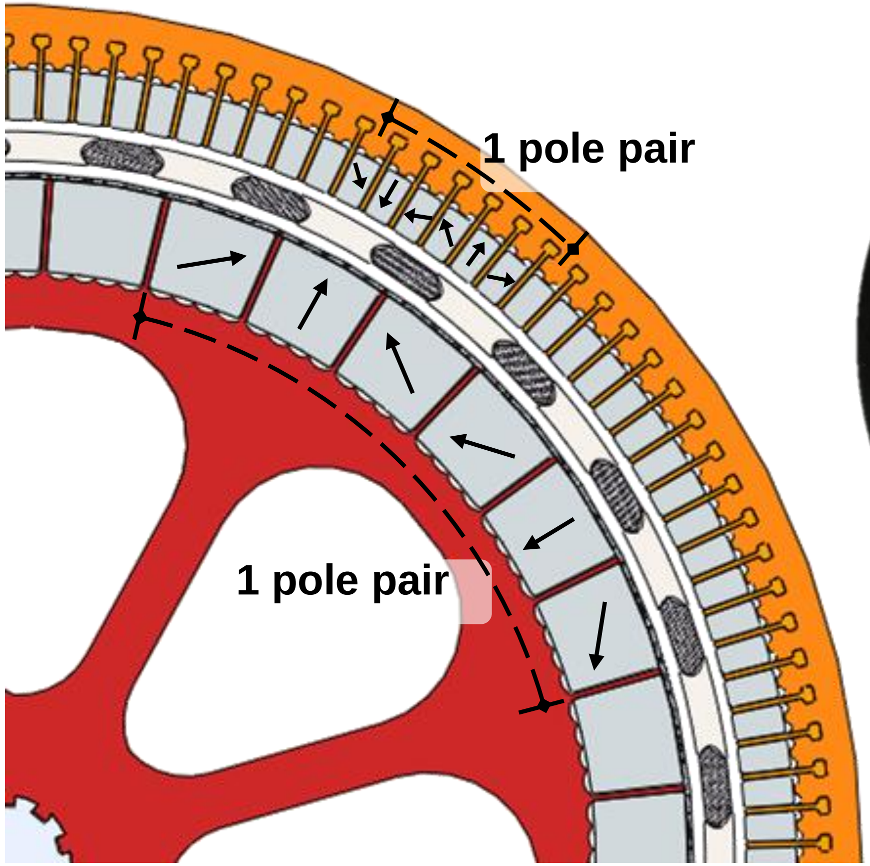
Goal: Create a high efficiency version of PT-2 (high specific torque gear)

Application

- Loosely tailored to X-57

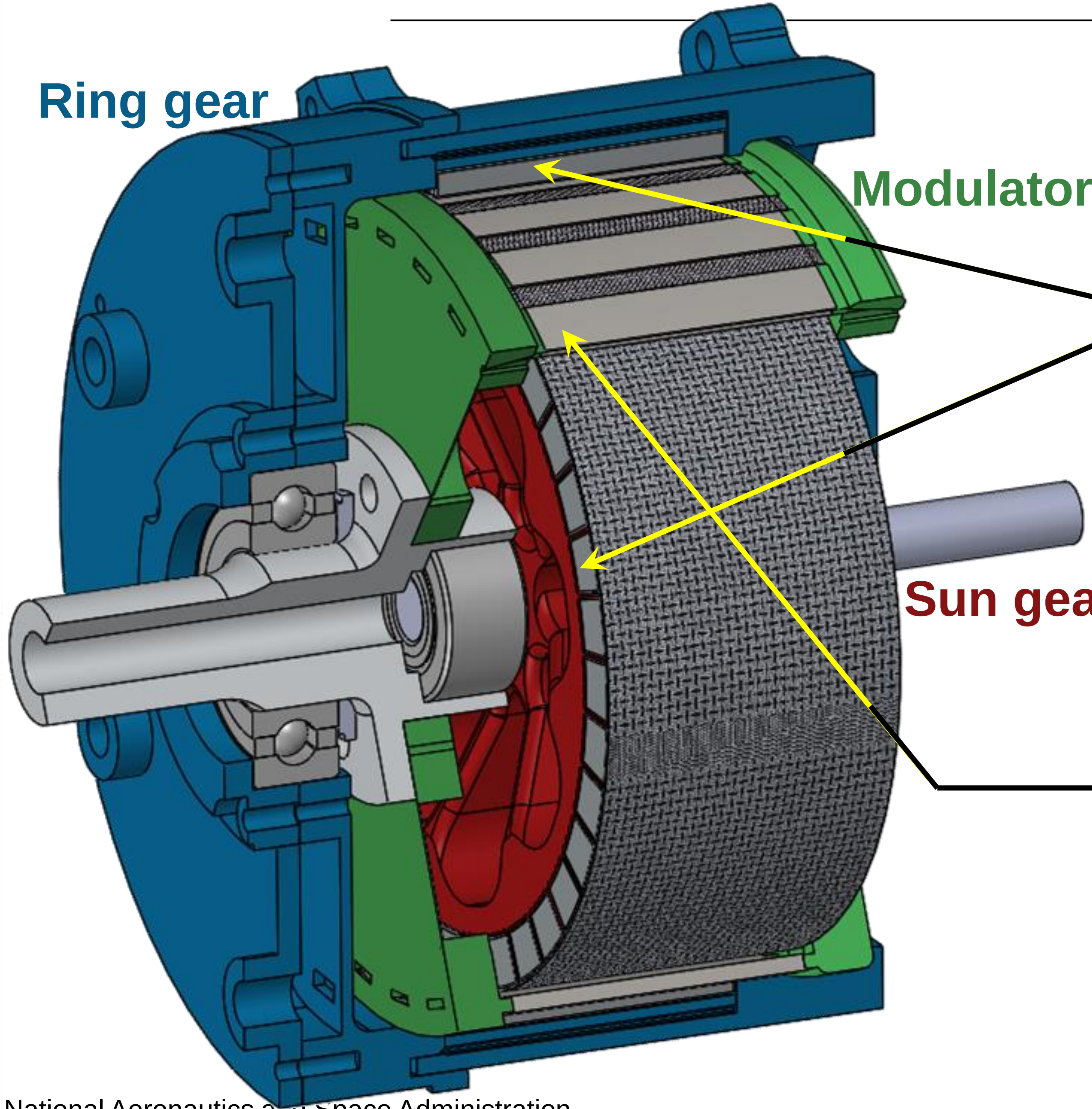
Gear ratio	4.83 : 1
Power	52.8 kW
Output speed	4,500 rpm
Output torque	112 Nm
Input speed	21,735 rpm
Input torque	23.2 Nm
Diameter	158 mm
Length (w/o shafts)	114 mm

Design



Prototype

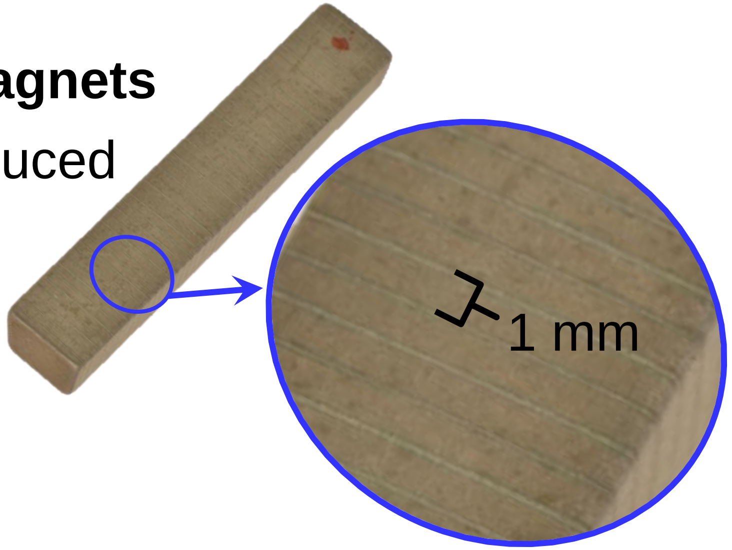
NASA's magnetic gear prototype 3 (PT-3)



Features enabling high efficiency

Laminated magnets

Tradeoff: reduced torque



Lower loss soft magnetic material (FeCo)

