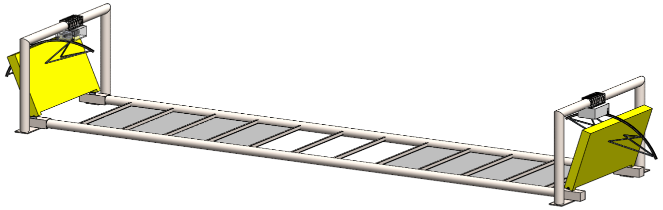
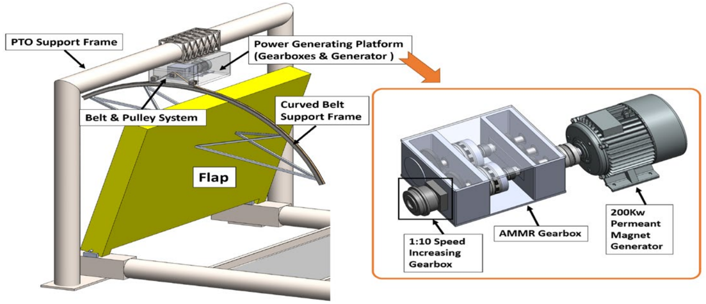
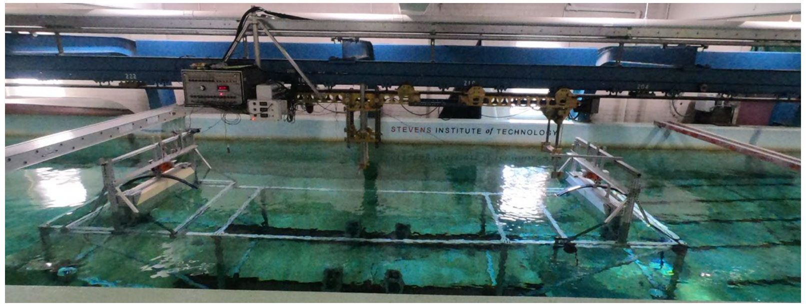
EE0008953 – Floating Oscillating Surge Wave Energy Converter with Controllable Efficient Power Takeoff System







Muhammad Hajj* and Lei Zuo**
*Stevens Institute of Technology
** Virginia Tech

mhajj@stevens.edu
leizuo@vt.edu

July 20, 2022

Project Overview

Project Summary

The100-kW dual-flap floating oscillating surge wave energy converter (FOSWEC), as designed here, can be deployed at any water depth. One innovation is to position the flaps on a semisubmersible platform in a way to realize out of phase motions, and thus enhance the structural stability at minimum cost. A second innovation is to design, build and test an active mechanical motion rectifier as an integral component of the FOSWEC. The project scope also includes development of manufacturing plan, ocean test plan, risk register, basis of design, compliance with IEC/IEEE standards, commercialization plan, and NEPA compliance requirements.

Intended Outcomes

Take advantage of dual flap design to:

- Increase Capture Width Ratio from 18% (RM5) to 40%
- Reduce Peak to Average Ratio by 50%
- Reduce Levelized Cost of Electricity by 40%

Project Information

Principal Investigator(s)

- Muhammad Hajj & Raju Datla (Stevens)
- Lei Zuo (Virginia Tech)

Project Partners/Subs

- Bill Staby and Marcus Gay (RME).
- Michael Lawson, Scott Lambert, Rebecca Fao, David Ogden, Sal Husain (NREL).
- Budi Gunwan, Giorgio Bacelli, Steve Spencer (Sandia)
- Zhongfu GE (ABS)

Project Status

Ongoing

Project Duration

- June 1, 2020
- December 31, 2022

Total Costed (FY19–FY22)

$2.2 M + $0.45M (cost shared)

Project Objectives: Relevance

Relevance to Program Goals:

- This effort is in direct support of expanding and diversifying the Nation’s energy portfolio and is a critical step on the way to developing both grid-scale and distributed power generation WEC systems by extending bottom-hinged OSWEC in shallow water to floating OSWEC in deep ocean with a floating platform and controllable active PTO.

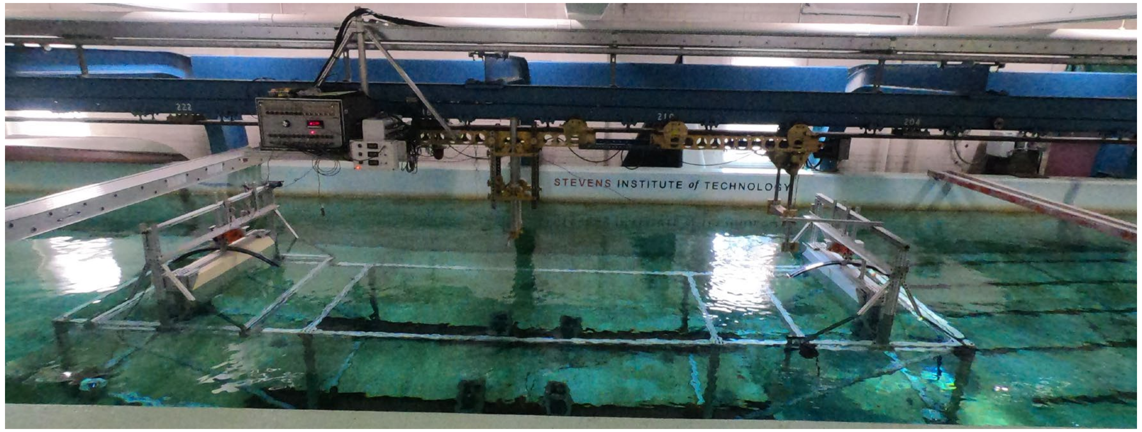
- Designing a full-scale WEC according to rigorous MHK design standards, as performed here, will boost Wave Energy Converter (WEC) technologies from early stages of development to the testing of cost competitive utility-scale WEC technologies.

