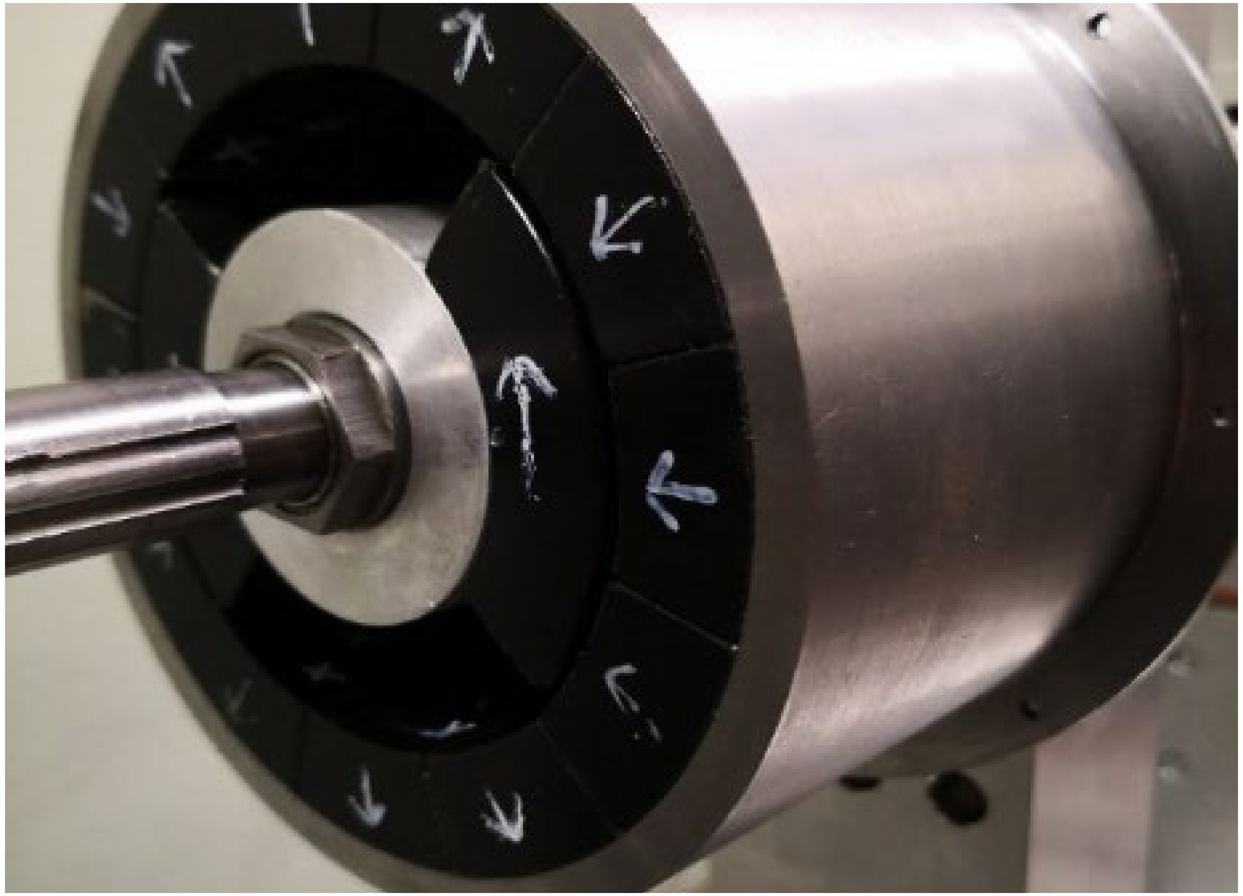
DE-EE-0008631 – Performance Testing of an Integrated Magnetic Power Take-Off



Presenter: Jonathan Bird

Organization: Portland State University,
AquaHarmonics, Inc.,
Sandia National Laboratory,
University of NC at Charlotte.

Email(s): bird@pdx.edu

Presentation Date: Tuesday, July 19, 2022

Project Overview

Project Summary

- Design, build and experimentally test a new type of adjustable stiffness magnetic spring for use in wave energy converters.
- Integrate the adjustable stiffness magnetic spring with a magnetic gear and show that this magnetic power take-off (mPTO) can operate at resonance over a wide bandwidth.
- Demonstrate a competitive energy density capability of the mPTO.
- Experimentally demonstrate that using a mPTO a control system can increase the peak-to-average absorbed power ratio by >50% over baseline values.

Intended Outcomes

- Verified performance potential of new types of highly reliable linear and rotary adjustable stiffness magnetic springs with negative stiffness controllability.
- Demonstrate, through controls, that the magnetic spring can operate at resonance over a wide band-width,
- Integrate an adjustable stiffness magnetic spring with a magnetic gear
- Demonstrate the scalability of the adjustable stiffness magnetic spring by building and testing a 1:20th adjustable stiffness magnetic spring.

