Negative Stiffness Magnetic Torsion Springs for Wave Energy

by

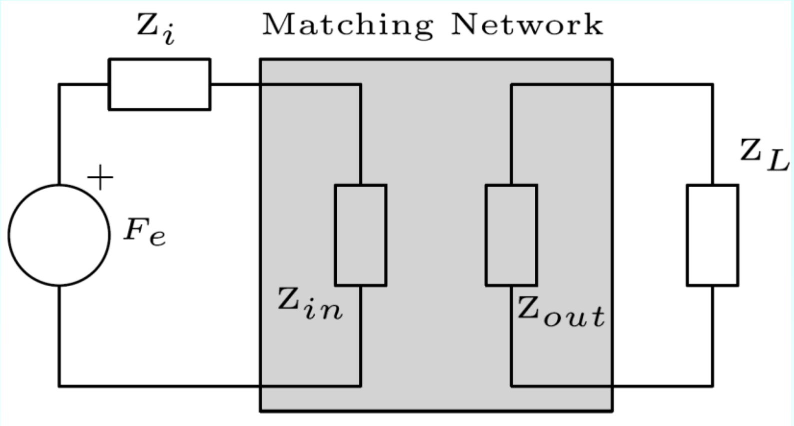
Payam Emami[1], Dawei Che[1], Jonathan Z. Bird[1,2],
Colton Bruce[2], Bert Dechant[2]

Laboratory for Magnetomechanical Energy Conversion and Control
Electrical and Computer Engineering Department
Portland State University
http://magnetics.us/

[2] **FluxMagic, Inc.**
1920 SE 10th Ave, Portland, OR, 97214, USA
https://fluxmagic.com/

What are We Doing and Why ?

Wave energy converter can be modelled as a two-port electrical analogue



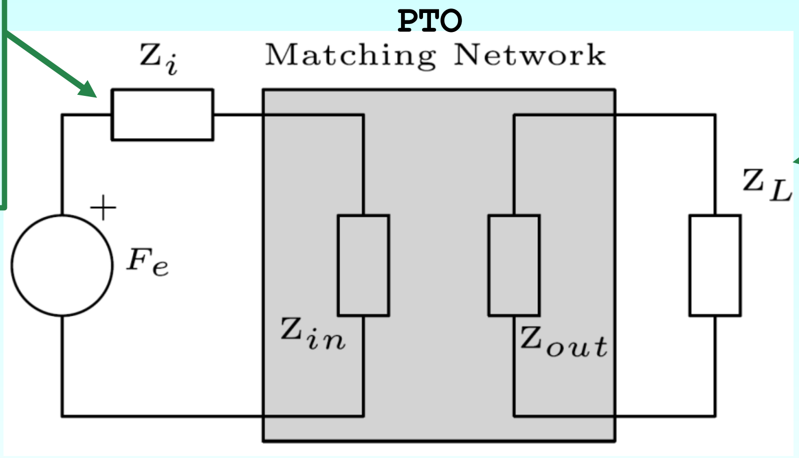
Two-port electrical analogue [*]

[*] G. Bacelli and R. G. Coe, "Comments on Control of Wave Energy Converters," *IEEE Transactions on Control Systems Technology*, vol. 29, no. 1, pp. 478-481, 2021, doi: 10.1109/TCST.2020.2965916.

What are We Doing and Why ?

Wave energy converter can be modelled as a two-port electrical analogue

Z_i = wave energy converter impedance



Z_L = generator load impedance

Two-port electrical analogue [*]

To maximizing power transfer through to the load requires the simultaneously matching of the bi-conjugate condition [*]:

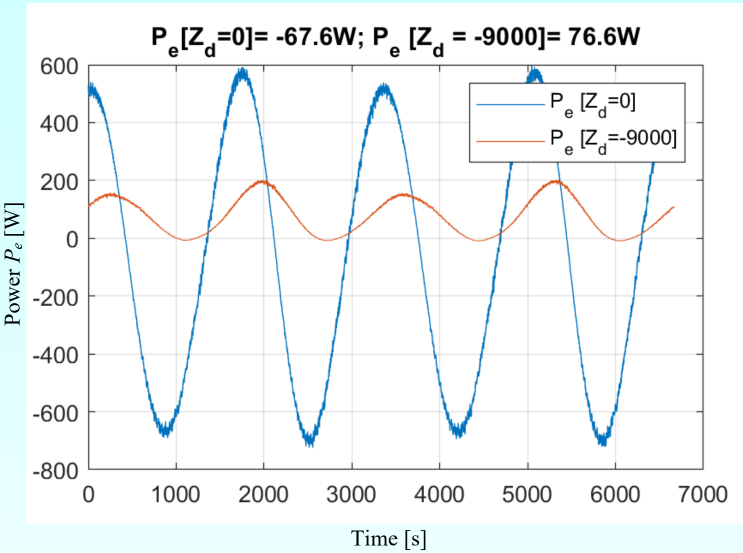
$$Z_i^* = Z_{in}$$

$$Z_{out} = Z_L^*$$

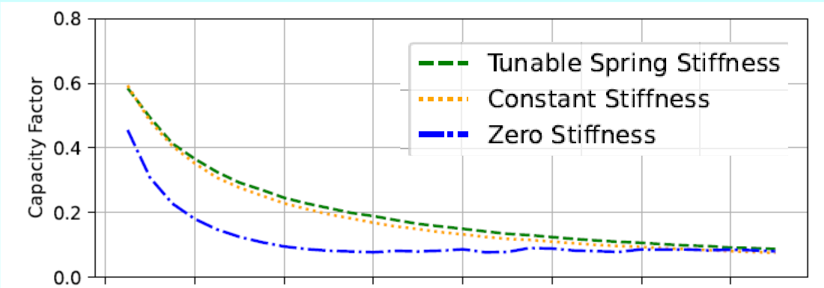
What are we doing ? – Design magnetic components to allow much improved PTO impedance matching

[*] G. Bacelli and R. G. Coe, "Comments on Control of Wave Energy Converters," *IEEE Transactions on Control Systems Technology,* vol. 29, no. 1, pp. 478-481, 2021, doi: 10.1109/TCST.2020.2965916.

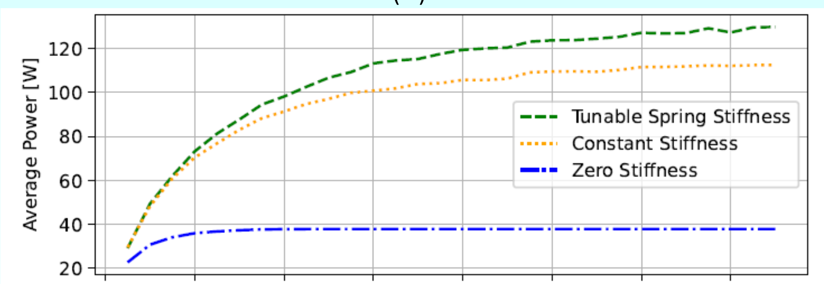
Why Spend Time on This?