Tradeoff: higher cost

Outline

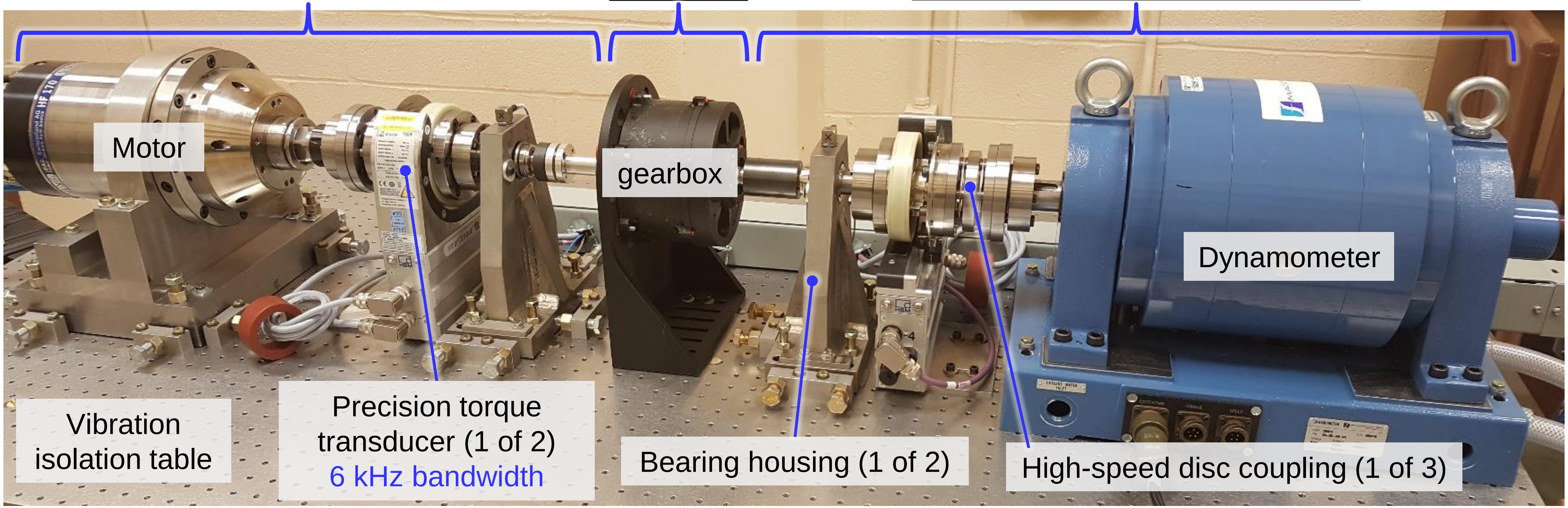
- Motivation & summary of NASA’s prior work
- NASA’s high efficiency magnetic gear
- **Overview of test rig – E-Drives Rig**
- Measurements
- Conclusions

E-Drives Rig – Overview

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

Test Article

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



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

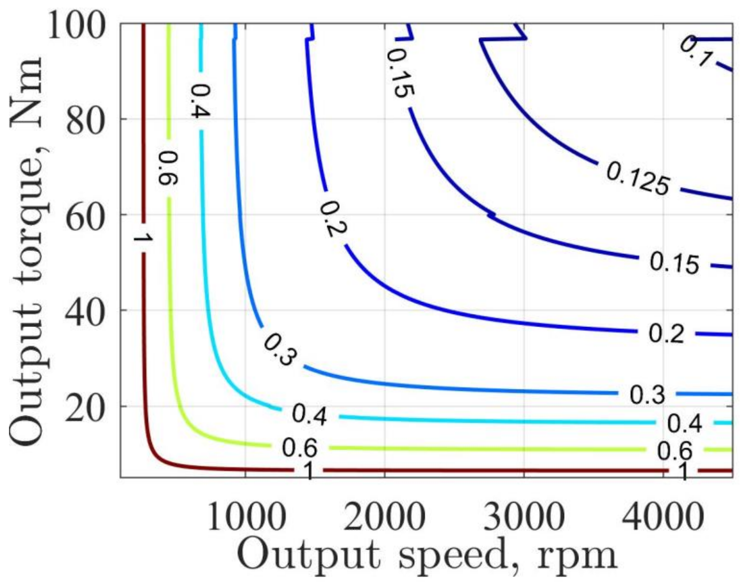
<u>Note</u>**:** noted specifications are for continuous operation

E-Drives Rig – Uncertainty Analysis

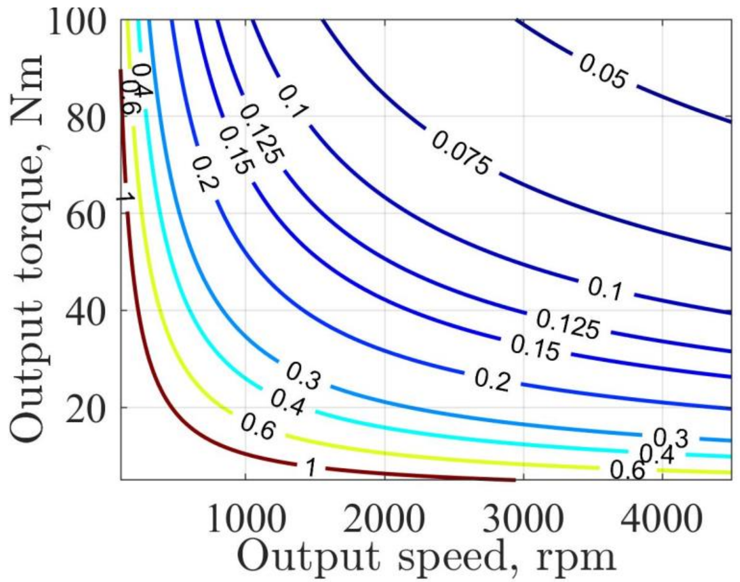
- Torque uncertainty depends on torque & temperature
- Efficiency uncertainty depends on input speed, output torque, & gear ratio
- At a 95% confidence level, can often measure…

Torque to better than ±0.03%	Power to better than ±0.2%	Efficiency to better than ±0.3%

From measured torques & speeds



From measured powers



Efficiency uncertainty (%)

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

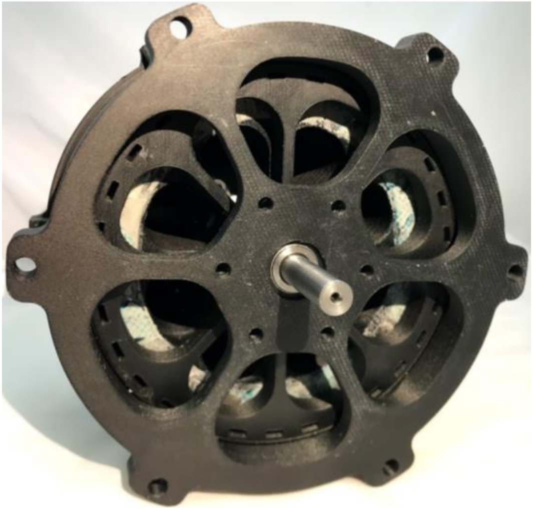
Outline

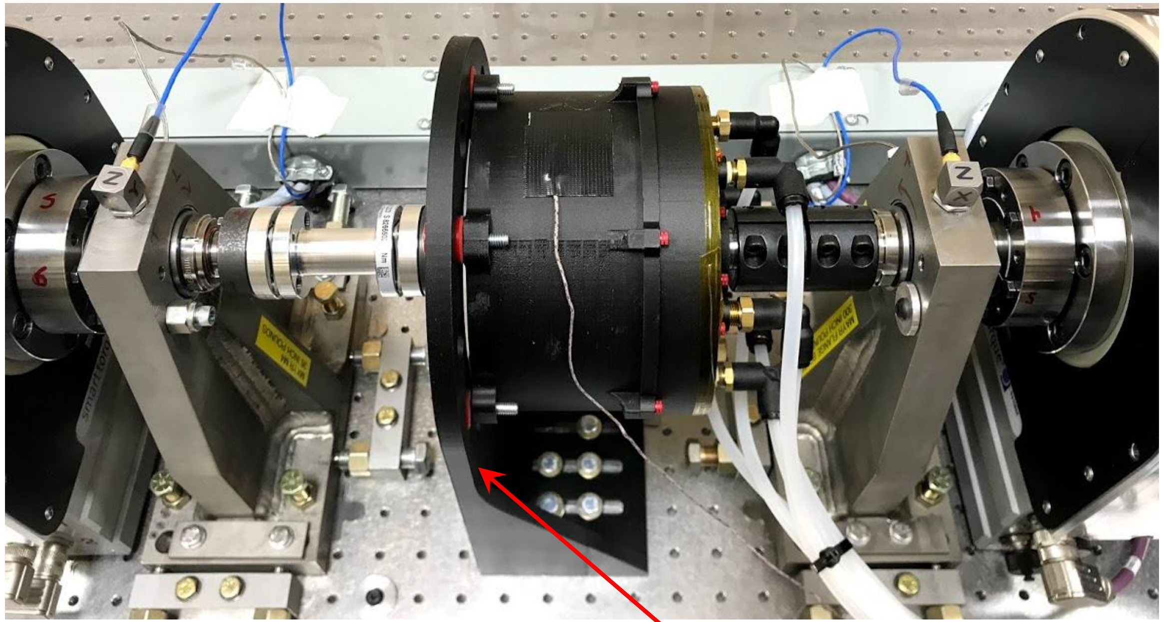
- Motivation & summary of NASA's prior work
- NASA's high efficiency magnetic gear
- Overview of test rig – E-Drives Rig
- **Measurements**
- Conclusions