Project Information

Principal Investigator(s)

- Jonathan Bird
- Alex Hagmüller
- Giorgio Bacelli
- Wesley Williams

Project Partners/Subs

- AquaHarmonics, Inc.
- Sandia National Laboratory
- University of North Carolina at Charlotte

Project Status

Ongoing

Project Duration

- Project Start Date: 6/01/2019
- Project End Date: 6/30/2023

Total Costed (FY19–FY21)

$1,395,553

Project Objectives: Relevance

Relevance to Program Goals:

- This research is Foundational R&D
- This research drives innovation in components, controls and systems
- Connects foundational R&D with commercialization partners and end users
- Involve underrepresented students in research
- This research could result in a dramatic reduction in LCOE
  - Increases power generation capability of smaller wave energy converters
  - Decouples the stiffness and damping needs of the generator
  - Eliminating the resonant reactive power loading requirement on the generator.
  - Increase reliability through non-contact torque transfer
  - Provides overload torque protection

Project Objectives: Approach

Approach: - Co-design approach - receive end-user specifications and control developer guidance

Resonant wave frequency is low:

$$\omega_o(t) = \sqrt{\frac{k}{m}}$$

System spring stiffness:

$$k = k_w(t) + k_g(t)$$

k_w = WEC stiffness
k_g = PTO stiffness

m = mass
Making WEC large is very costly

Lower stiffness by designing, building and testing newly invented adjustable negative stiffness magnetic spring

Project Objectives: Expected Outputs and Intended Outcomes

Outputs:

- Validate newly invented linear adjustable stiffness magnetic spring
- Validate newly invented rotary adjustable stiffness magnetic spring
- Confirmation of control performance potential of rotary adjustable stiffness magnetic spring
- Demonstrate scalability of adjustable stiffness magnetic spring
- Publication of research (7 to date)
- Patent (2 to date)

Outcomes:

- Modeling and simulation validation
- PTO de-risked through characterization and testing of individual components and integrated system
- Position technology to be integrated into a wave energy converter
- Position technology to be tested in a wave energy converter.
- License technology to commercialization partner

Project Timeline

BUDGET PERIOD 1 - ROTARY AND LINEAR MAGNETIC POWER TAKE-OFF (mPTO) COMPONENT VERIFICATION

Task 1. Design, Build and Test a 1:50 Scale Linear Adjustable Stiffness Magnetic Spring (Month 1 - 10)

- Subtask 1.1. Magnetic Design and Analysis – Completed
- Subtask 1.2. Mechanical/Thermal Analysis – Completed
- Subtask 1.3. Construction of 1:50 Scale Linear AMS – Completed
- Subtask 1.4. Testing of AMS –Completed
- Subtask 1.5. Form an MHK Advisory Board – Completed

Task 2. Design, Build and Test a 1:50 Scale Rotary Adjustable Stiffness Magnetic Spring (Month 4 – 17)

- Subtask 2.1. Magnetic Design and Analysis – Completed
- Subtask 2.2. Mechanical/Thermal Analysis – Completed
- Subtask 2.3. Construction of 1:50 Scale Rotary AMS – Completed
- Subtask 2.4. Testing of Rotary AMS – Completed

Task 3. Critical Design Review for the Work Completed in Task #1 and #2 – Completed

Go-no-go Review Tasks

Task 4. Construct 1:20 Scale Magnetic Lead Screw

- Subtask 2.1. Magnetic Design and Analysis – Completed
- Subtask 2.2. Mechanical/Thermal Analysis – Completed
- Subtask 2.3. Construction of Magnetic Lead Screw –
- Subtask 2.4. Testing of Magnetic Lead Screw–

Series rotary spring Invention makes redundant

Task 7. Concurrent Control Design for mPTO (Month 1 - 32) – Worked on

- Subtask 7.1. Controller Design for the Linear mPTO – Now not needed
- Subtask 7.2. Controller Design for the Rotary mPTO – Worked on (Phase 2 focus area)
- Subtask 7.3. Sandia National Laboratory Control Verification of the mPTO – Sending adjustable spring to SNL - 7/2022

Project Timeline

Subtask 1.5. Advisory Board

AquaHarmonic, Inc.
Alex Hagmüller, President and CEO
Email: aquaharmonics@gmail.com

CalWave Power Technologies
Thomas Boerner
Email: thomas@calwave.energy

Sandia National Laboratory
Giorgio Bacelli
Email: gbacell@sandia.gov

Advisory board defined requirements for 1:20th scale adjustable stiffness rotary magnetic spring