Example Wavebot tank testing results provided by Sandia National Laboratory [1]. The experimental results are from the variable stiffness magnetic spring testing at Carderock. Z_d = 0 shows the power output with and without magnetic spring [1]



(a)



(b)

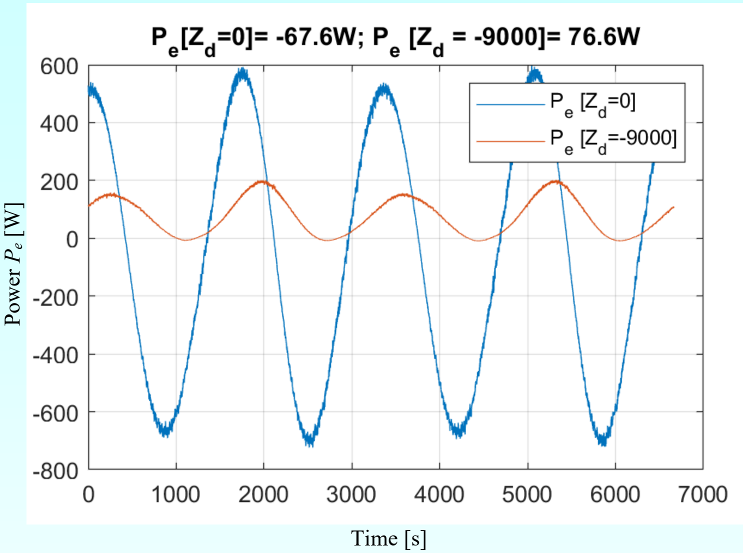
WecOptTool analysis using magnetic spring with Complex conjugate impedance matching (a) Capacity factor, (b) average annual power [2]

[1] D. D. Forbush *et al.*, "MASK4 Test Campaign for Sandia WaveBot Device," Sandia National Laboratories, United States, Jan 18, 2024. [Online]. Available: https://www.osti.gov/biblio/2280836

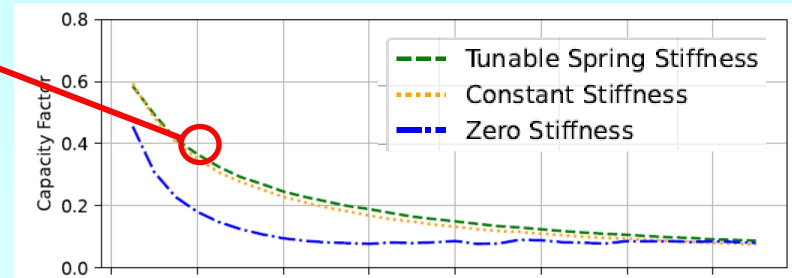
[2] Jeff T. Grasberger, Ryan G. Coe, Giorgio Bacelli, Jonathan Bird, Alex Hagmüller, Carlos A. Michelén-Ströfer, *Maximizing Wave Energy Converter Power Extraction by Utilizing a Variable Negative Stiffness Magnetic Spring*, Presented at the 15th European Wave and Tidal Energy Conference, 3rd– 7th Sept. 2023, Bilbao, Spain DOI: https://doi.org/10.36688/ewtec-2023-510

Why Spend Time on This?

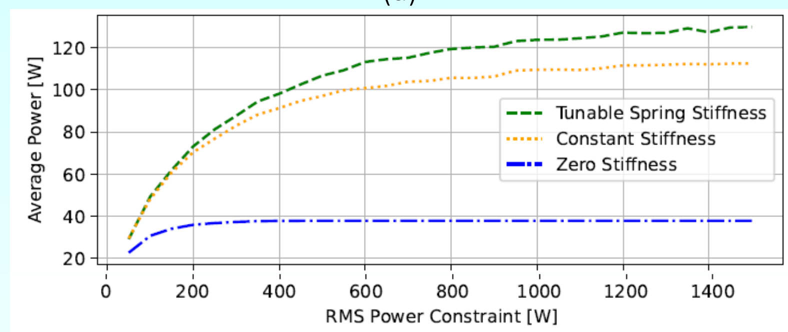
Wind turbines experience similar capacity factors in the range of 30% to 35%



Example Wavebot tank testing results provided by Sandia National Laboratory [1]. The experimental results are from the variable stiffness magnetic spring testing at Carderock. Z_d = 0 shows the power output with and without magnetic spring [1]



(a)



(b)

WecOptTool analysis using magnetic spring with Complex conjugate impedance matching (a) Capacity factor, (b) average annual power [2]

Could greatly lower power oscillations and increase capacity factor – so close to wind/solar

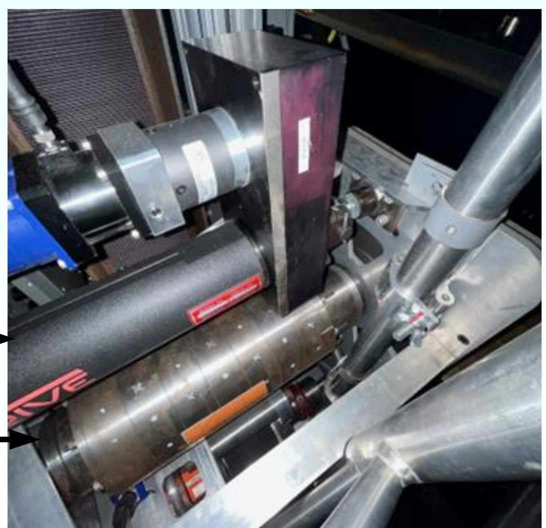
[1] D. D. Forbush *et al.*, "MASK4 Test Campaign for Sandia WaveBot Device," Sandia National Laboratories, United States, Jan 18, 2024. [Online]. Available: https://www.osti.gov/biblio/2280836

[2] Jeff T. Grasberger, Ryan G. Coe, Giorgio Bacelli, Jonathan Bird, Alex Hagmüller, Carlos A. Michelén-Ströfer, *Maximizing Wave Energy Converter Power Extraction by Utilizing a Variable Negative Stiffness Magnetic Spring*, Presented at the 15th European Wave and Tidal Energy Conference, 3rd– 7th Sept. 2023, Bilbao, Spain
DOI: https://doi.org/10.36688/ewtec-2023-510

Subtask 2. Background

Magnetic Spring Integrated into Wave Energy Converter end of 2023

This work completed under prior DOE grant



Linear actuator (stiffness adjustment)

Variable stiffness magnetic spring (torsional spring)

Since WecOptTool analysis and Wave tank testing by SNL not completed till 3/2024. specification had to be decided before with limited information.