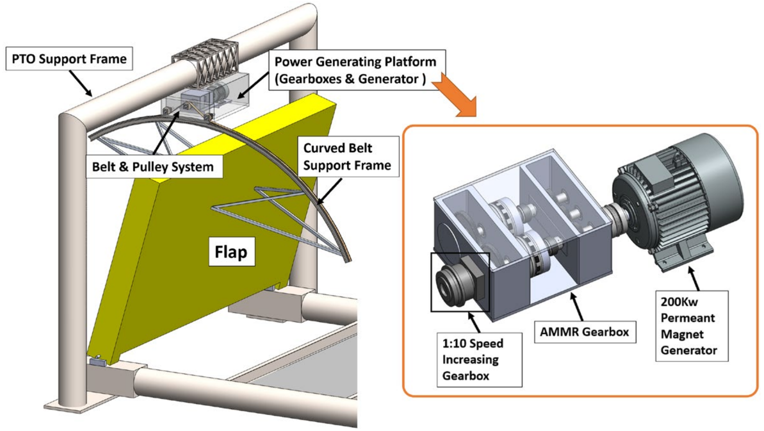
- The ultimate goal is to build and test the designed system in the PacWave South test site.

Project Objectives: Approach

System Design and Validation:

System level co-design: natural frequency vs. wave torque, flap shape, flap buoyancy, flap moment of inertia, mooring platform, PT, and PTO control





Multiple scale design, prototyping and testing: scaling down and integrated approach in design / testing of components- full scale design, 1:2 scale PTO testing, and 1:10 scale tank test of integrated system.

Performance evaluation and validation: Hydrodynamics, PTO, operation in extreme conditions, parametric cost breakdown, Levelized cost of energy.

Project Objectives: Approach

Covered plans and procedures in design report: Transportation plan, Commissioning and Systems Integration procedure, Installation procedure, Operations procedure, Scheduled maintenance procedure, Unscheduled maintenance procedure, Decommissioning procedure, Disposal procedure

International standards for device performance and insurance certification: IEC TS 62600 – 2 (design requirements), -10 (mooring), -100 (performance assessment), -103 (model testing)

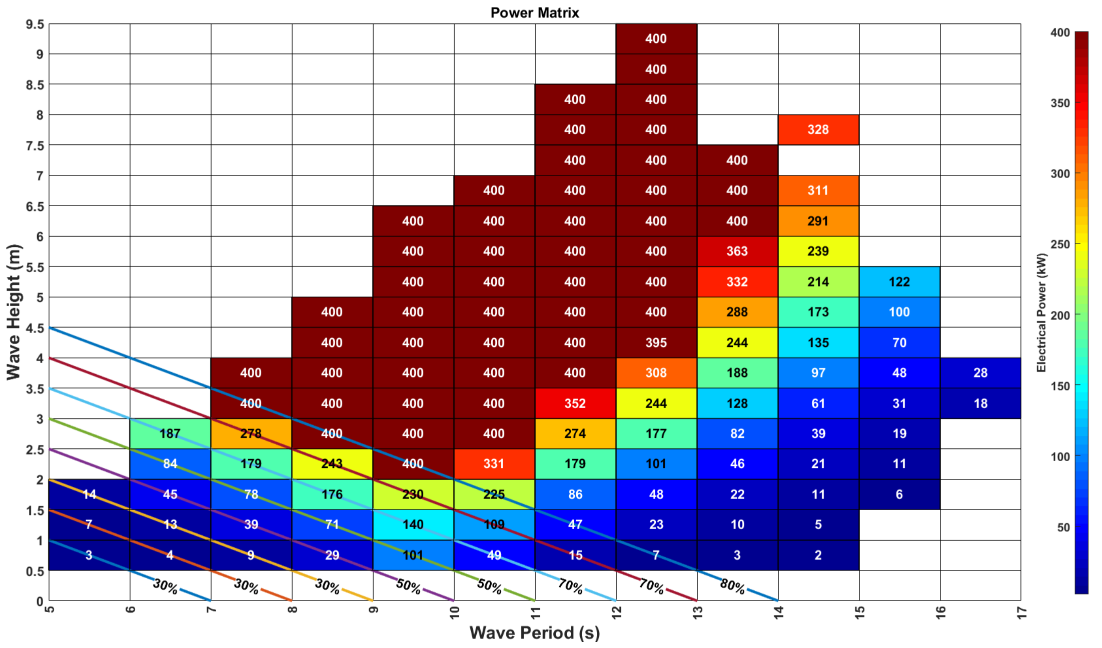
Design process: addresses manufacturing and practical WEC issues including strength and fatigue analysis, inspection and quality control, identification and reduction of risks to acceptable levels using a risk register based on NREL's Risk Management Template.

Leveraged expertise: Team includes two universities, a leading marine energy company, two national labs, and American marine standards organization ABS.

Project Objectives: Expected Outputs and Intended Outcomes

Outputs:

- 100 – kW Floating Oscillating Surge Wave Energy Converter (PacWave South)



Outcomes

- Annual electrical energy = 2.05 GWh
- Annual average electrical power = 234 kW (expected to be reduced to **100 kW** with irregular waves)
- Peak to average ratio= **10: 1** (could be larger based on simulation duration)
- Capture Width Ratio for both flaps =**1.1**

Project Timeline

FY 2020

June 1: Kickoff

September 30: Revised SOPO

FY 2021

January 21: Preliminary report and presentation

July 21: Tank testing of integrated model

September 21: RME risk register and basis for design

December 21: Hydrodynamic performance optimization

FY 2022

May 22: 1:10 scale PTO control test (Sandia)

June 22: 1:2 scale PTO built

September 22: 1:2 scale PTO test (NREL)

October 22: Third party validation (ABS)

Timeline slightly adjusted to cover issues as they arose and from new knowledge (e.g. cable fatigue, quality control, risk identification).