Project Timeline

BUDGET PERIOD 2 - ROTARY AND LINEAR MAGNETIC POWER TAKE-OFF (mPTO) COMPONENT VERIFICATION

Task 5. Design, Build and Construct 1:20 Scale Rotary AMS (Month 19 - 28) – **Worked on**
- Subtask 5.1. Magnetic Design & Analysis – **Completed FY22**
- Subtask 5.2. Mechanical & Thermal Analysis of the AMS – **Completed FY22**
- Subtask 5.3. Construction of the 1:20 Scale AMS – **Completed FY22**
- Subtask 5.4. Testing of 1:20 AMS

Task 6. Laboratory Testing the 1:20 scale mPTO (Month 28 - 31)
- Subtask 6.1. Laboratory Testing of the Rotary AMS – **Worked on 2022**

Task 7. Concurrent Control Design for mPTO (Month 1 - 32) – **Worked on**
- Subtask 7.1. Controller Design for the Linear mPTO – **Now not needed**
- Subtask 7.2. Controller Design for the Rotary mPTO – **Worked on (Phase 2 focus area)**
- Subtask 7.3. Sandia National Laboratory Control Verification of the mPTO – **Sending adjustable spring to SNL - 7/2022**

Task 8. Tank Testing 1:20 Scale mPTO (Month 34 - 37)
- Subtask 8.1. Water Tank Testing mPTO

Task 9. Scaling and Cost Analysis (Month 29 - 37)
- Subtask 9.1. Scaling Analysis - 1:7 to Full Scale
- Subtask 9.2. Cost-Performance Comparison

Task 10. Final Reporting (Month 37)
- Subtask 10.1. Final Report

Project Budget

Total Project Budget – Award Information		
DOE	**Cost-share**	**Total**
$1,500,000	$500,625	$2,000,625

FY19	FY20	FY21	Total Actual Costs FY19–FY21
Costed	**Costed**	**Costed**	**Total Costed**
$124,804	$490,150	$780,599	$1,395,553

- No variance from planned budget
- No sizeable discrepancy in the costed vs authorized numbers
- Some delays in the scaled up magnetic spring construction

End-User Engagement and Dissemination

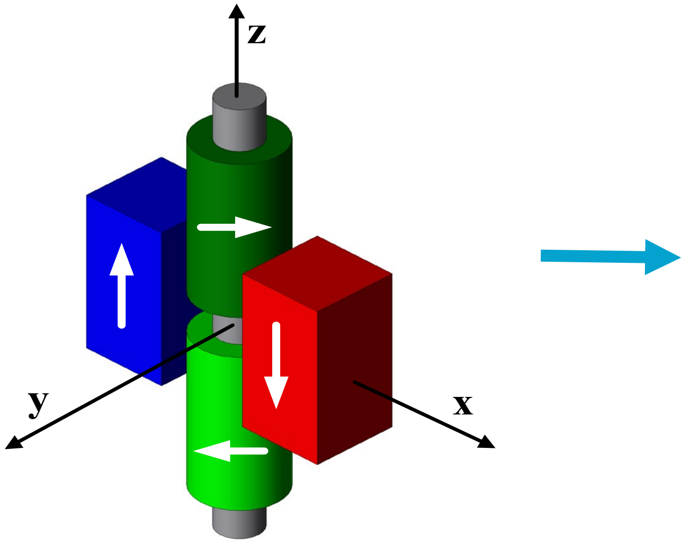
Performance: Accomplishments and Progress

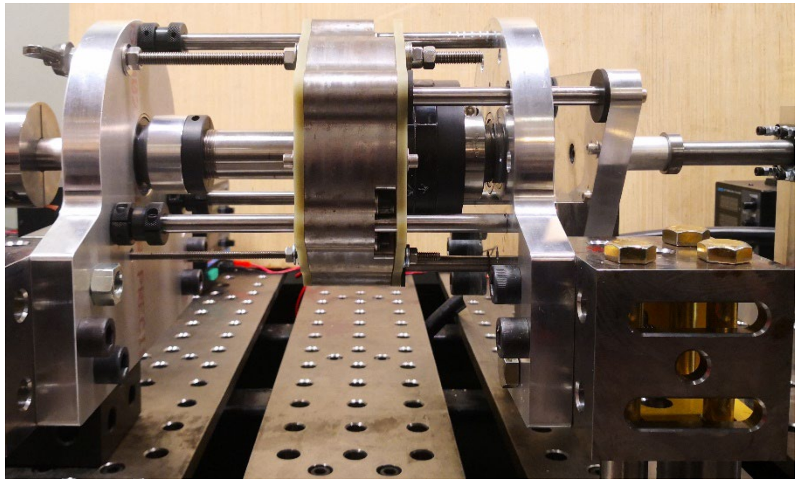
Most important technical accomplishments achieved between FY19 – FY21:

- Validated the performance of the newly invented adjustable stiffness linear magnetic spring (Task 1)
- Validated the performance of the adjustable stiffness torsional magnetic spring (Task 2)
- Selected the torsional spring to be scaled up in size.
- Demonstrated resonance tuning ability of the adjustable stiffness torsional magnetic spring

Performance: Accomplishments and Progress

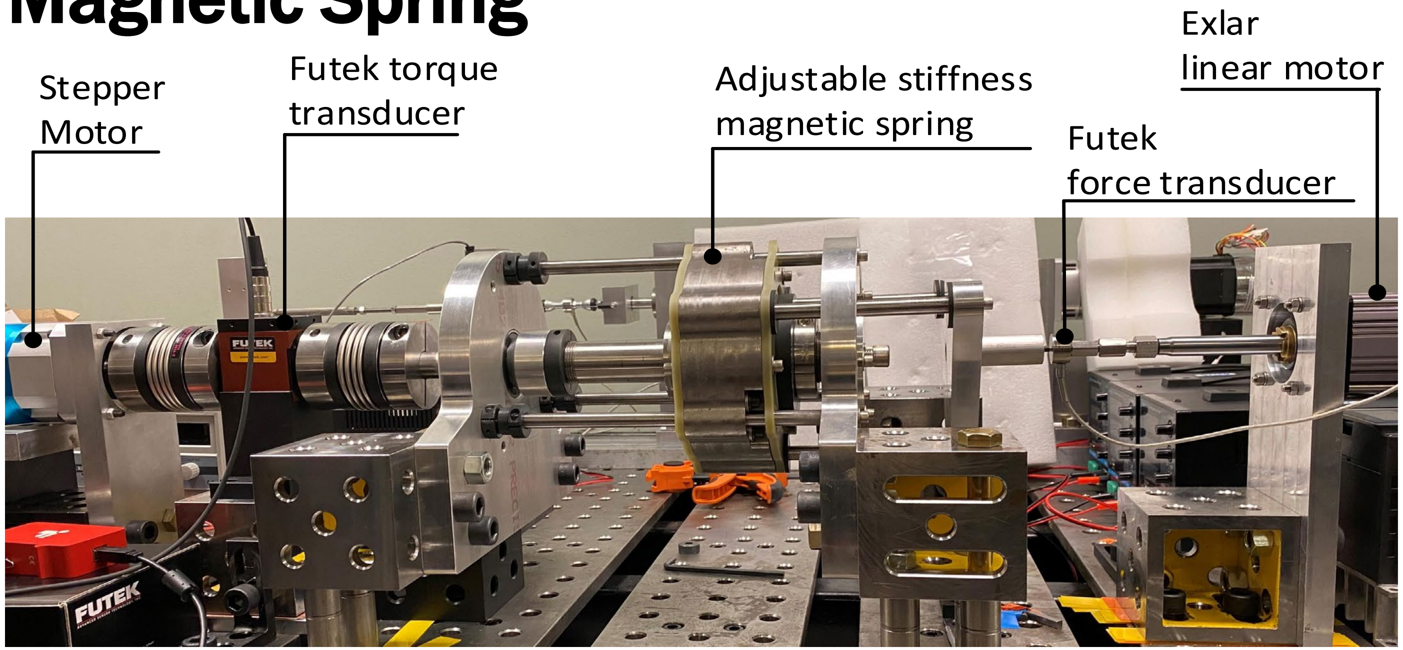
Task 1:
Design, Build and Test a 1:50 Scale Linear Stroke Length Adjustable Stiffness Magnetic Spring