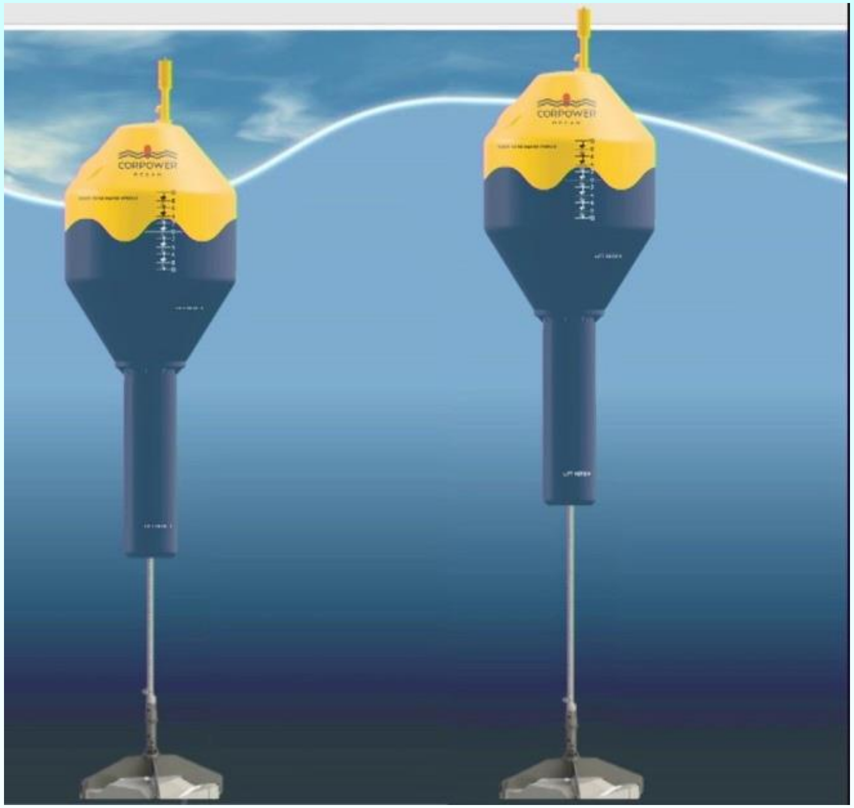
<u>Main Take-aways from Analysis:</u>

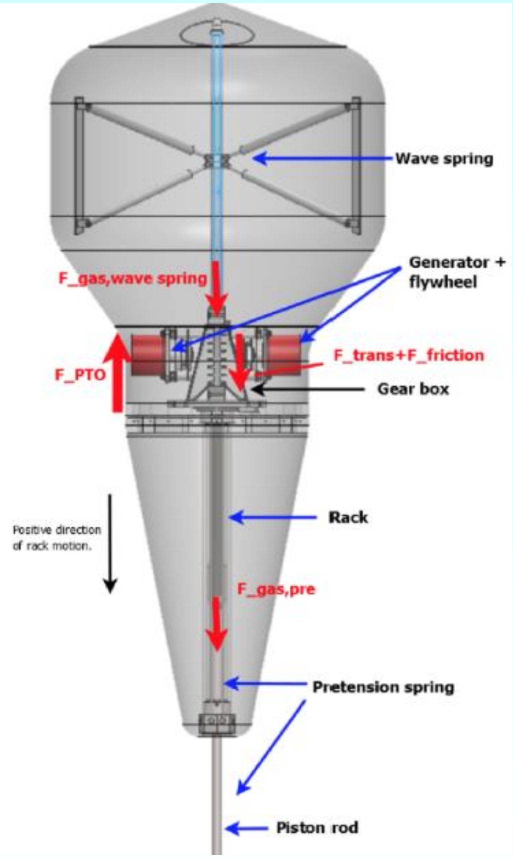
- SNL analysis* showed using fixed negative stiffness resulted in significant improvement.
- To limit PacWave testing risk and reduce complexity it was decided to design spring for fixed stiffness

* J. T. Grasberger, J. Bird, R. G. . Coe, G. Bacelli, C. A. Michelén Ströfer, and A. Hagmüller, “Maximizing Wave Energy Converter Power Extraction by Utilizing a Variable Negative Stiffness Magnetic Spring”, *Proc. EWTEC*, vol. 15, Sep. 2023.