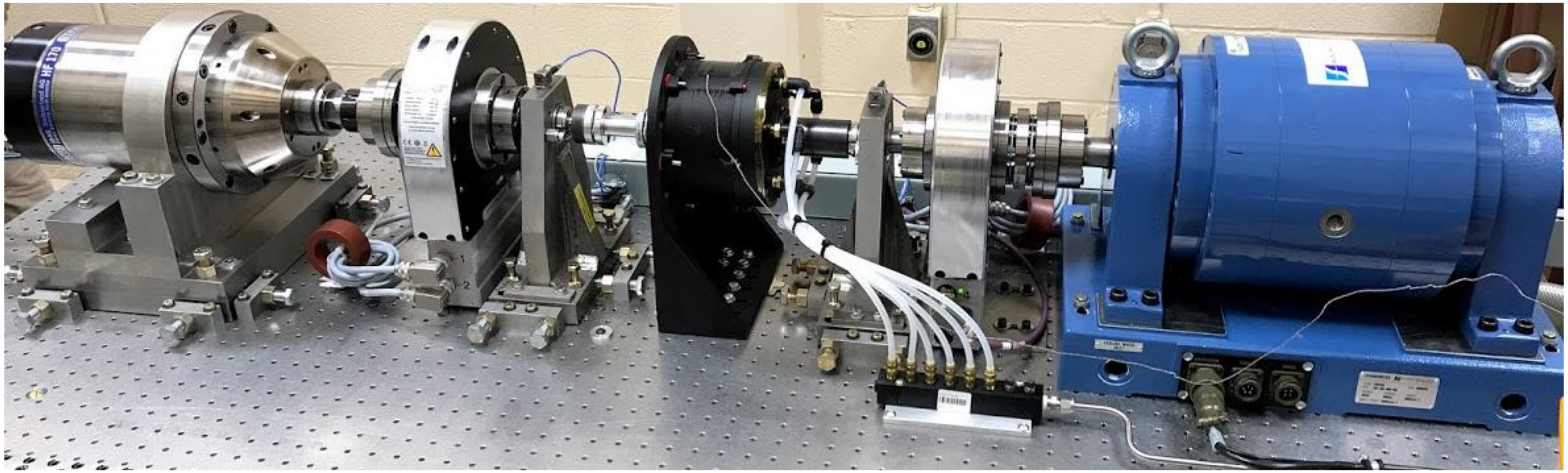
Measurements – PT-3 (High Efficiency)

Output side
(high torque)

Input side
(low torque)