Performance: Accomplishments and Progress

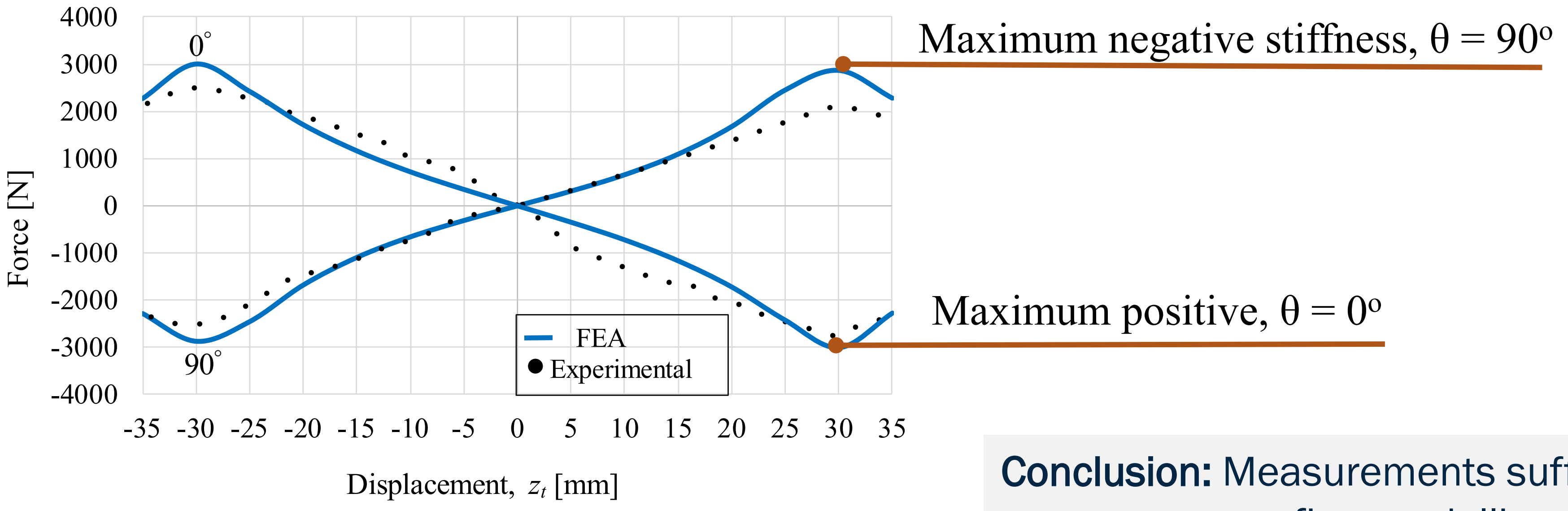
Task 1: Design, Build and Test a 1:50 Scale Linear Stroke Length Adjustable Stiffness Magnetic Spring

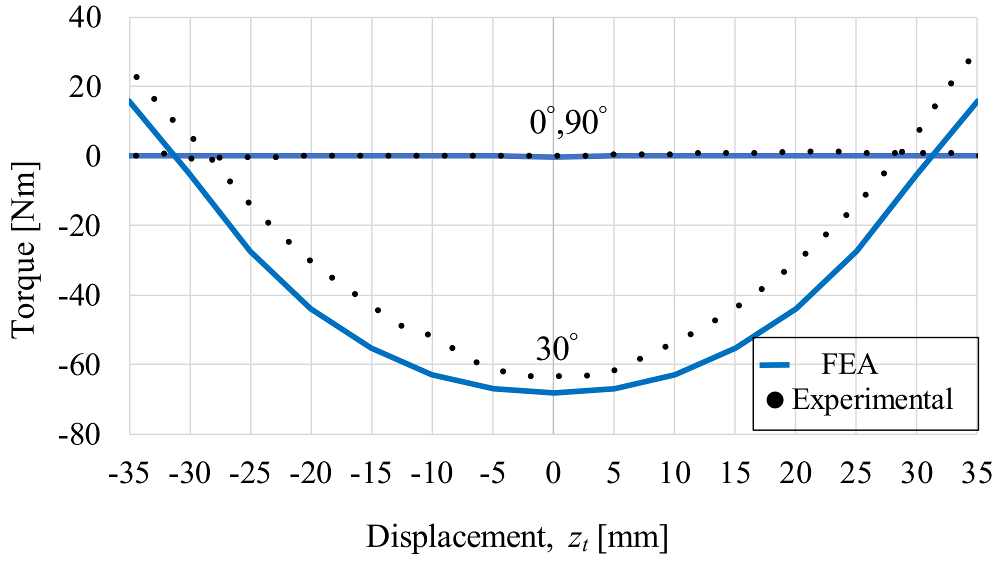


Adjustable stiffness linear magnetic spring test-stand

- Stepper motor used to adjust stiffness
- Brake used to hold new stiffness value with zero power loss
- Current stepper motor not holding torque at peak values

Performance: Accomplishments and Progress





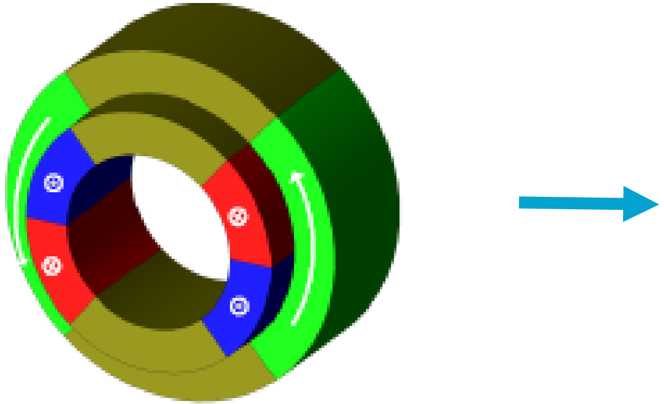
Conclusion: Measurements sufficiently confirm modelling.