CorPower

Negative stiffness spring using sets of three large mechanical springs

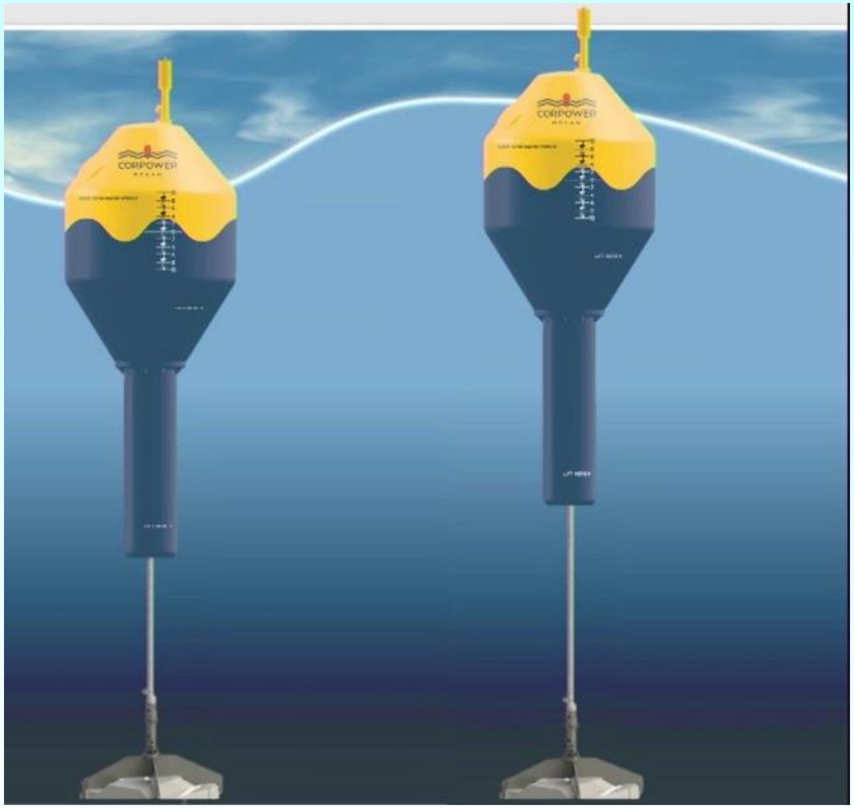


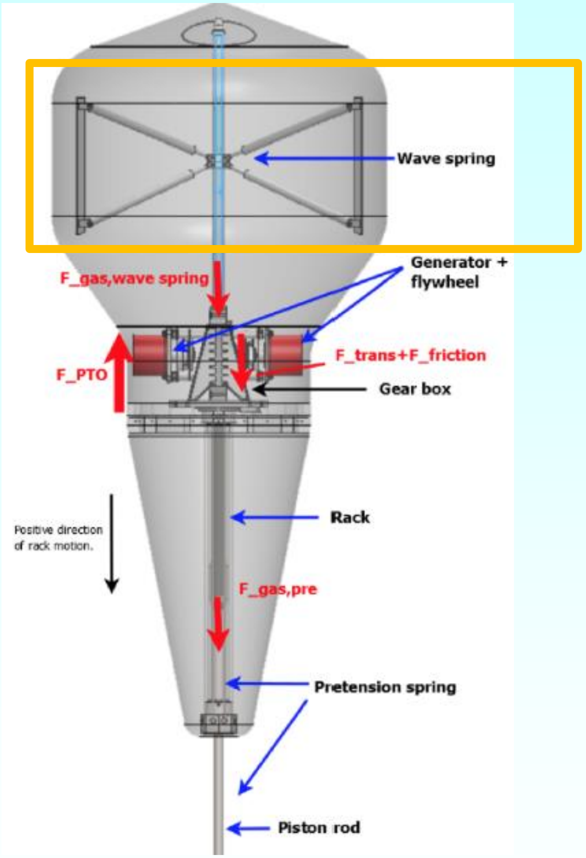


Resonant frequency: $\omega_r = \sqrt{\frac{k}{m}}$ k = stiffness, m = mass

CorPower

Negative stiffness spring using sets of three large mechanical springs

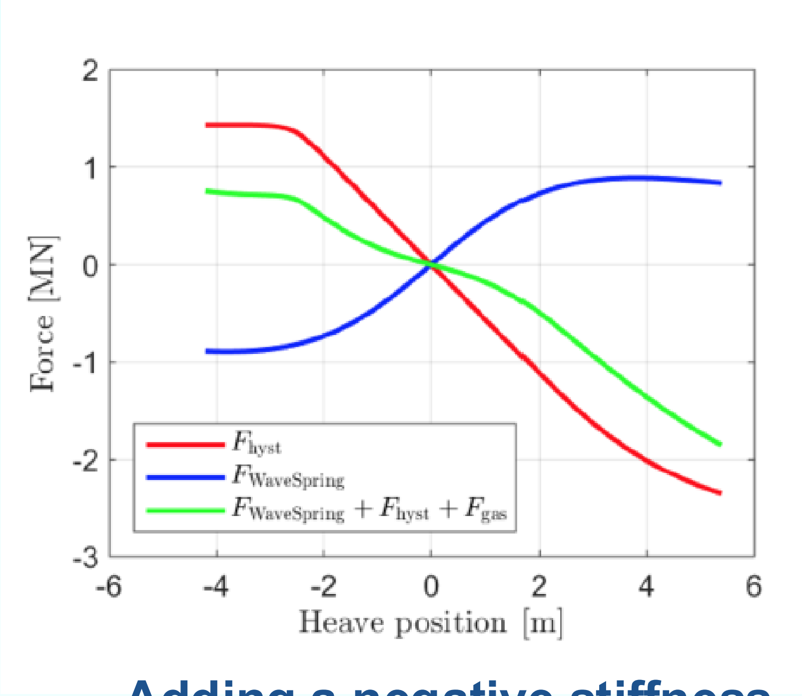


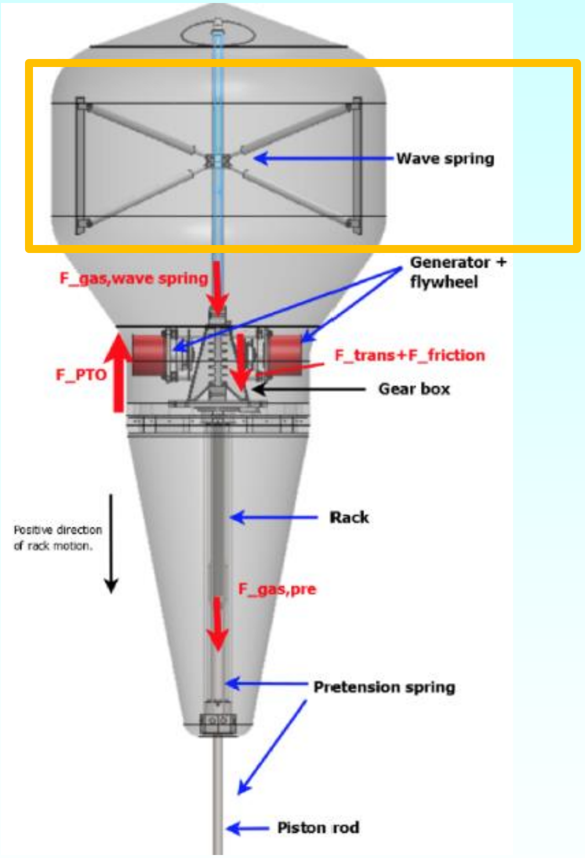


Resonant frequency: $\omega_r = \sqrt{\frac{k}{m}}$ k = stiffness, m = mass

CorPower

Negative stiffness spring using sets of three large mechanical springs





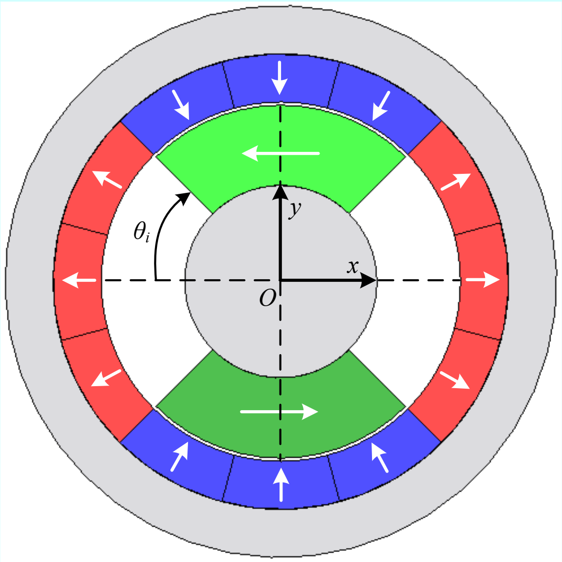
Adding a negative stiffness allows a smaller wave energy converters to resonate