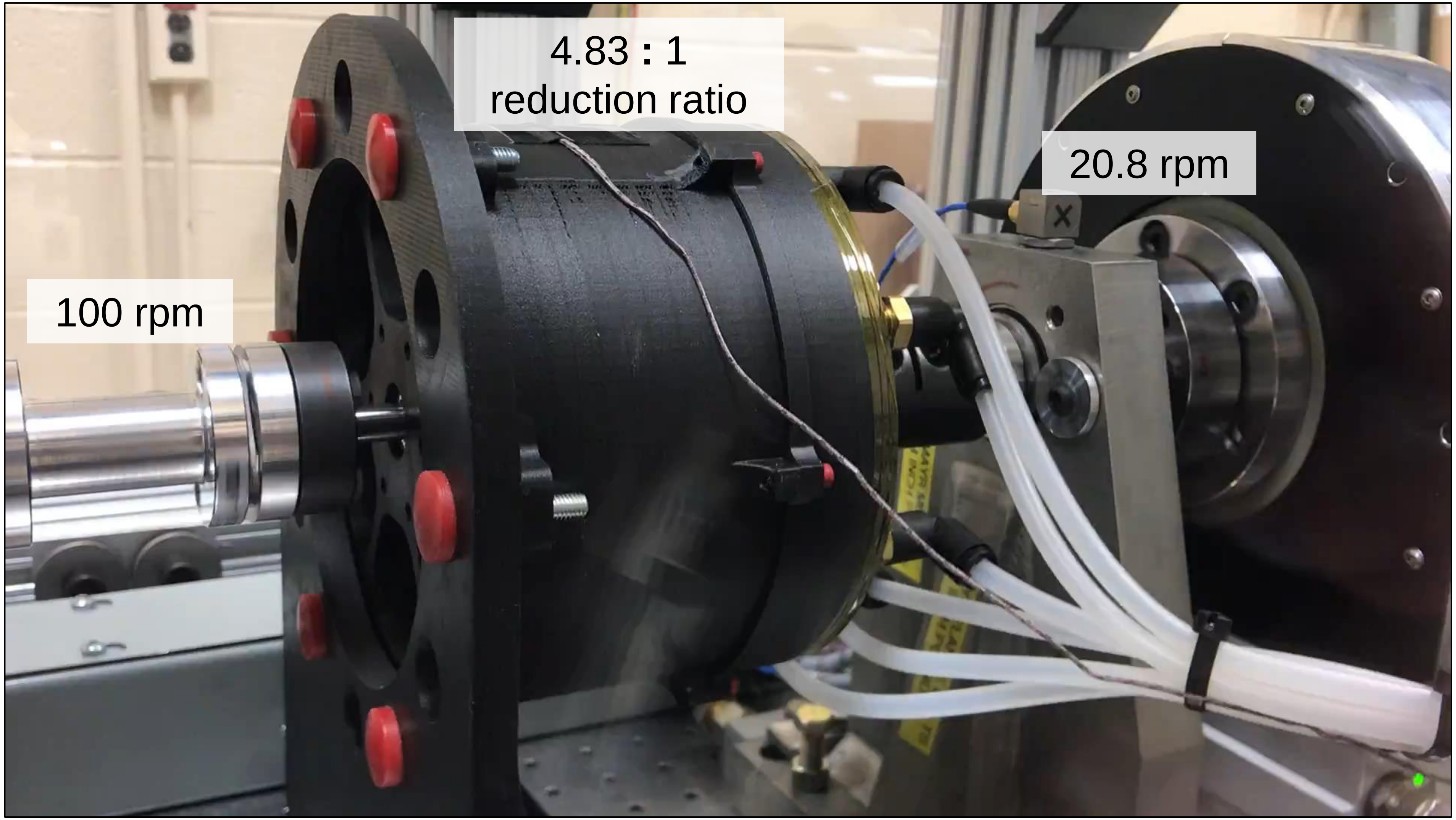




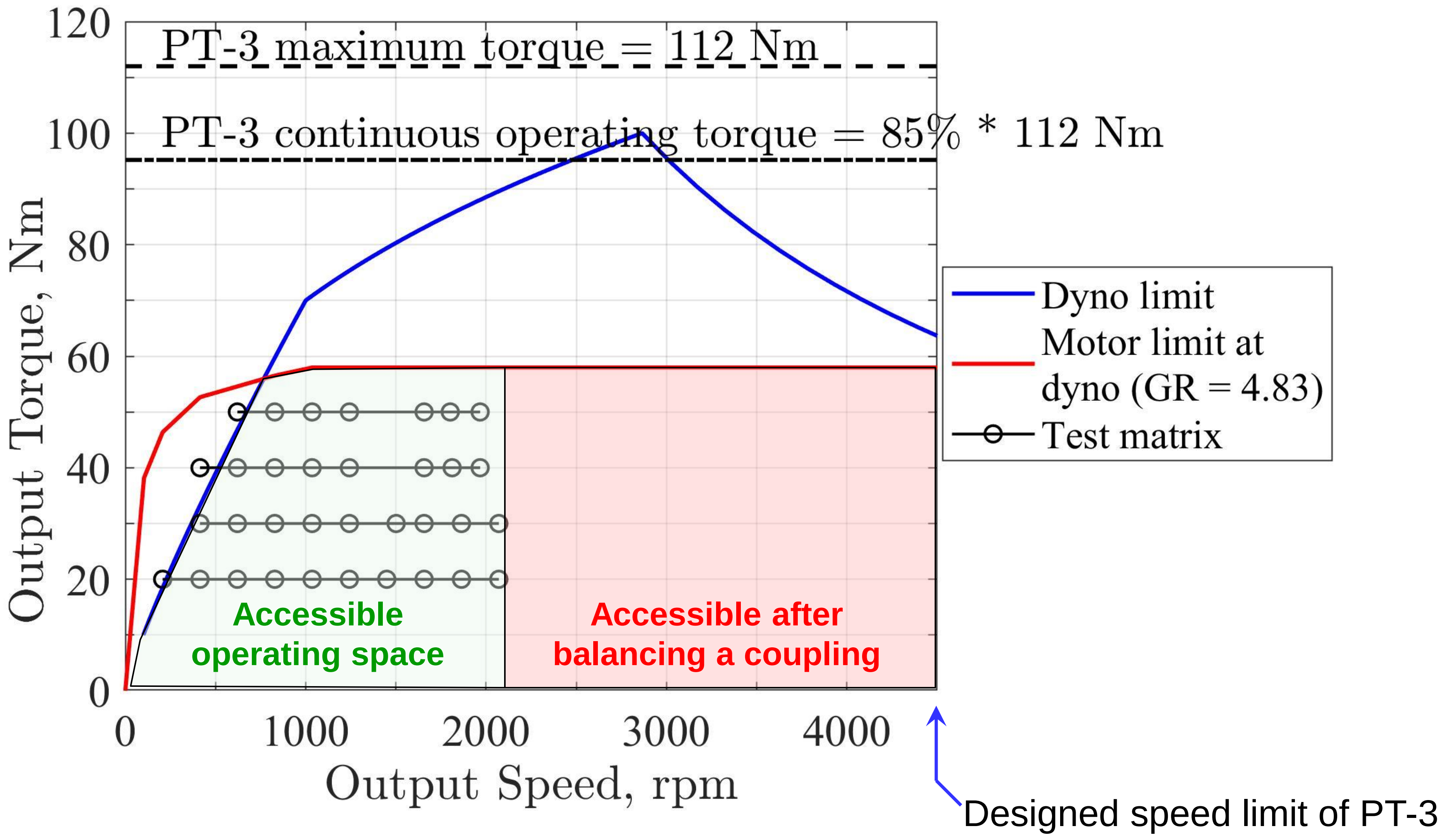


Torque reaction structure (does not constrain radial or axial position)

Measurements – PT-3 (High Efficiency)

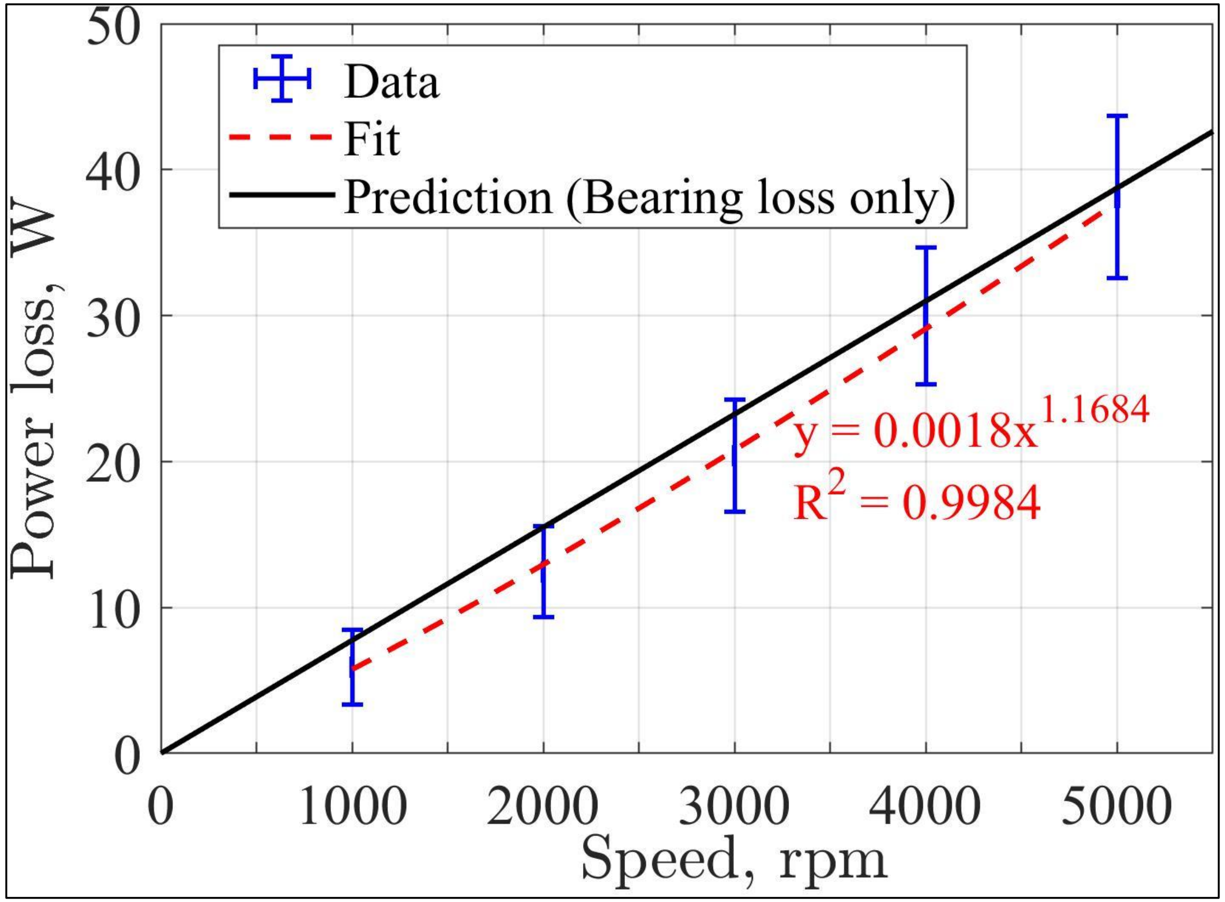


Test matrix - PT-3 testing round 2



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:

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

ω = rotational speed in rad/s

μ = coefficient of friction = 0.002 (angular contact, non-contact seal)