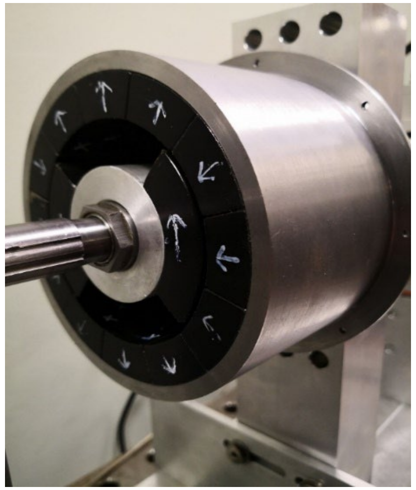
Rotary spring design shown to be superior for MHK applications

Performance: Accomplishments and Progress

Task 2:

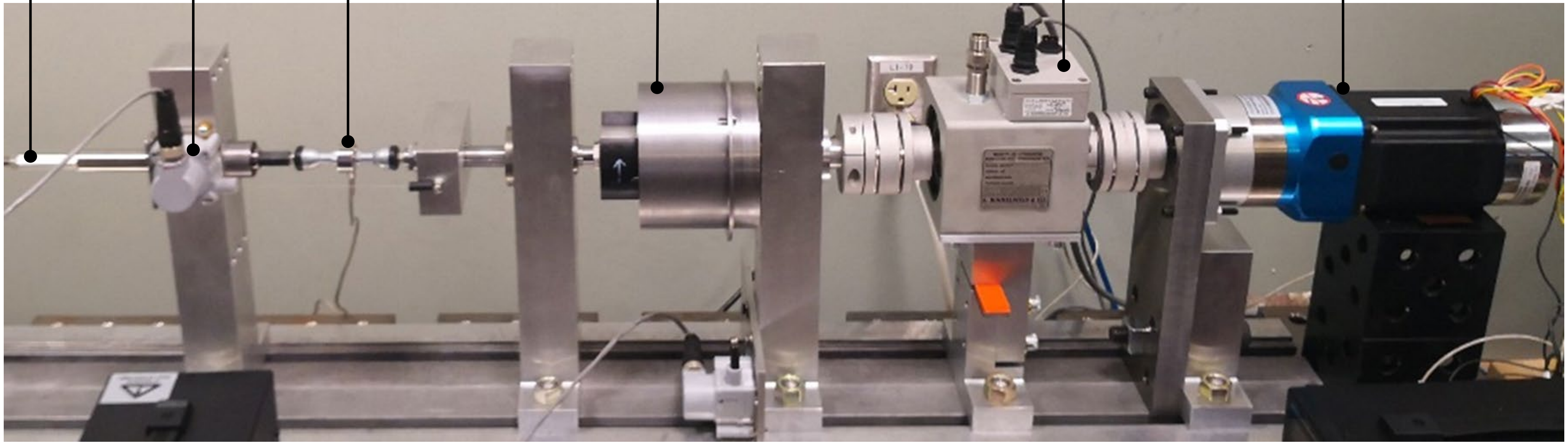
Design, Build and Test a 1:50 Scale Rotary Stroke Adjustable Stiffness Magnetic Spring