Project Budget

Total Project Budget – Award Information		
DOE	**Cost-share**	**Total**
$1,800K	$450K	$2,250K

FY19	FY20	FY21	Total Actual Costs FY19–FY21
Costed	**Costed**	**Costed**	**Total Costed**
$0K	$136K	$941K	$391K

- No variations from planned budget.
- No-cost extension till December 31, 2022

End-User Engagement and Dissemination

- Testimony by PI Muhammad Hajj to the NJ Assembly Committee on Natural Resources in March 2022. Participants included industry representatives.

- Demonstrations of FOSWEC to state government (NJ Assembly Committee on Natural Resources) in May 2022

- Invited webinars /seminars by PIs Muhammad Hajj (SNAME NY metro chapter) and Lei Zuo (UC Berkely, UM Ann Arbor, UIUC, Keynote at MAOME2021, VEH 2021)

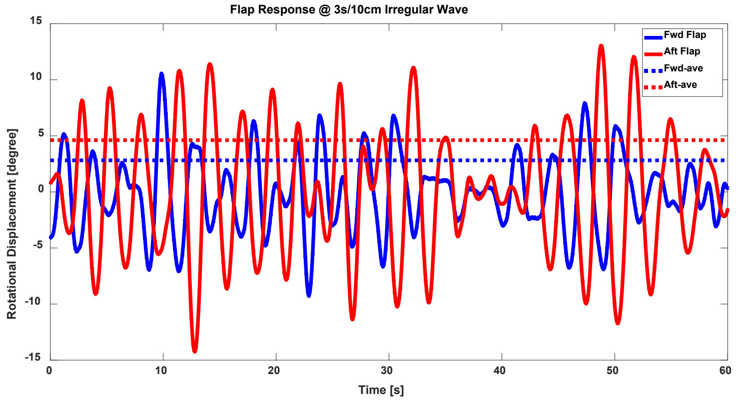
- Interview by NY CBS news of PI Muhammad Hajj on wave power

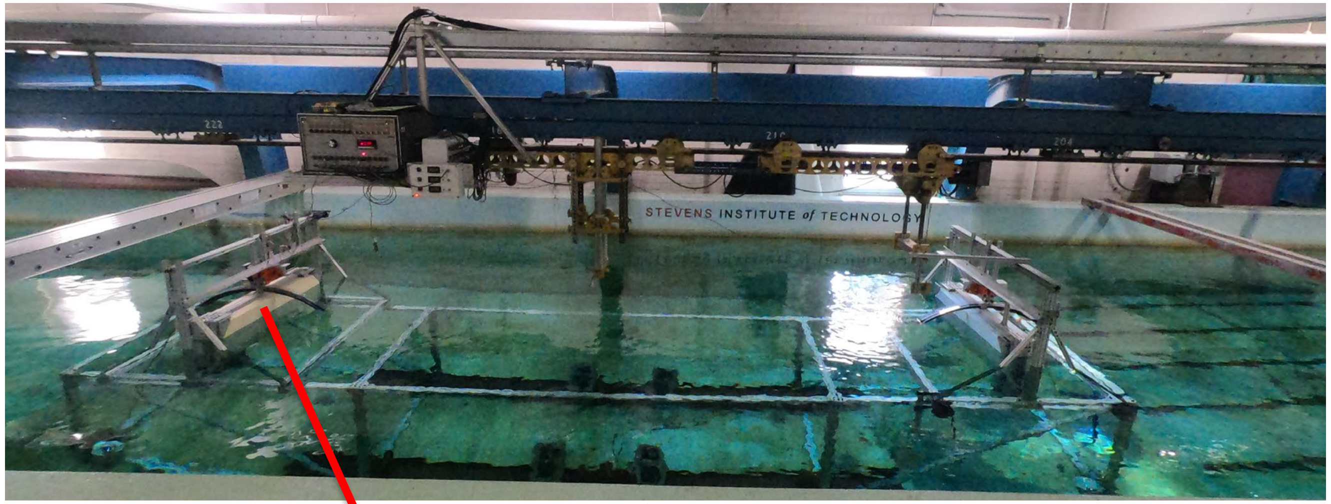
- ~15 presentations by students at various conferences (Engineering Mechanics Conference, ICOE 2021, MOVIC 2022, IDTEC ASME 2022)

Performance: Accomplishments and Progress

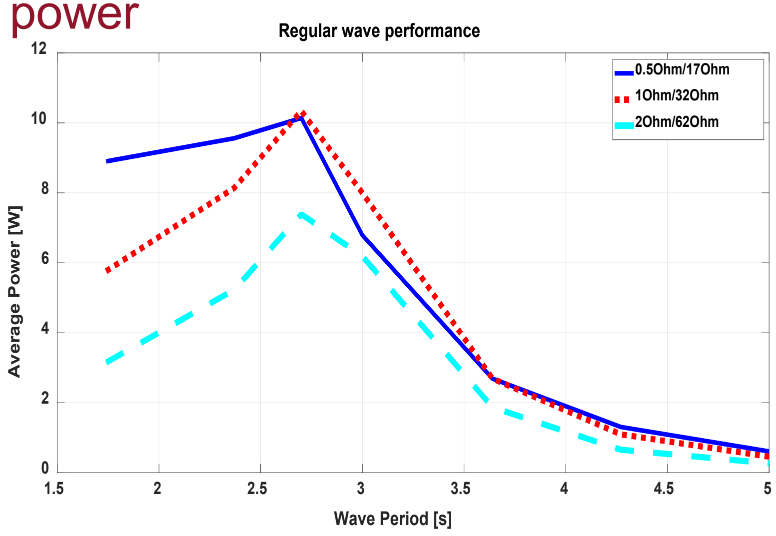
Wave tank testing:

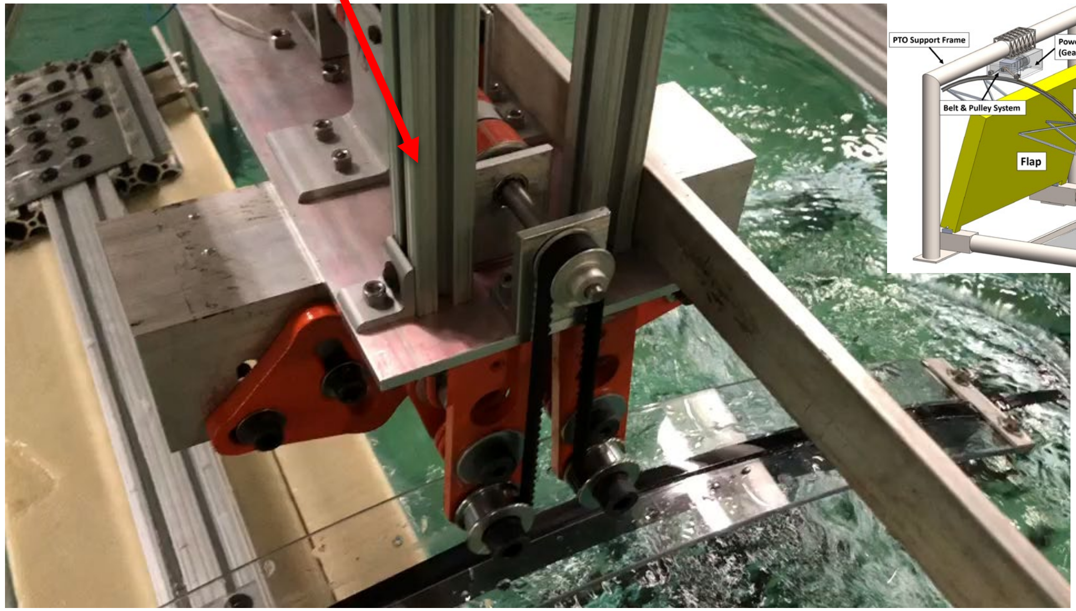
Out of phase motions

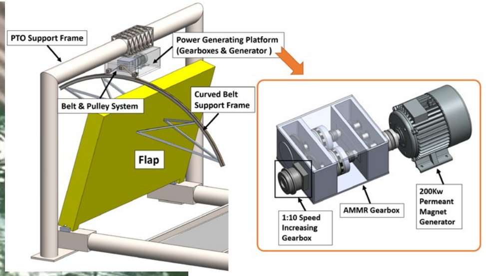




Generated power







Performance: Accomplishments and Progress

State-Space Model:

- The equation of motion after replacing the convolution term and accounting for the non-linear damping is:

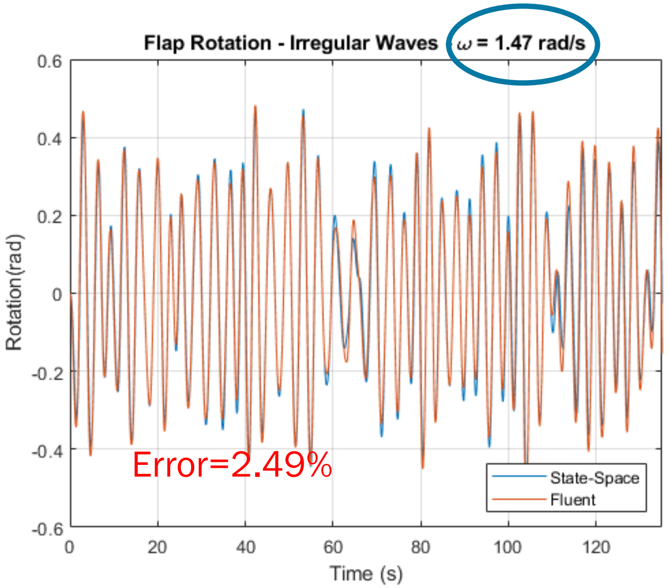
$$(I + I_a)\ddot{\theta} + C_{rad}X_{rad}(t) + K\theta + C_D\dot{\theta}|\dot{\theta}| = T_{exc}$$

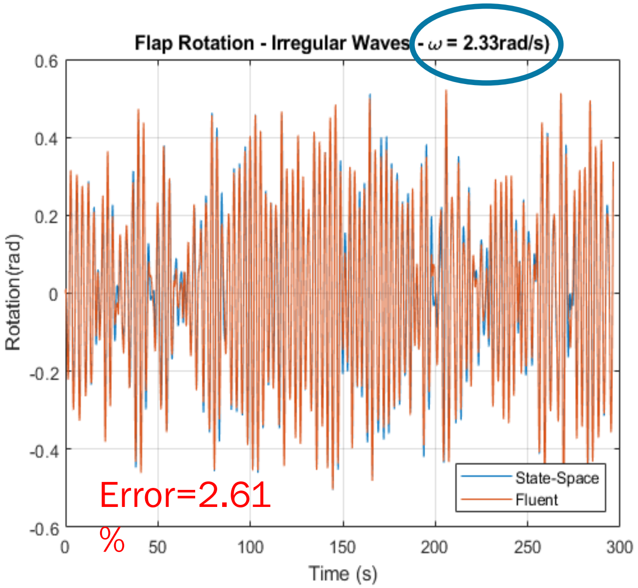
$$\dot{X}_{rad}(t) = A_{rad}X_{rad}(t) + B_{rad}\dot{\theta}(t)$$