L = dynamic load rating = 7.4 kN

d = bearing bore diameter = 25 mm

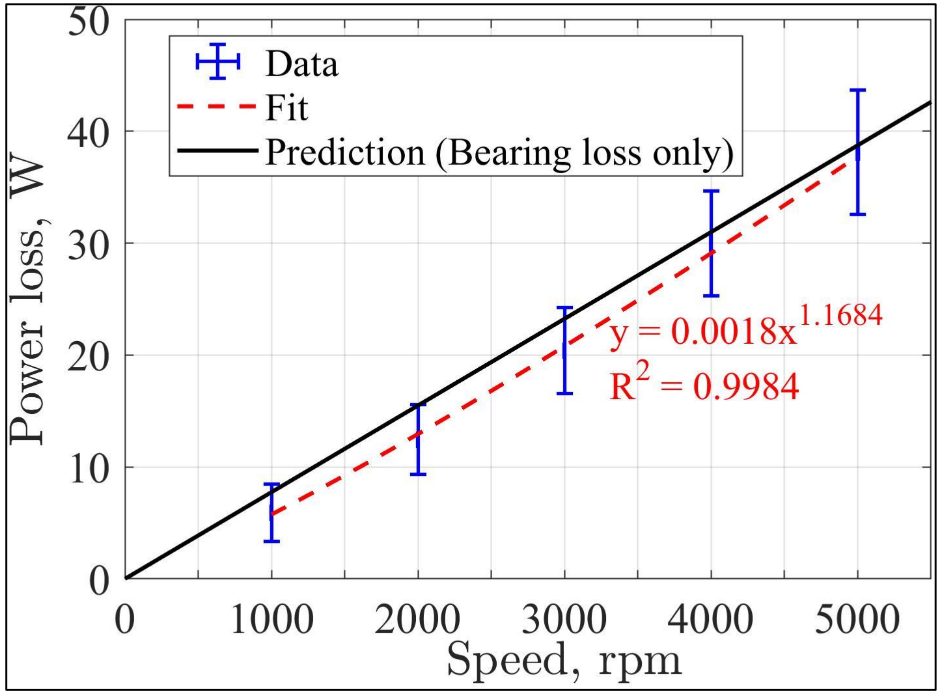
Tare loss correction

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

Tare loss, input side — Tare loss, output side

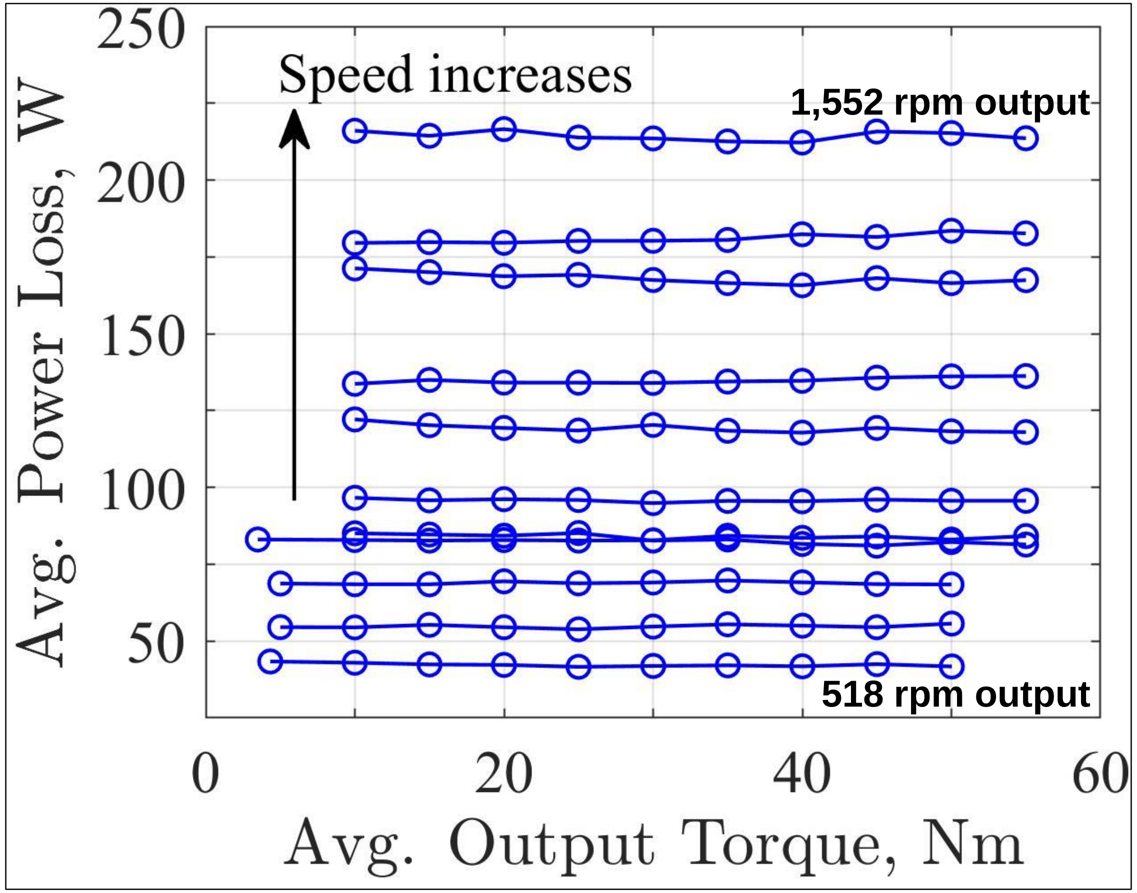
need to extrapolate measured tare loss for this

- 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

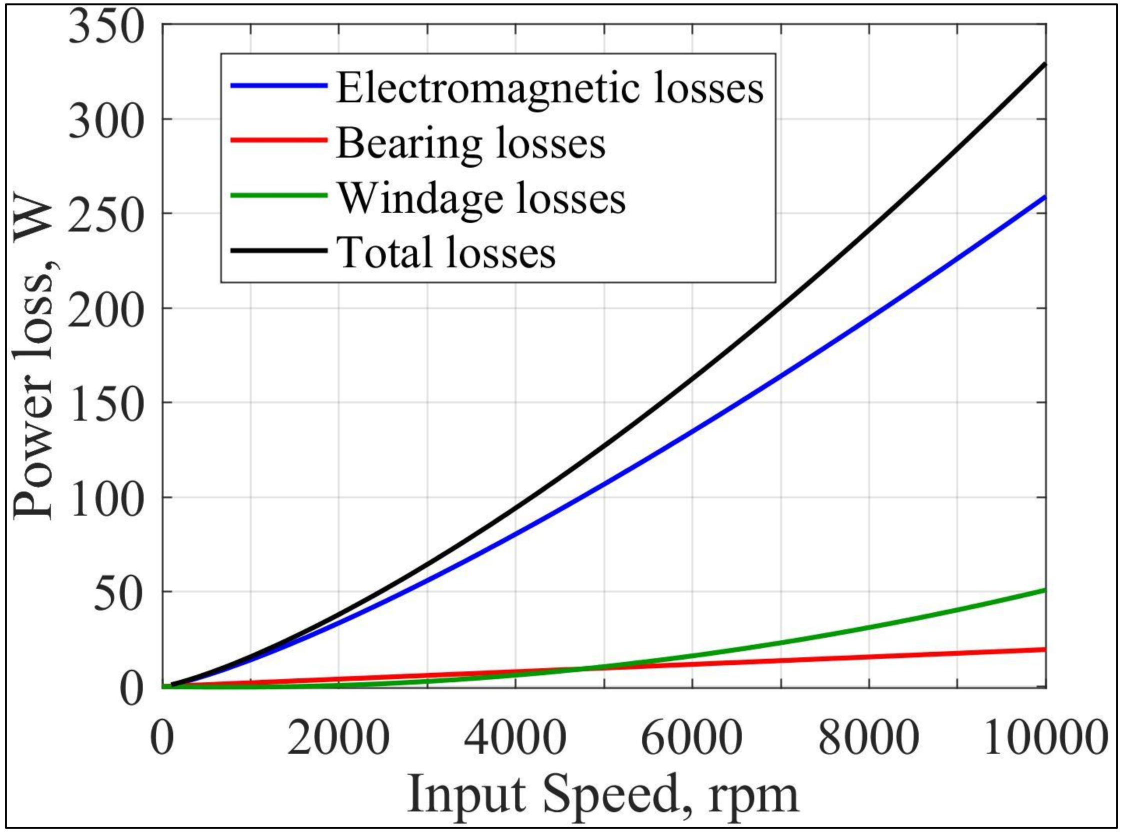


Note: data from PT-3 testing round 1

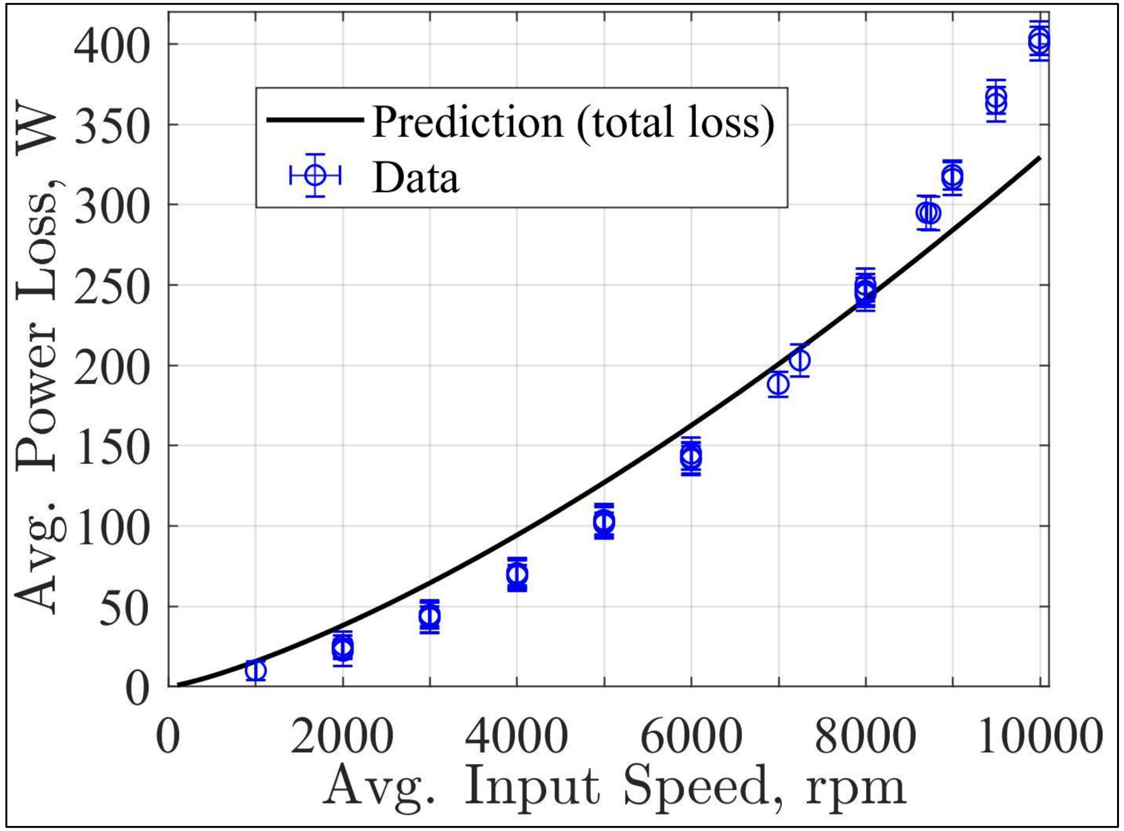
PT-3 Power loss – measured and predicted