Performance: Accomplishments and Progress

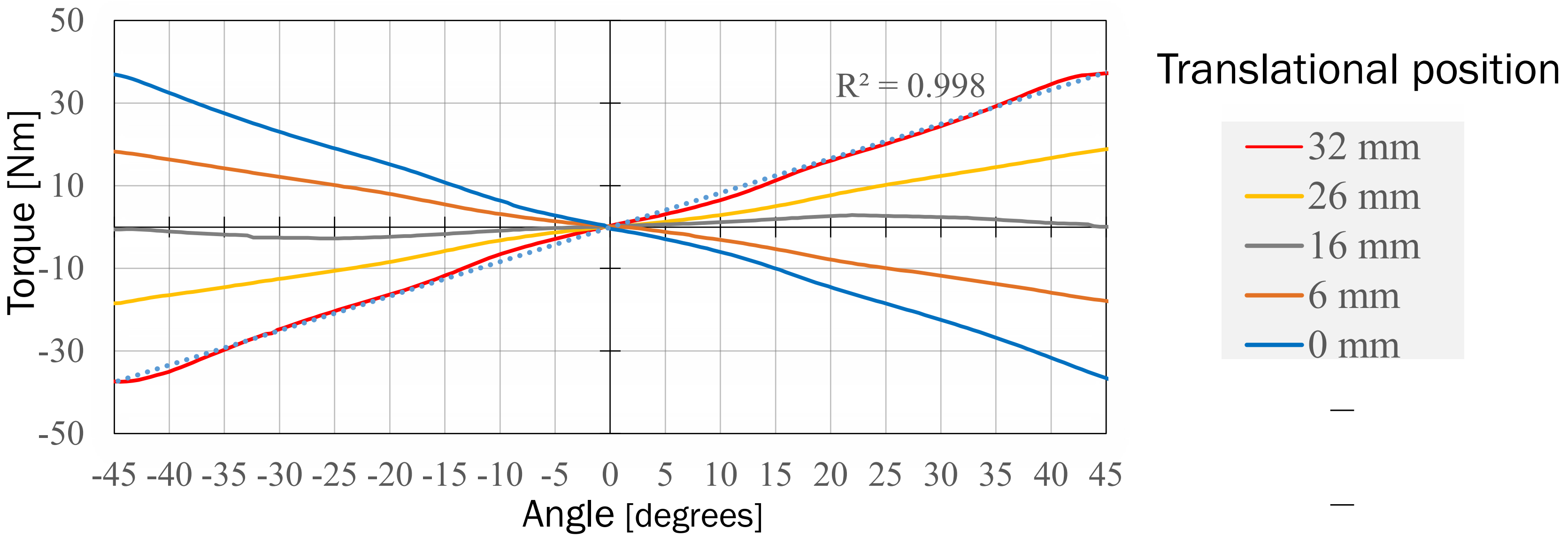
Task 2: Design, Build and Test a 1:50 Scale Rotary Stroke Length Adjustable Stiffness Magnetic Spring



45^{o} Adjustable stiffness rotary magnetic spring test-stand

Performance: Accomplishments and Progress

Experimentally measured torque as a function of angle for different axial positions



Parameter	FEA Calculated Value	Measured Value	Units	% Difference
Peak torque	43	33	N·m	-22.1
Spring rate	53.6	42.1	N·m/rad	-21.4
Peak Energy	16.65	13	J	-21.9
Total mass	1.8	1.8	kg	0
Energy density	9.25	7.22	J/kg	-24.6
	52.8	41.3	kJ/m³	-21.7
Efficiency	TBD	-	-	-
Stroke length	45°	45°	Degrees	0
Rated angular speed	≤ 50	≤ 50	r/min	-

Performance: Accomplishments and Progress (cont.)

Patent Disclosures

[1] J. Bird, Variable Stiffness Magnetic Spring, US Patent application # US 2021/0054897 A1, Publication Date Feb. 25, 2021

[2] J. Bird, Magnetic Torsion Spring, US Patent application # 63255718, filed: 14 Oct. 2021

Journal Papers

[3] H. Baninajar, J. Z. Bird, V. Albarran, Investigating the Performance of a New Type of Preloaded Linear Stroke Length Magnetic Spring, *Prog. in Electromagnetics Research C*, Vol. 111, 1-14, 2021, DOI: http://dx.doi.org/10.2528/PIERC21011507

[4] D. Che, J. Z. Bird, A. Hagmüller, Designing and Experimentally Testing an Adjustable Stiffness Torsional Magnetic Spring Resonant Generator, Submitted to *IEEE Transactions on Industrial Applications,* June 2022

Conference Papers

[5] M. E. Hossain and J. Z. Bird, "Investigating the Performance of a Variable Stiffness Magnetic Spring for Resonant Ocean Power Generation," Presented at *2019 IEEE Energy Conversion Congress and Expo.*, Baltimore, MD, USA, 2019, pp. 5002-5008, DOI: http://dx.doi.org/10.1109/ECCE.2019.8912306

[6] W. Williams, Performance Testing of an Integrated Magnetic Power Take-Off , presented at *The North Carolina Renewable Ocean Energy Symposium*, April 17, 2020.