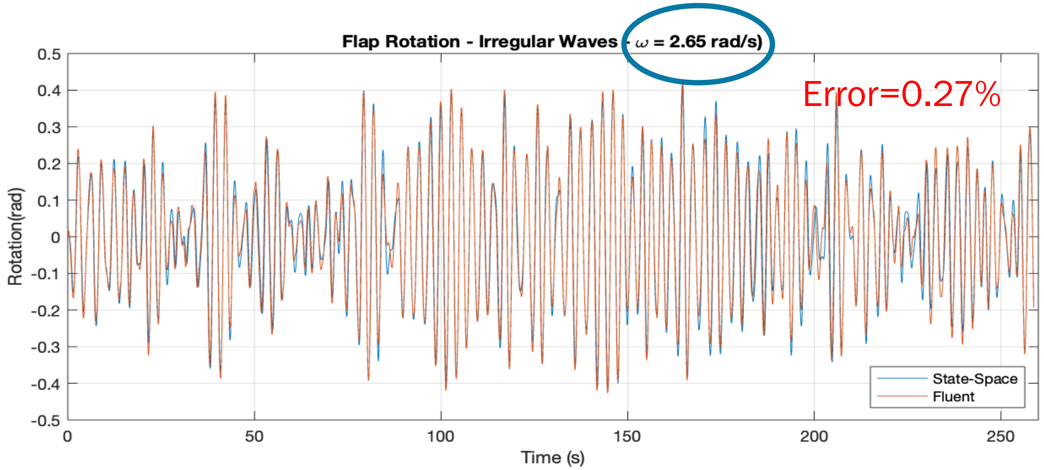
- The parameters were tuned based on simulations under regular conditions.

- The computational time was reduced from **17 days** using ANSYS Fluent to **13 minutes** using the state-space model.

- Will be effectively used in implementing control







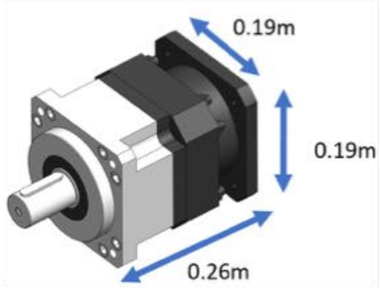
Performance: Accomplishments and Progress

5KW AMMR PTO System Hardware – Testing at NREL September 2022

5KW AMMR Gearbox Assembly (In transit)

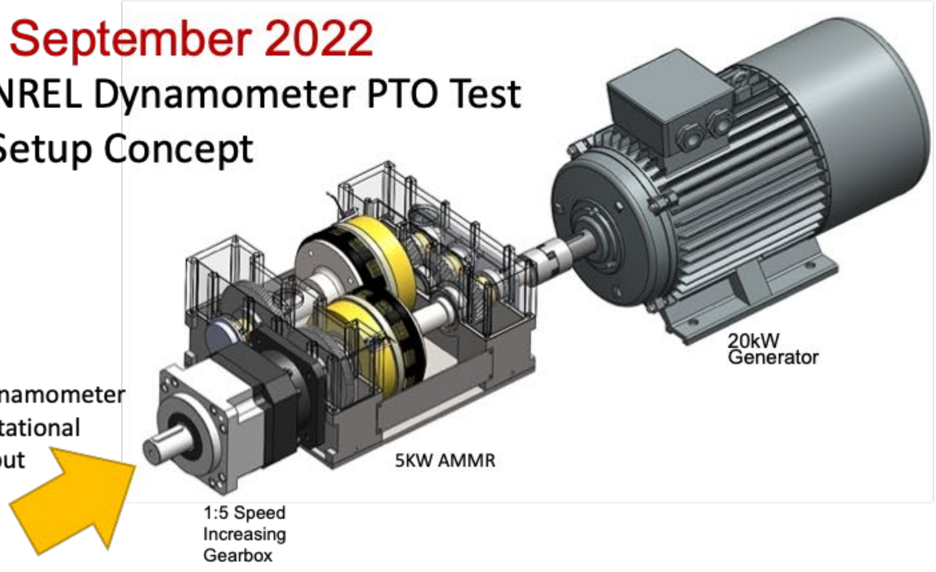
- Electromagnetic Clutch (EMA 0800) *2
- Rated static torque: 816 N.m

1:5 Speed Increasing Gearbox
- Split Casing Design
- Max Torque: 2400 N.m (high speed side)
- Rated Torque: 1200 N.m (high speed side)
- Backlash: <= 10 arcmin (high speed side)