Resonant frequency: $\omega_r = \sqrt{\frac{k}{m}}$

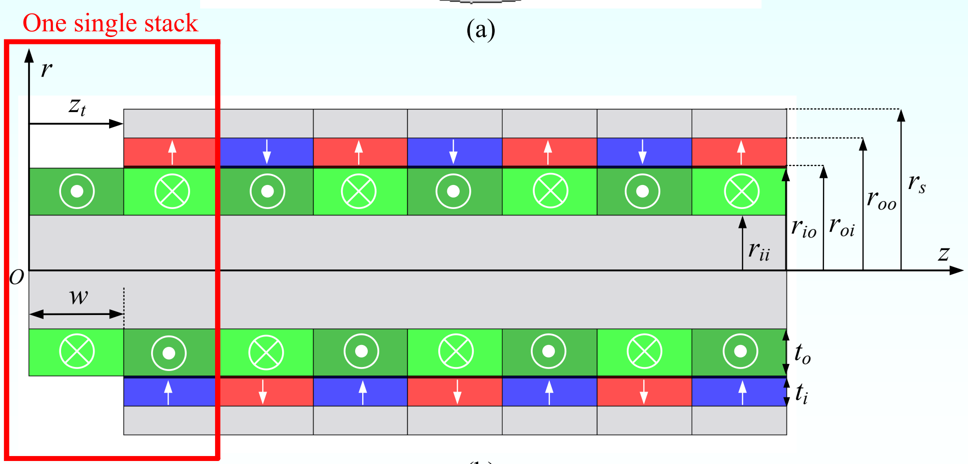
k = stiffness

m = mass

Tangential Flux Magnetic Torsion Spring

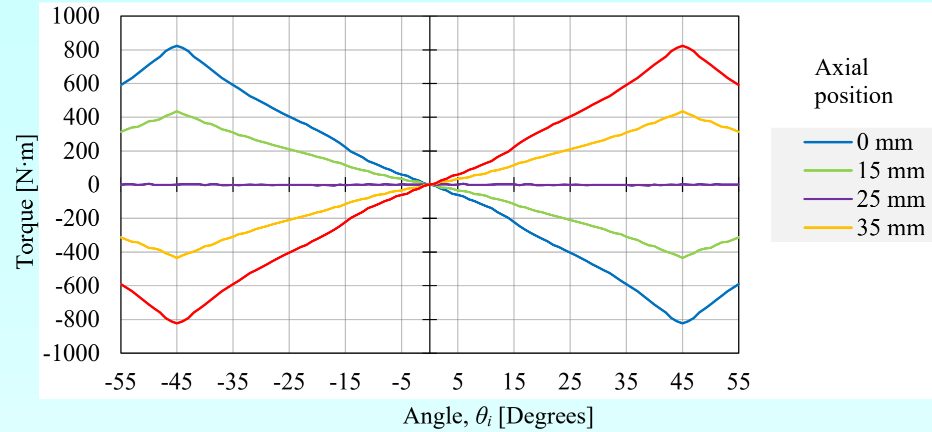


(a)



(b)

Variable stiffness magnetic torsion spring (a) front view (b) cut-through view, the outer rotor is back-iron and the inner rotor magnet support are made of 1018 steel



Torque vs. angle

PERFORMANCE METRIC AT THE PEAK STROKE LENGTH

Parameter	Value		Units
Stack number, n_s	1	7	
Peak torque, T_p	133.7	822.7	N·m
Peak spring rate, k_m	170.2	1047.8	N·m/rad
Peak energy	52.5	323.0	J
Total mass	4.7	25.4	kg
Energy density	11.4	12.6	J/kg
	8.5	9.4	kJ/m^3

Based on prior design:

- Longer stroke length requested
- Increased energy density

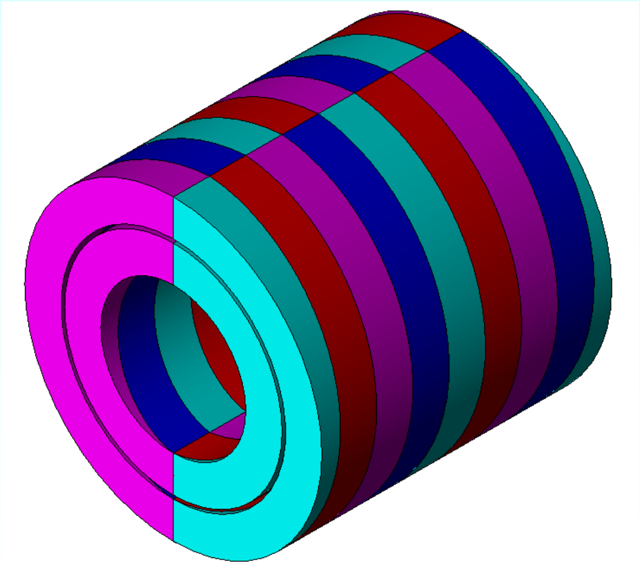
Problem:

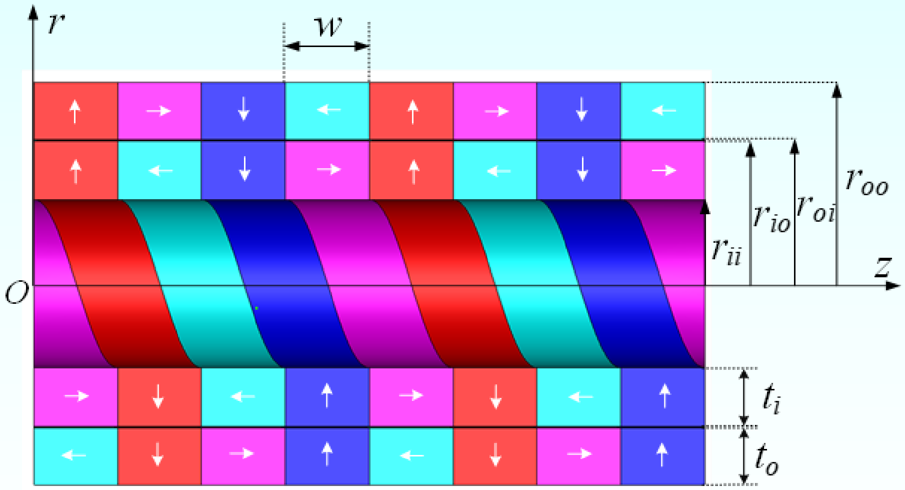
- Stroke length limited to 45°
- Design not scalable (due to large magnets)

Helical Magnetic Torsional Spring

Helical magnetic spring invented
- Increases stroke length by 3x
- Almost doubled energy density
- Scalable to any axial and radial size (due to smaller magnets)