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

Power loss prediction



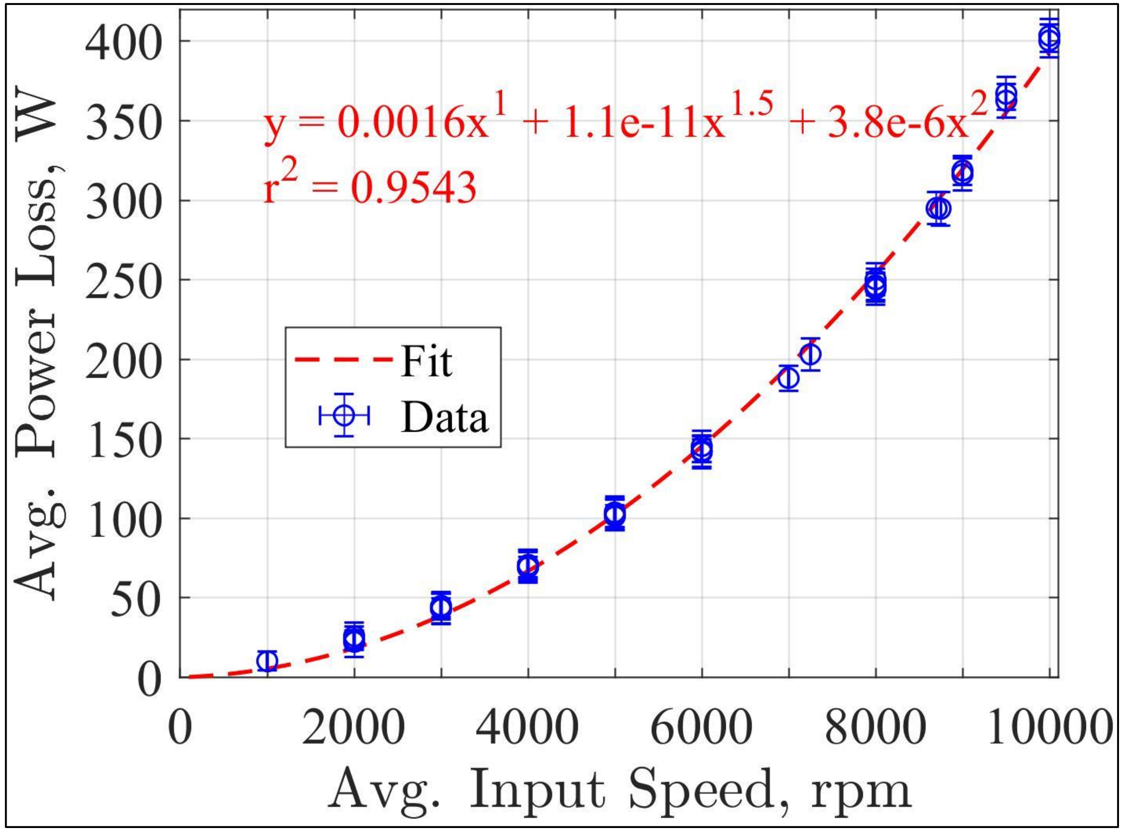
Prediction vs measured
(data with 95% confidence error bars)