Controllability, efficiency and failure mode identification

NREL Dynamometer PTO Test Setup Concept

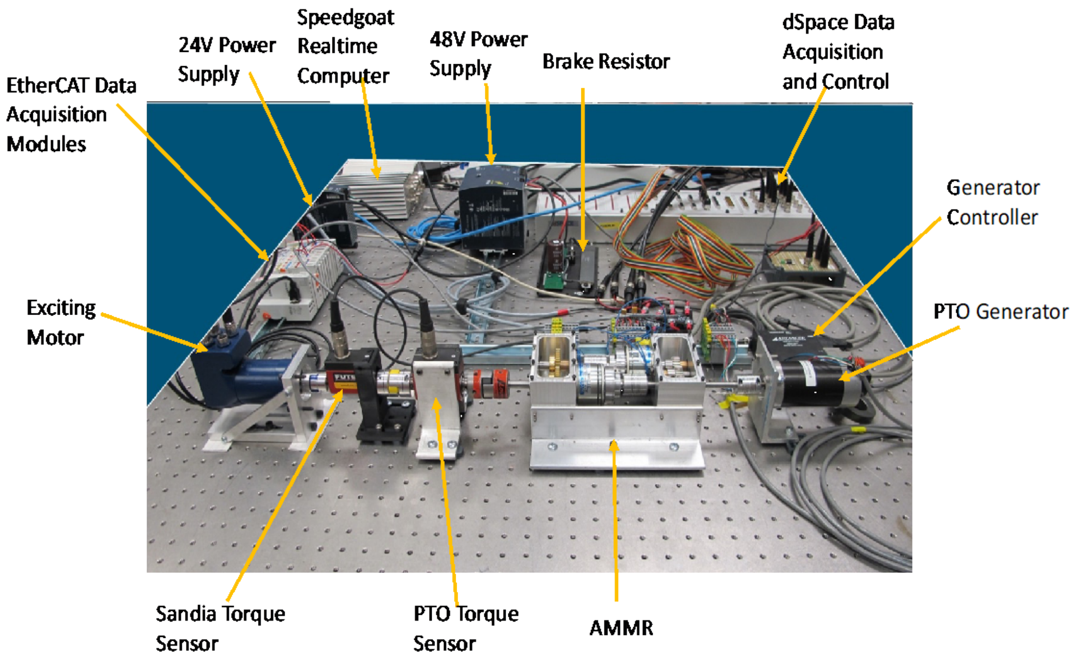


Permanent Magnet Generator	
Model	YGDLF-20kW
Rated power	20kW
Rated speed	500rpm
Rated voltage	380VAC
Rated current	30.4A
Phase number	3-phase
Frequency	50Hz
Numbers of Poles	12
Rated torque	410Nm
Startup torque	10Nm
Insulation Class:	H
Protection Class	IP54
Efficiency	93%
Power factor	0.97

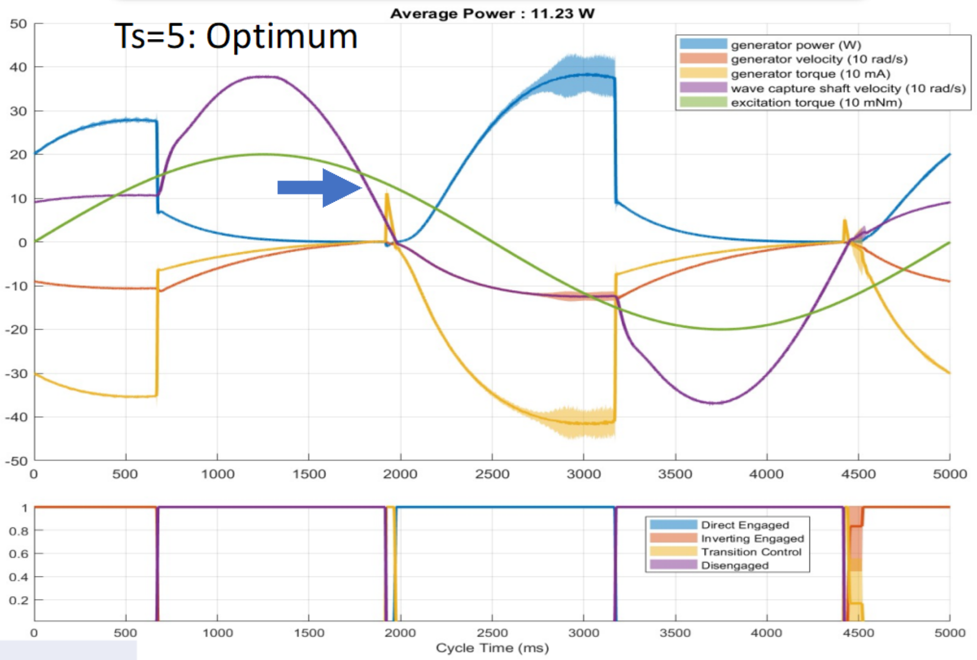
Rated 500rpm 20kW Generator (In transit)

Performance: Accomplishments and Progress

AMMR Test and Control Verification at SNL



Optimized over four parameters for maximum power export for several regular wave cases.



Found Significant Improvements Using AMMR

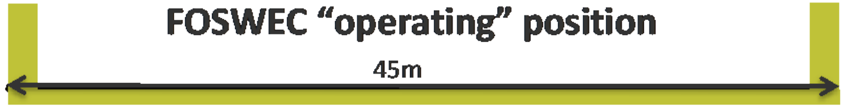
Wave Period (s)	Excitation Amplitude (Nm)	Optimal Engaged Damping (mNms/rad)	Optimal Disengaged Damping (mNms/rad)	Optimal phase from excitation torque (rad)	Optimal Duty Cycle %	Optimal Power Export (W)	Optimal Power Export – Direct Clutch Only (W)	AMMR Improvement
5	0.2	3.32	0.688	2.41	27%	11.1	6.45	72%
4	0.12	1.49	1.031	2.64	23%	4.59	3.63	26%
3	0.06	0.29	1.031	3.43	18%	0.095	0.063	51%
2	0.17	0.89	---	4.46	33%	1.4	1.266	11%

Performance: Accomplishments and Progress

Mooring Design and Analysis

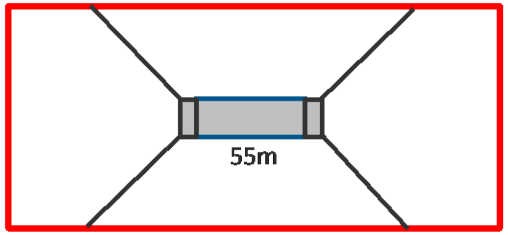
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

FOSWEC "operating" position

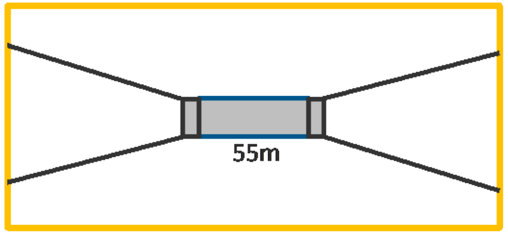


FOSWEC "extreme waves" position

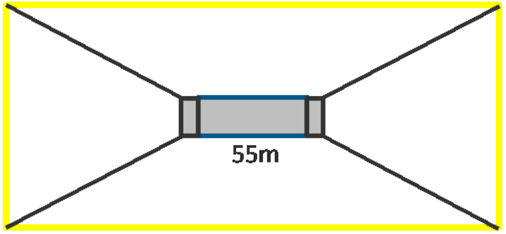
The FOSWEC was simulated in WEC-Sim+MoorDyn in its "extreme waves" position for mooring design iterations