Ideal Design

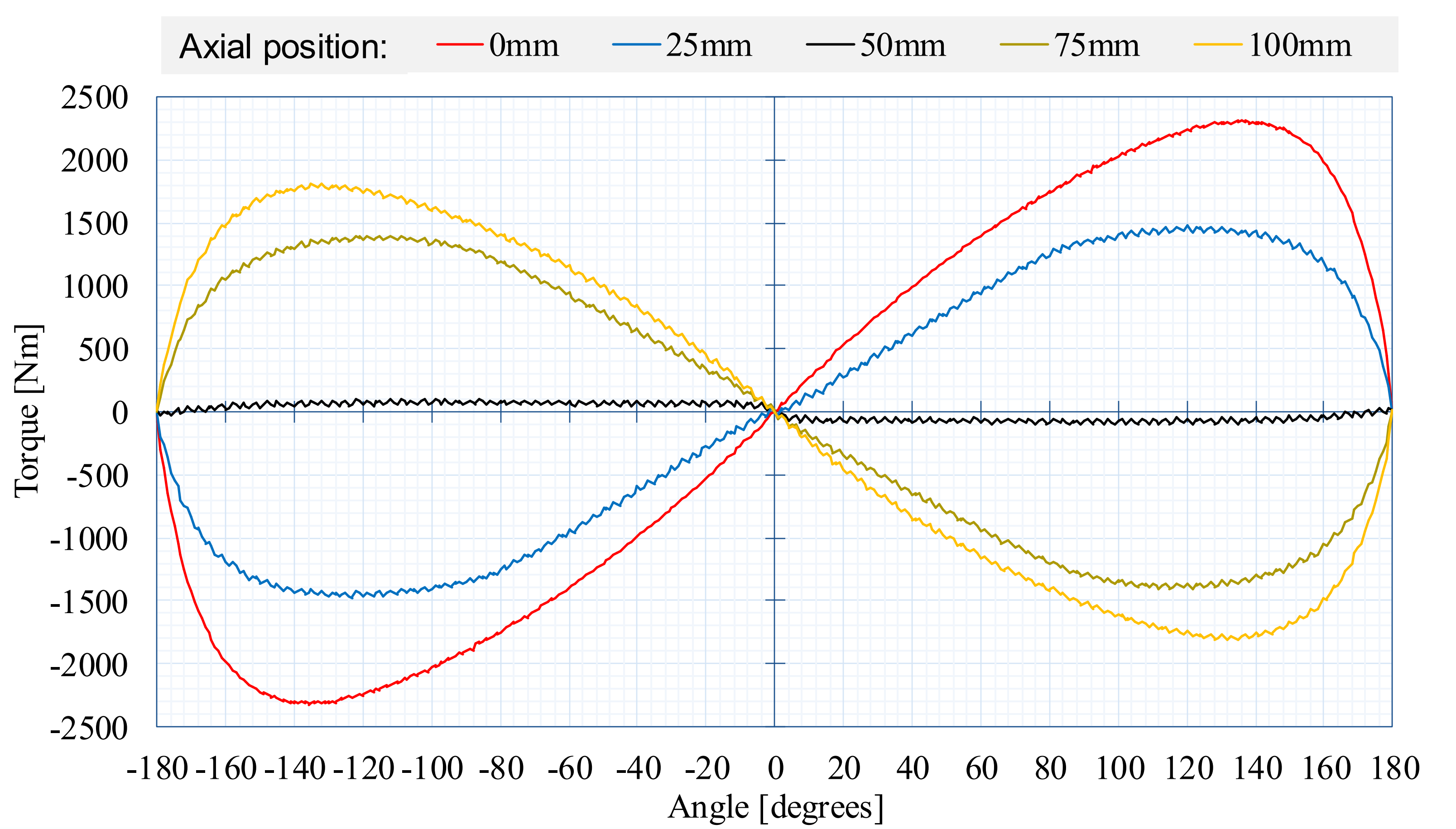




(a) (b)

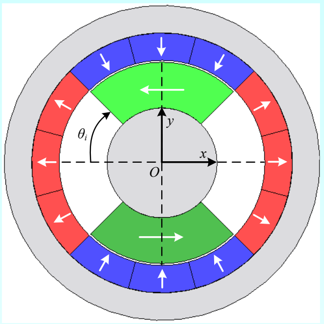
(a) Halbach array 2-pole helical spring design, (b) cross-section view showing magnetization magnet directions along with geometric values

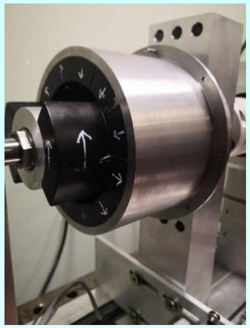
Torque Characteristics



Performance Comparison

Prior Design Torque 850Nm at 45^{O}

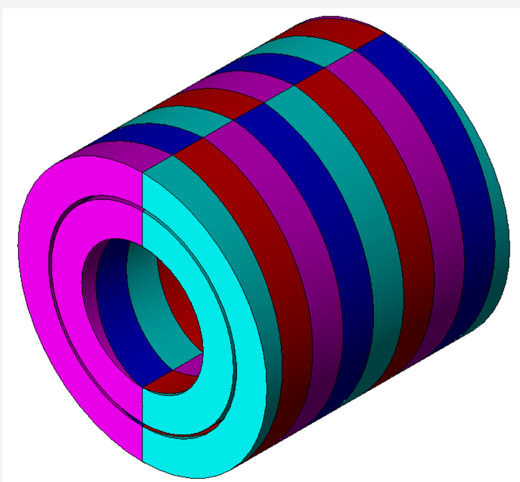




PERFORMANCE METRIC AT THE PEAK STROKE LENGTH

Parameter	Value		Units
Stack number, n_s	1	7	
Peak torque, T_p	133.7	822.7	N·m
Peak spring rate, k_m	170.2	1047.8	N·m/rad
Peak energy	52.5	323.0	J
Total mass	4.7	25.4	kg
Energy density	11.4	12.6	J/kg
	8.5	9.4	kJ/m^3

Helical magnetic spring

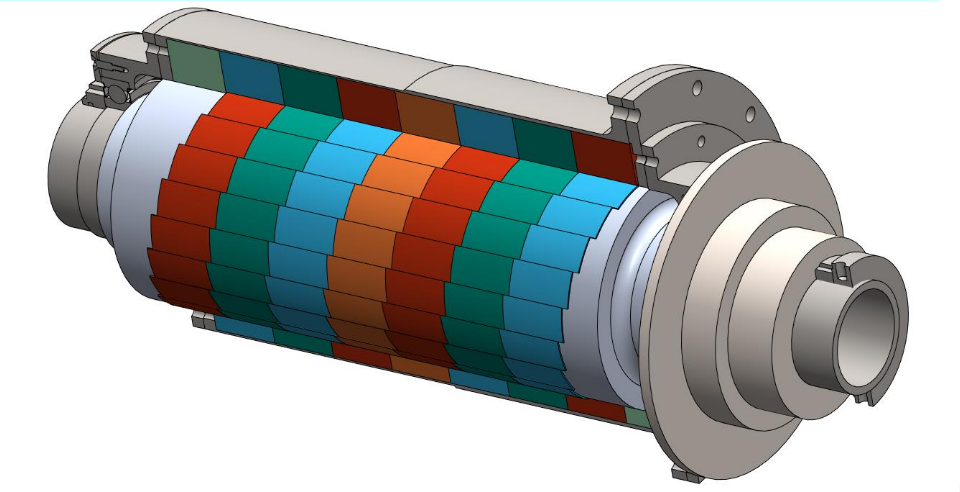


Parameters		Ideal Design	Units
Peak torque at 120°		2,243	Nm
Peak torque at 45°		1,101	Nm
Peak stroke length		±136	degrees
Mass		110.5	kg
Magnet volume		0.0147	m^3
Torque density	Mass	20.3	Nm/kg
	Volume	152.6	Nm/L
Energy density	Mass	21.26	J/kg
	Volume	159.8	J/L