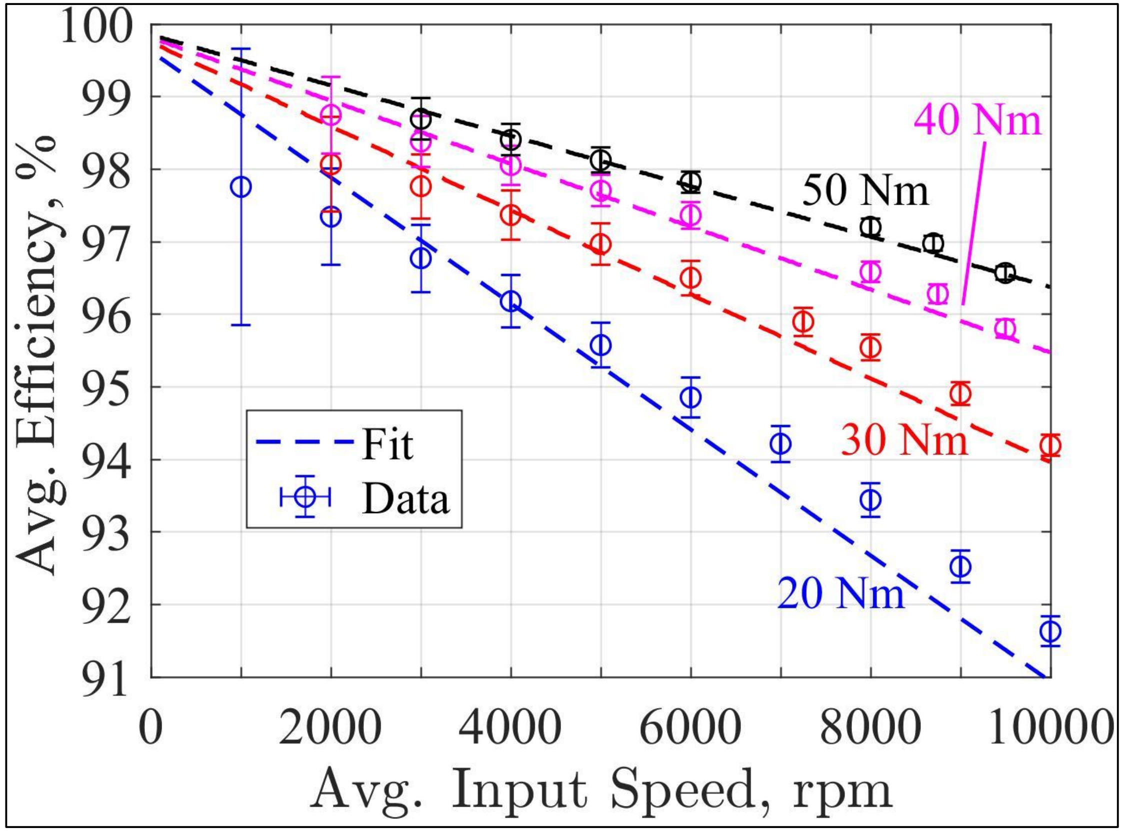
PT-3 Power loss – extrapolation

- 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

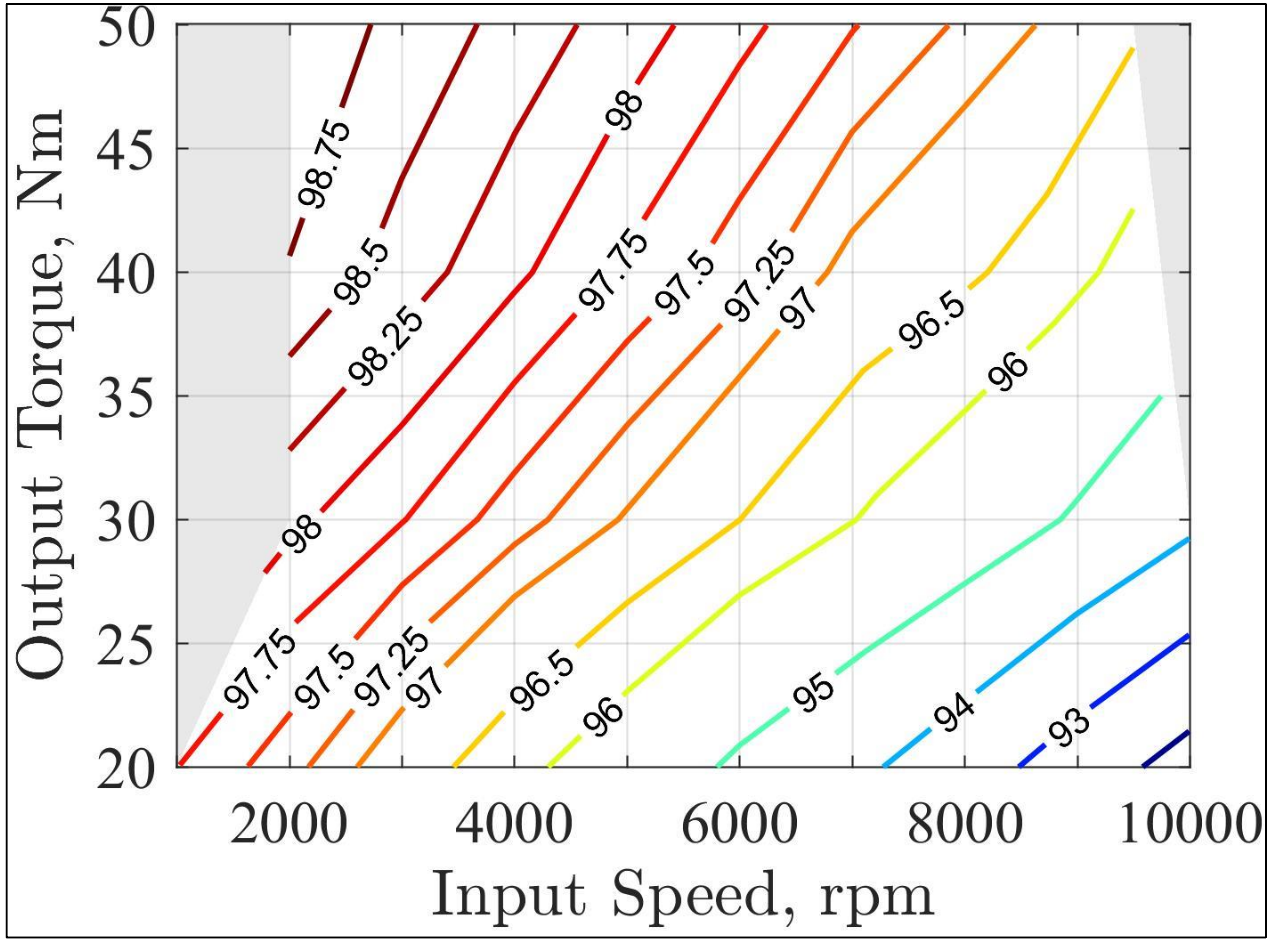
Power loss fit (data with 95% confidence error bars)



Prediction vs measured (with 95% confidence error bars)

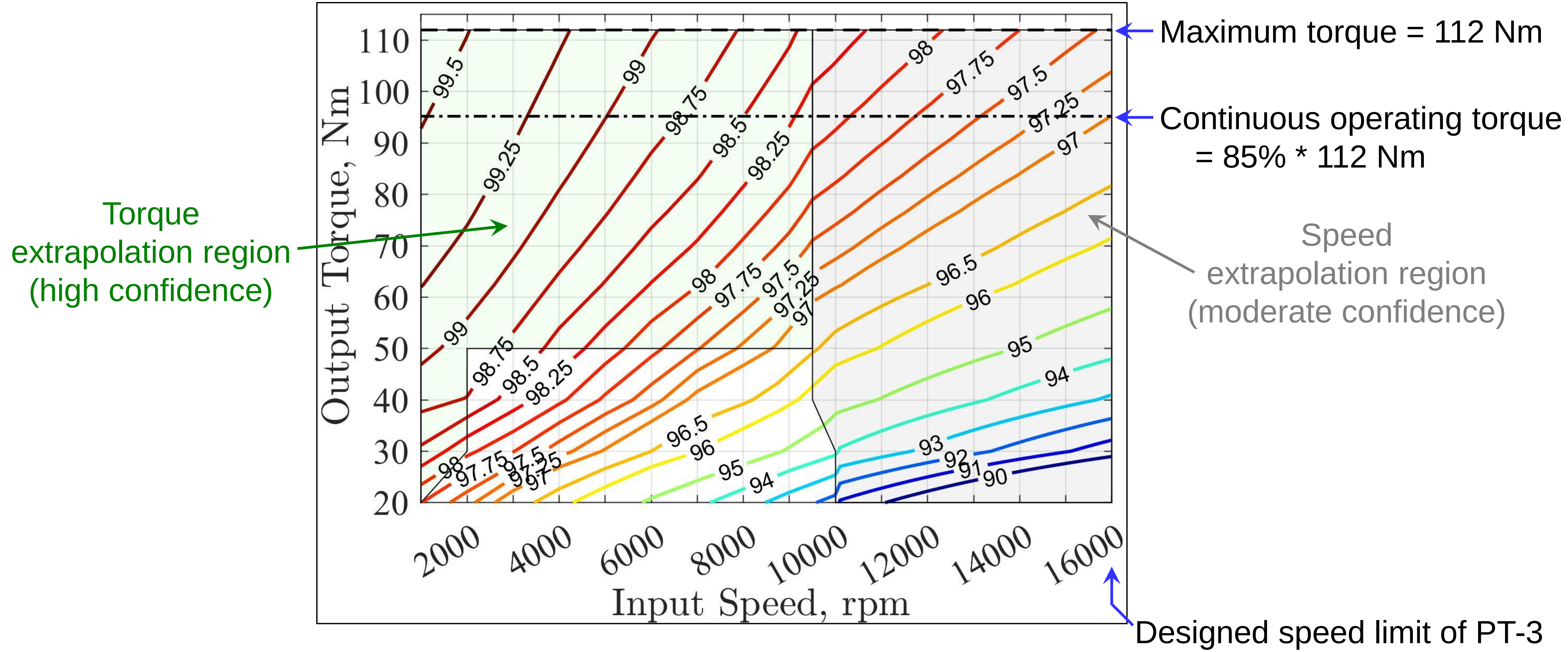


PT-3 Efficiency map – measured data only



- Efficiency increases as torque increases & speed decreases
- Efficiency over 98.7% measured

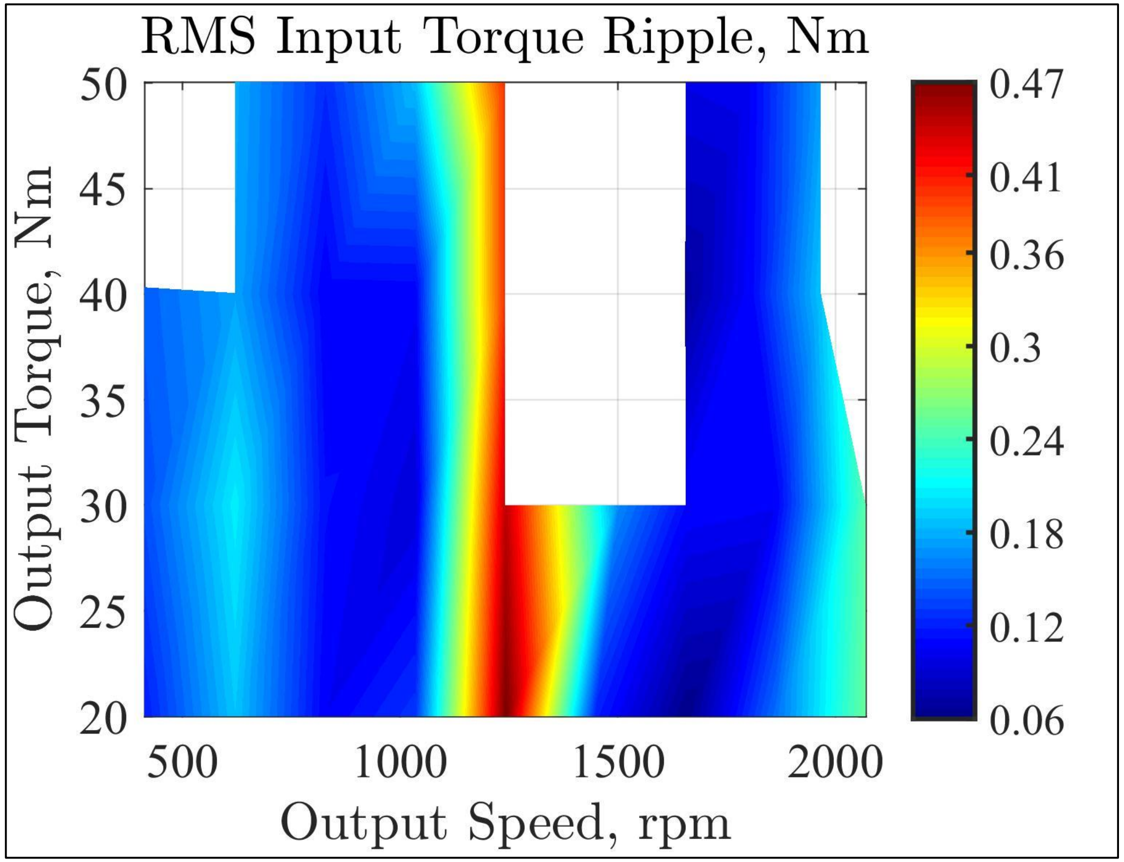
PT-3 Efficiency map – measured data & extrapolation