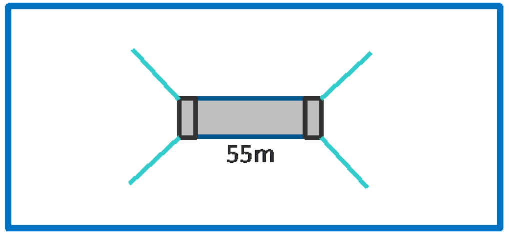
Catenary-Chain1
Headings = 45°; Kx = 60 kN/m
A=653m, L=652m, D=34mm
Chain Cost = $37,830
DEA Cost = $17,230
Total System Cost = $220,240



Catenary-Chain2
Headings = 12°; Kx = 60 kN/m
A=942m, L=921m, D=27mm
Chain Cost = $34,550
DEA Cost = $12,680
Total System Cost = $188,920



Catenary-Chain3
Headings = 27°; Kx = 60 kN/m
A=1,019m, L=1,013m, D=27mm
Chain Cost = $38,250
DEA Cost = $13,520
Total System Cost = $207,080



Taut-Polyester1
Headings = 45°; Kx = 60 kN/m
A=392m, L=355m, D=98mm
Polyester Rope Cost = $9,620
Suction Pile Cost = $179,850
Total System Cost = $757,880

Major Findings

- $\frac{d_{cost}}{d_{stiffness}}_{catenary-chain} \ll \frac{d_{cost}}{d_{stiffness}}_{taut-polyester}$
- Designs constrained by PacWave dimensions
- Hs=11.3m, Tp=19.2s was most extreme sea state

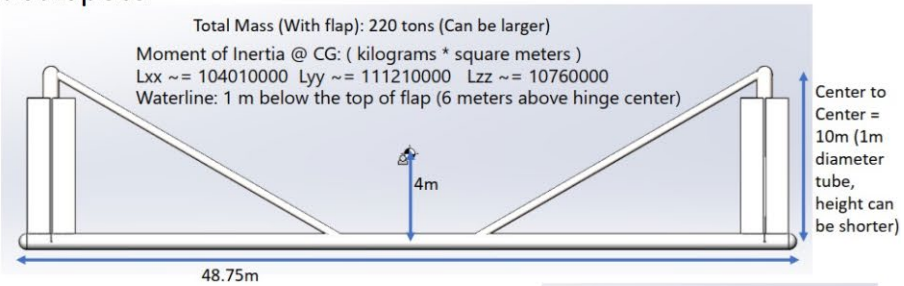
Future Work

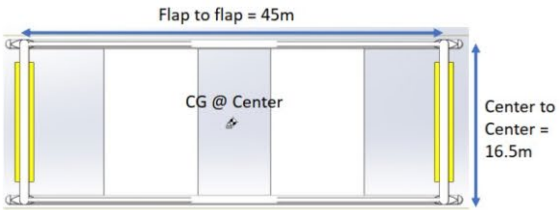
- **Redesign mooring systems for other WEC lengths**
- **Design other potential mooring configurations**
- **Design drag-embedment and suction pile anchors**

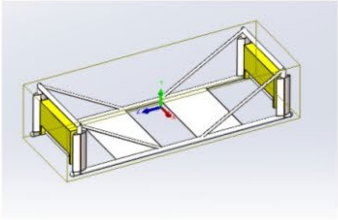
Performance: Accomplishments and Progress

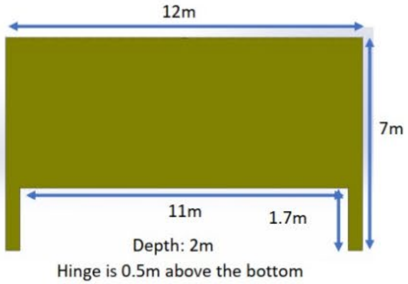
Full Scale System Validation with ABS

Provided Specs

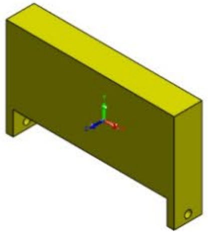


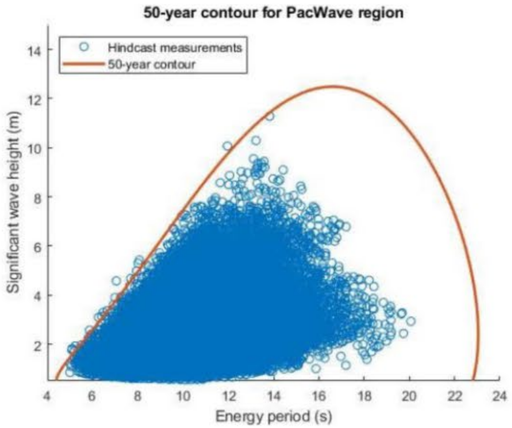


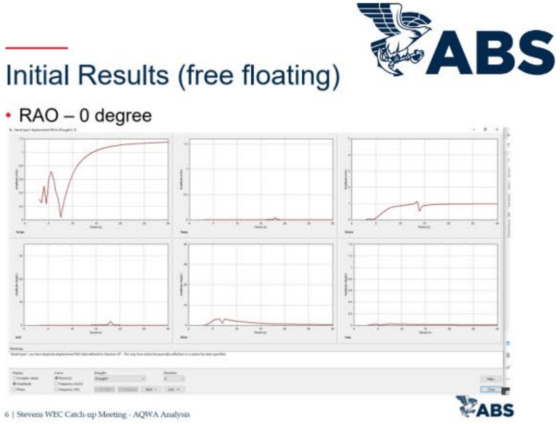




Moment of Inertia @ Hinge: (kilograms * square meters)
Lxx ~= 365600 Lyy ~= 437000 Lzz ~= 780000
Waterline: 1 m below the top of flap (5.5 meters above the hinge center)