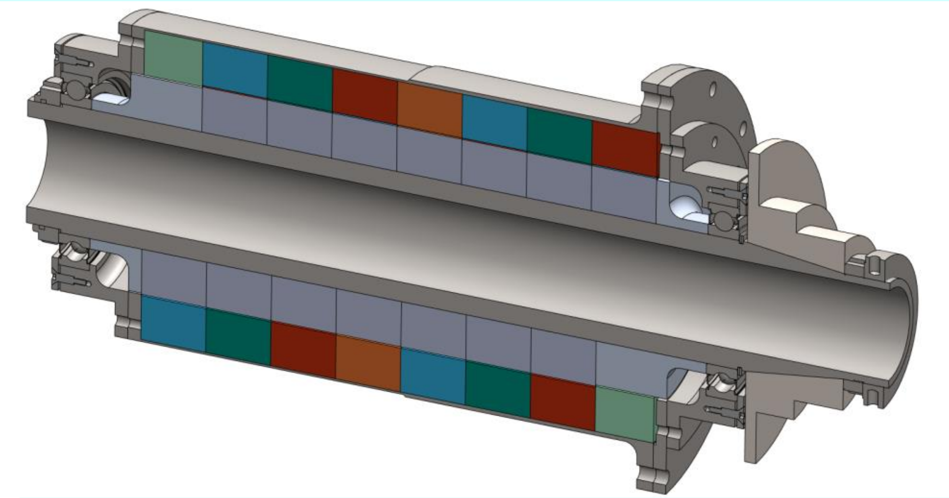
3x increase in stroke length

>70 % increase in energy density

Mechanical Design

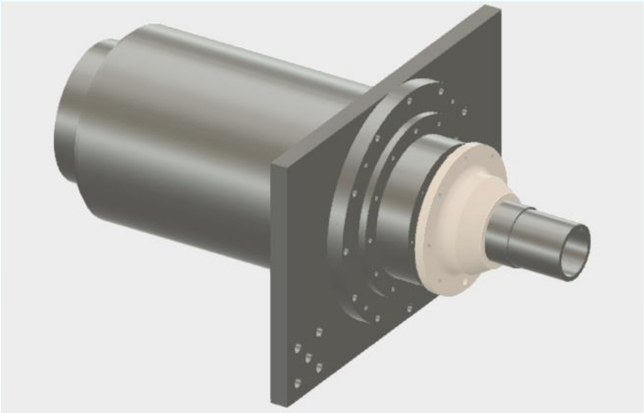


(a)



(b)

(a) A cut-through view showing individual magnet segments on the inner and outer rotors, (b) a 180 cut-through view of the helical magnetic spring mechanical assembly. The inner rotor is shown to contain 7 axial segments.



The helical magnetic spring design shown supported on a mounting block

Mechanical Design

Magnets made all the same size reduced torque but did not reduce torque characteristics.

Parameters		Ideal Design	Constant Magnet Width Design	Units
Peak torque at 120°		2,243	1,933	Nm
Peak torque at 45°		1,101	920	Nm
Peak stroke length		±136	±136	degrees
Mass		110.5	96.73	kg
Magnet volume		0.0147	0.0129	m^3
Torque density	Mass	20.3	20	Nm/kg
	Volume	152.6	149.8	Nm/L
Energy density	Mass	21.26	20.93	J/kg
	Volume	159.8	156.9	J/L

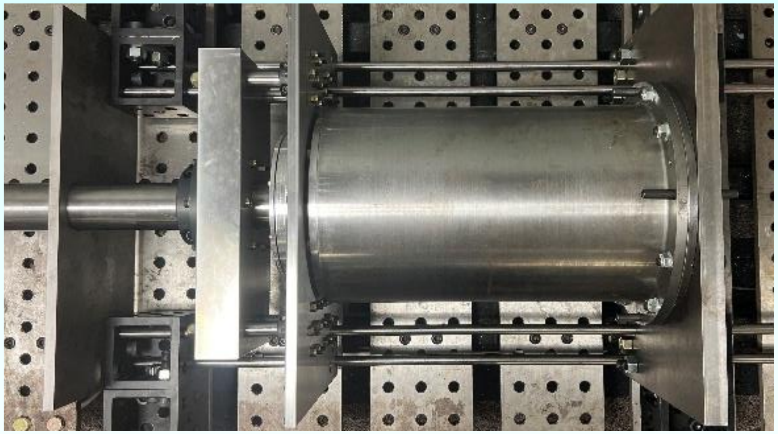
13% torque reduction

1.4% energy density reduction

Construction of the Magnetic Torsion Spring

(a)

(b)

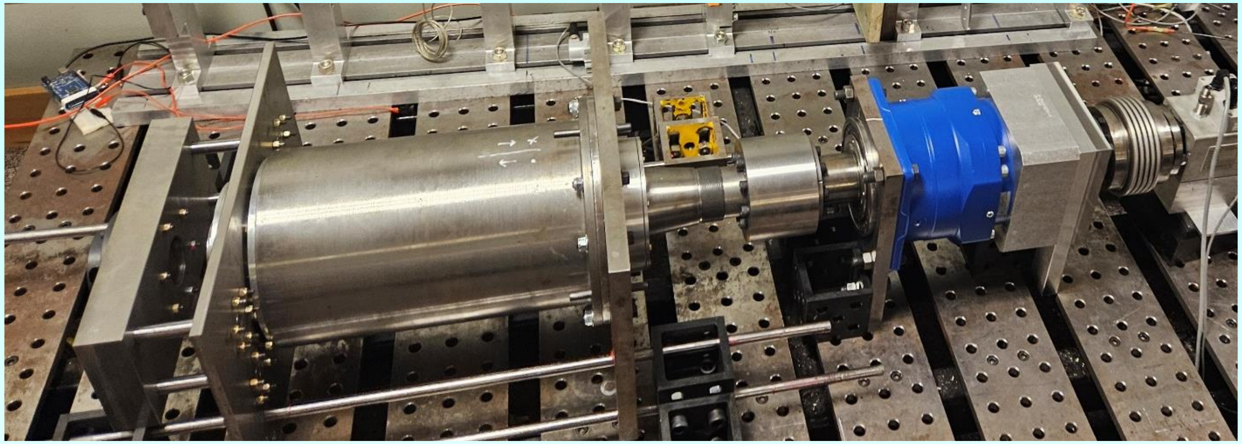


(c)