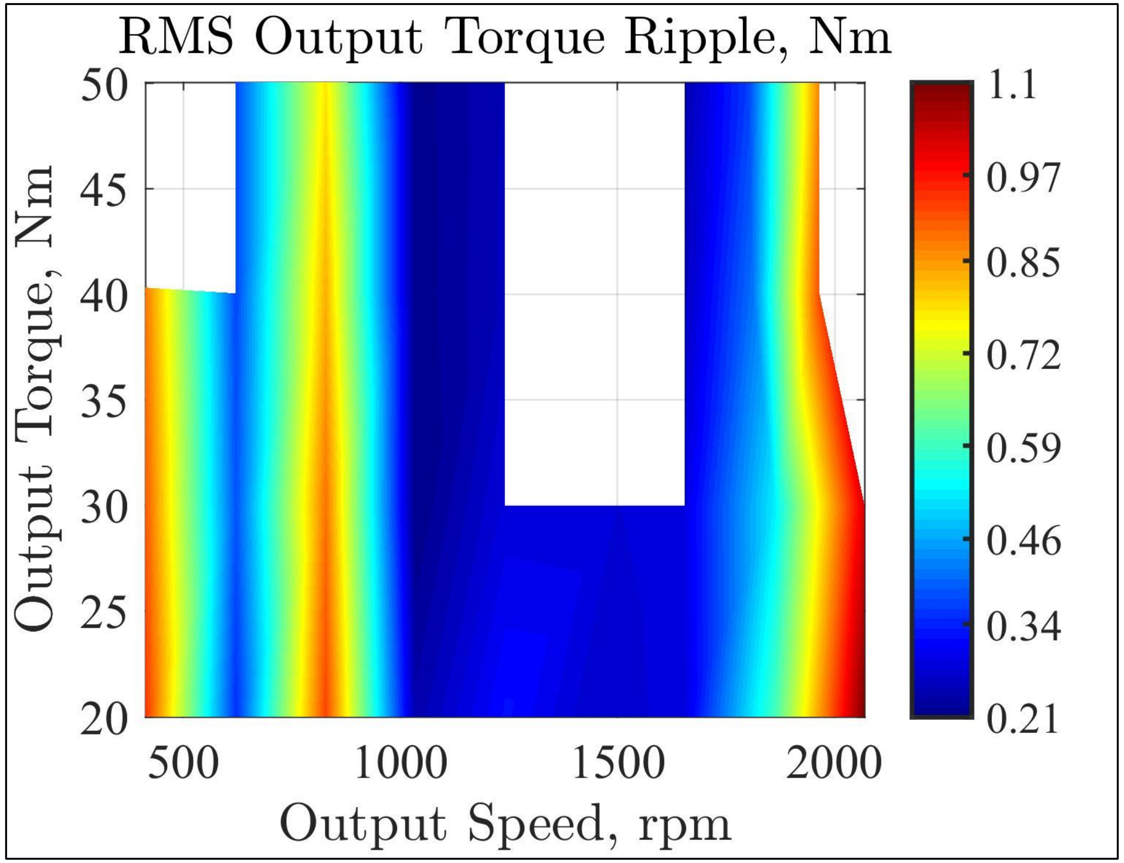
- Extrapolated efficiency exceeds 99.5% at low speeds
- > 99% efficiency up to about 5,000 rpm input speed; ~97% efficiency at max operating torque & speed

PT-3 torque ripple

0.3% to 2% of max input torque



0.2% to 1% of max output torque



Outline

- 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

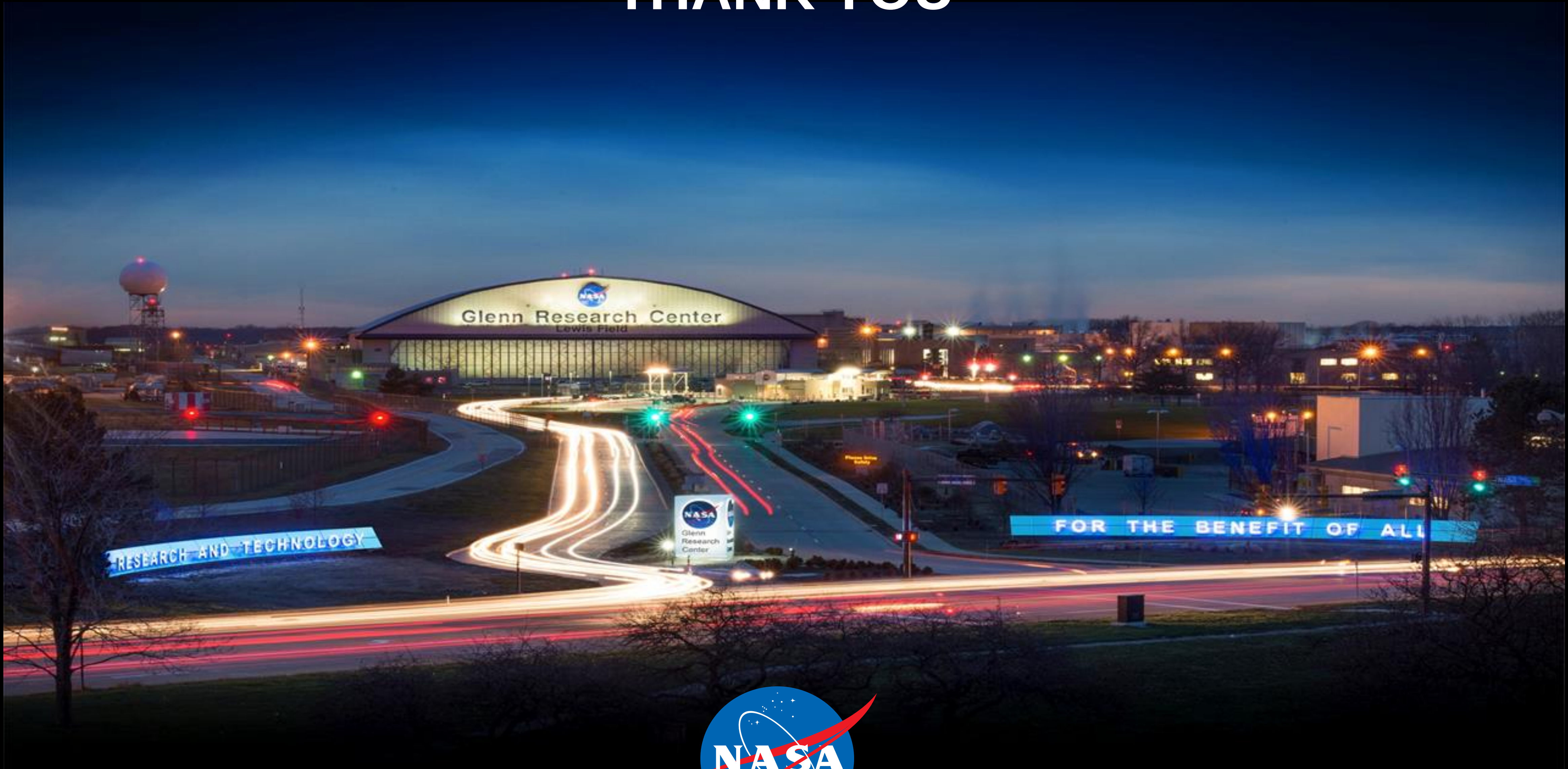
Future work

- 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


Glenn Research Center
Lewis Field
RESEARCH AND TECHNOLOGY
FOR THE BENEFIT OF ALL
NASA
Glenn
Research
Center

NASA