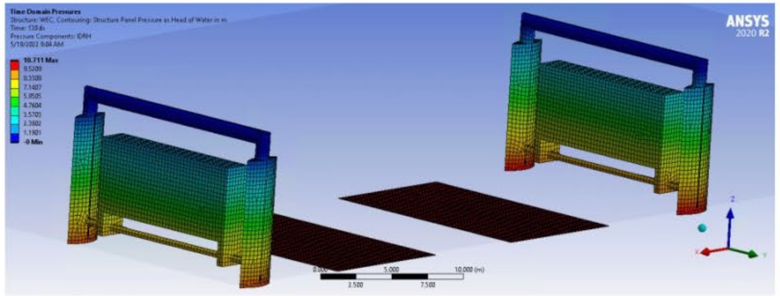
ABS Work Scope:

- High level CFD and structure FEA validation (Current Stage)
- Detail CFD and FEA validation on the revised full-scale system

(Validations will consider extreme wave conditions and different wave incoming directions.)

Initial Results (fixed WEC)

- Maximum Pressure – may be estimated as A+6 m water head at bottom
  - For T =14s and wave amplitude 4m in 0° heading, maximum pressure amplitude 10.711 m water head occurs at bottom, a little bit higher than the estimation 4+6=10m as nonlinear effect is considered in AQWA Naut.



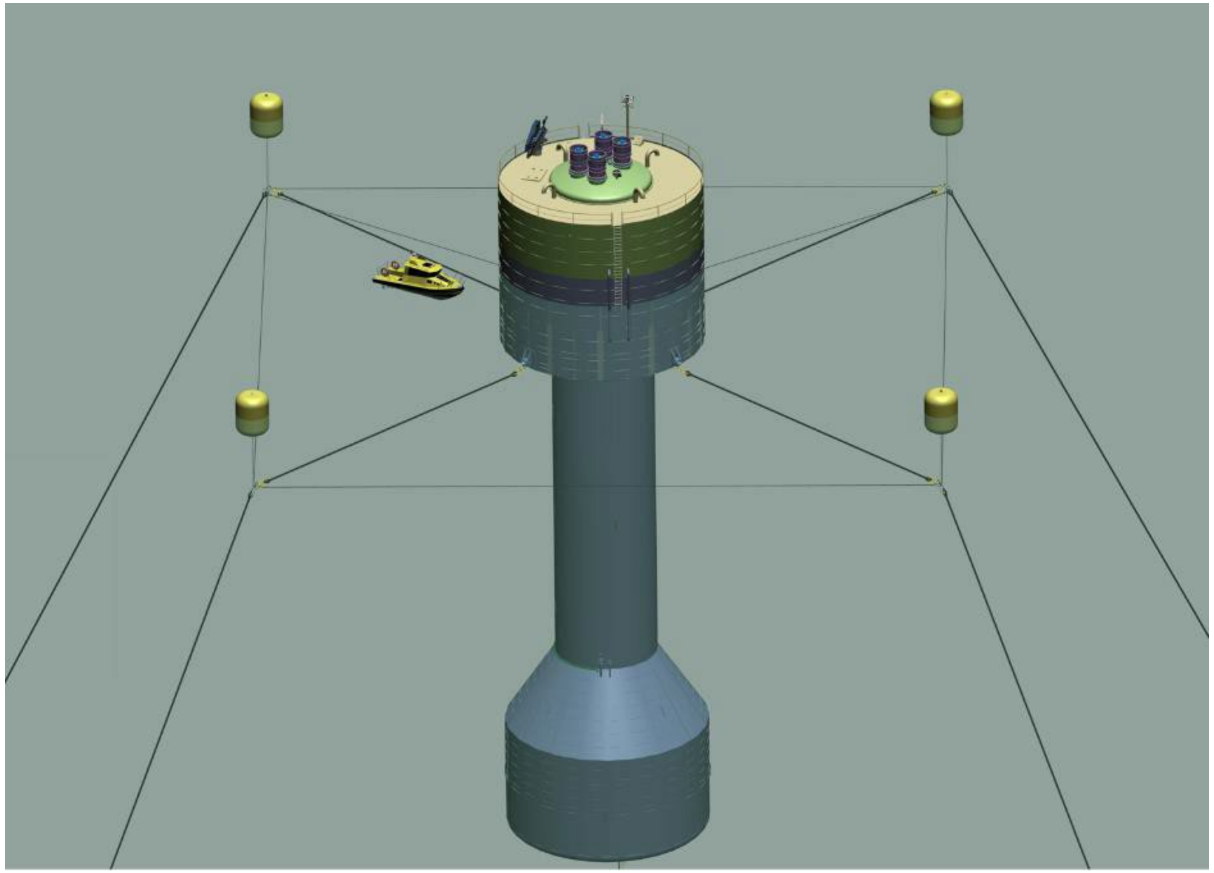
11 | Stevens WEC Catch-up Meeting - AQWA Analysis

Future Work

- NREL test of 1:2 PTO
- Integrated AMMR WEC tank test
- Third party validation
- Completion of RME reports
- Mooring system (NREL)
- Final design review

Q&A

EE0008952 – MARMOK- Oscillating Water Column (OWC)



Borja de Miguel

IDOM Inc.

bdemiguel@idom.com

July 20th 2022