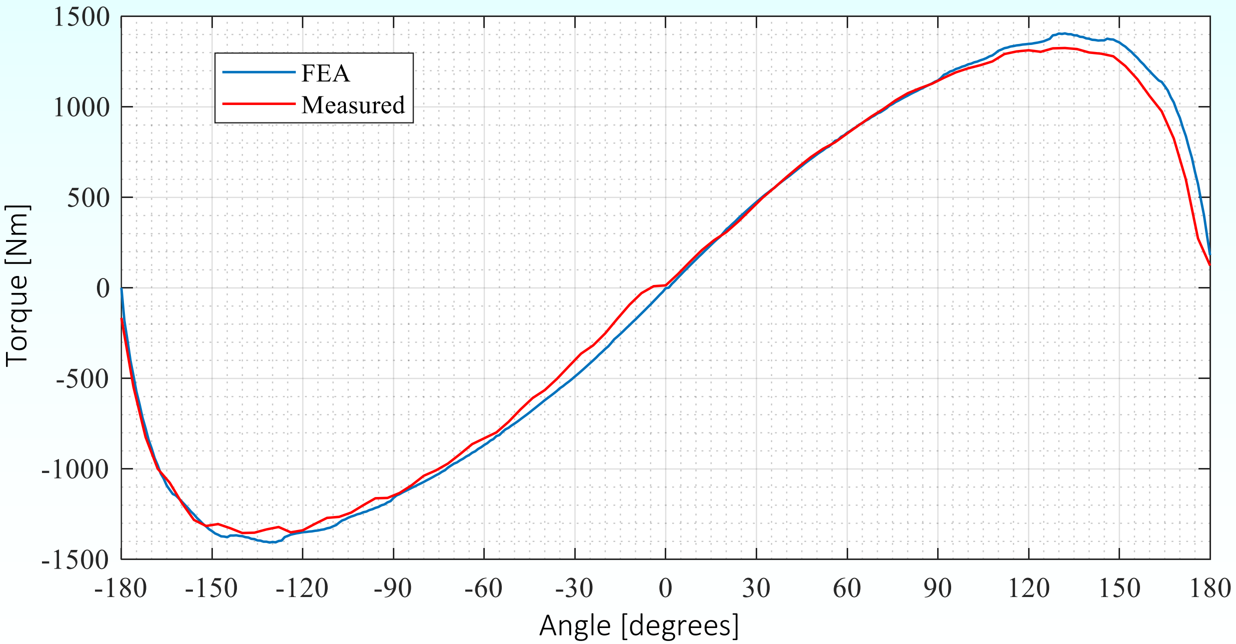
(a) Inner rotor (b) outer rotor for the helical magnetic torsion spring and (c) the test-stand showing the mounted outer rotor.

- Due to the budget time constraints inner rotor used 5 axial stacks of magnets rather than the 7 stacks in the simulation
- This reduced torque from 1933 Nm to 1406.15Nm.

Testing of the Helical Magnetic Torsion Spring



The fully assembled helical magnetic spring (on far left), the torque was measured after the mechanical gear stage (on right).

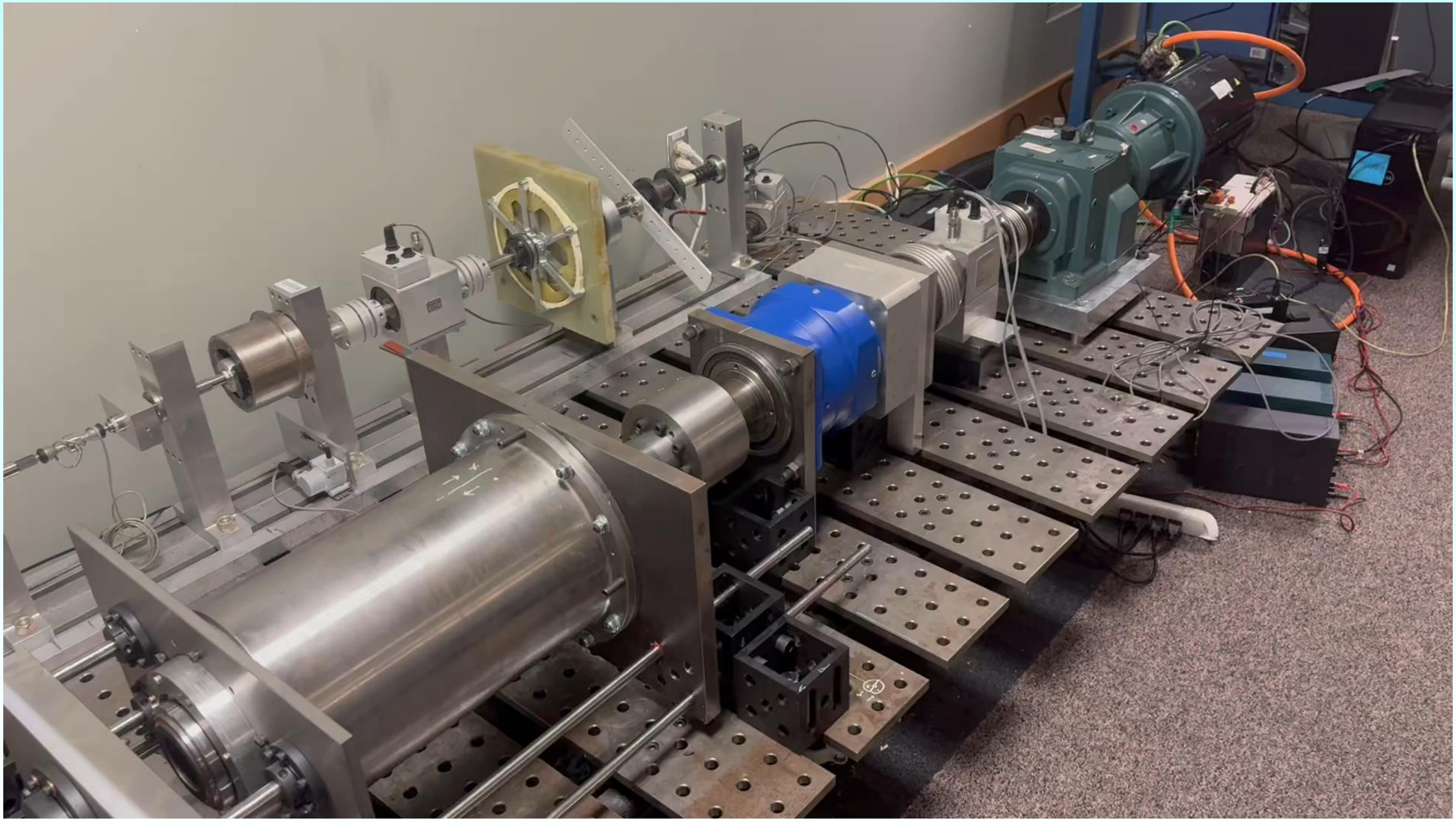


Measured helical magnetic spring torque as a function of angular position compared with the FEA calculated value.

- Calculated peak torque: 1406.15Nm
- Measured peak torque 1353Nm
- Discrepancy of 3.7%.

Experimental testing confirmed torque operation

Testing of the Helical Magnetic Torsion Spring



Advantages and Disadvantages

Advantages of Magnetic Springs:

- Over torque protection: No catastrophic failures, rotors just pole slip
- Non-contact operation: Improves reliability, removes failure modes.

Disadvantages:

- Lower energy density, initial cost higher.
- New technology needs ocean generator testing

Questions and Discussion