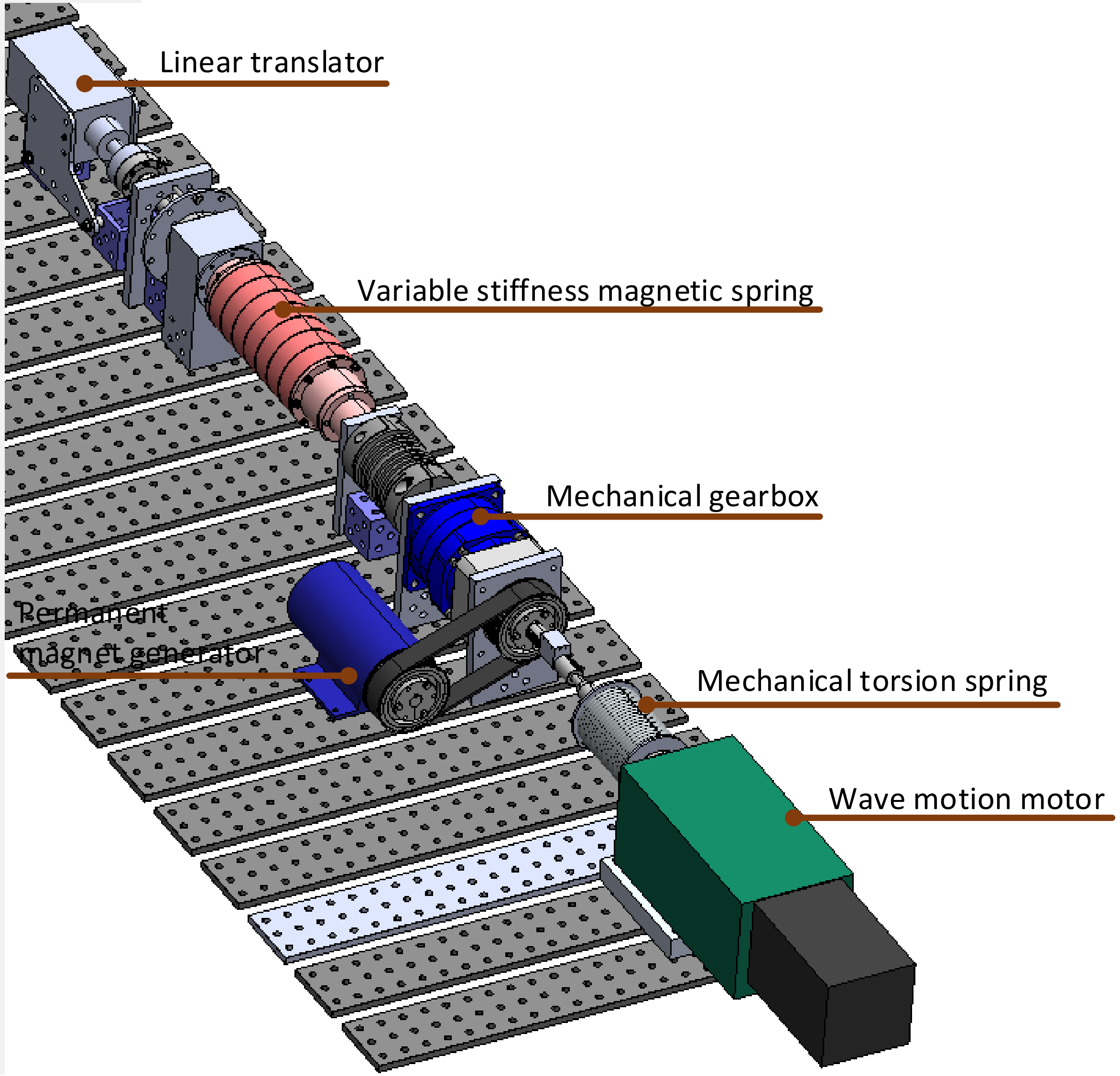
[7] D. Che, J. Z. Bird, A. Hagmüller, and M. E. Hossain, "An Adjustable Stiffness Torsional Magnetic Spring with a Linear Stroke Length," Presented at 13th *IEEE Energy Conversion Congress and Expo*, Vancouver, BC, Canada, 10-14 Oct. 2021, pp. 5944-5948, DOI: http://dx.doi.org/10.1109/ECCE47101.2021.9595267

[8] M. E. Hossain, J. Z. Bird, V. Albarran and D. Che, "Analysis and Experimental Testing of a New Type of Variable Stiffness Magnetic Spring with a Linear Stroke Length," Presented at 13th *IEEE Energy Conversion Congress and Expo.*, Vancouver, BC, Canada, 10-14 Oct. 2021, pp. 5961-5965, DOI: http://dx.doi.org/10.1109/ECCE47101.2021.9595241

[9] D. Che, J.Bird, and A. Hagmuller, " A Multi-Stack Variable Stiffness Magnetic Torsion Spring for a Wave Energy Converter to be presented at the *14th IEEE Energy Conversion Congress and Exposition*, Detroit, MI, Oct. 9 -13th, 2022

Future Work

- Sandia National Laboratory will complete rotary spring performance validation (Subtask 7.3)
- Complete assembly and testing of the 1:20th scale adjustable stiffness magnetic spring (Subtask 5.4)
- Complete testing of the 1:50th scale magnetic PTO - magnetic gear and spring, (Subtasks 6.1)
- Complete conjugate control lab testing of 1:20th and 1:50th scale magnetic torsion spring (Subtask 7.2)
- Complete further cost analysis and sizing design analysis (Subtask 9.1)
- Complete water tank testing of the magnetic PTO. (Subtask 8.1)



Q&A

Lunch
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