Ship-Based Wave Energy Converter development under parametric roll using passive tuning device

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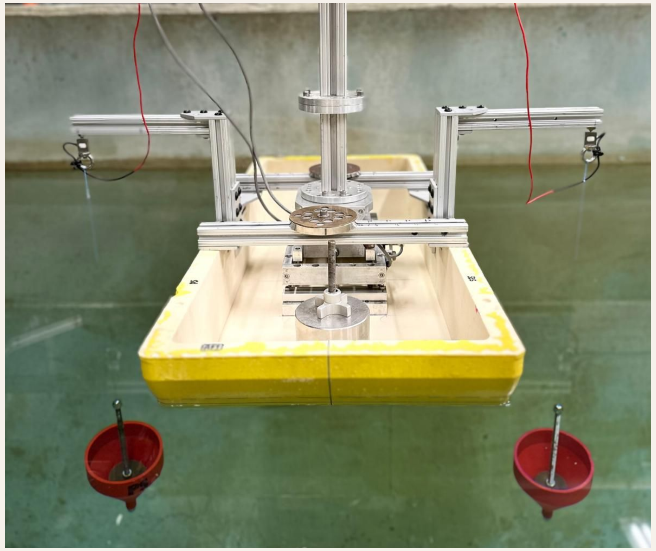
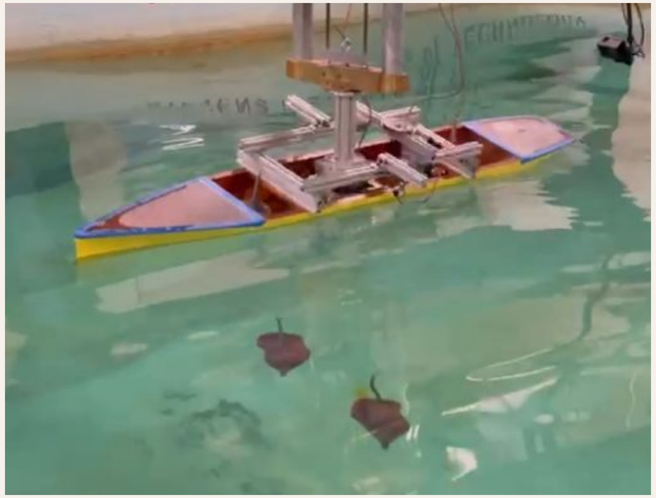
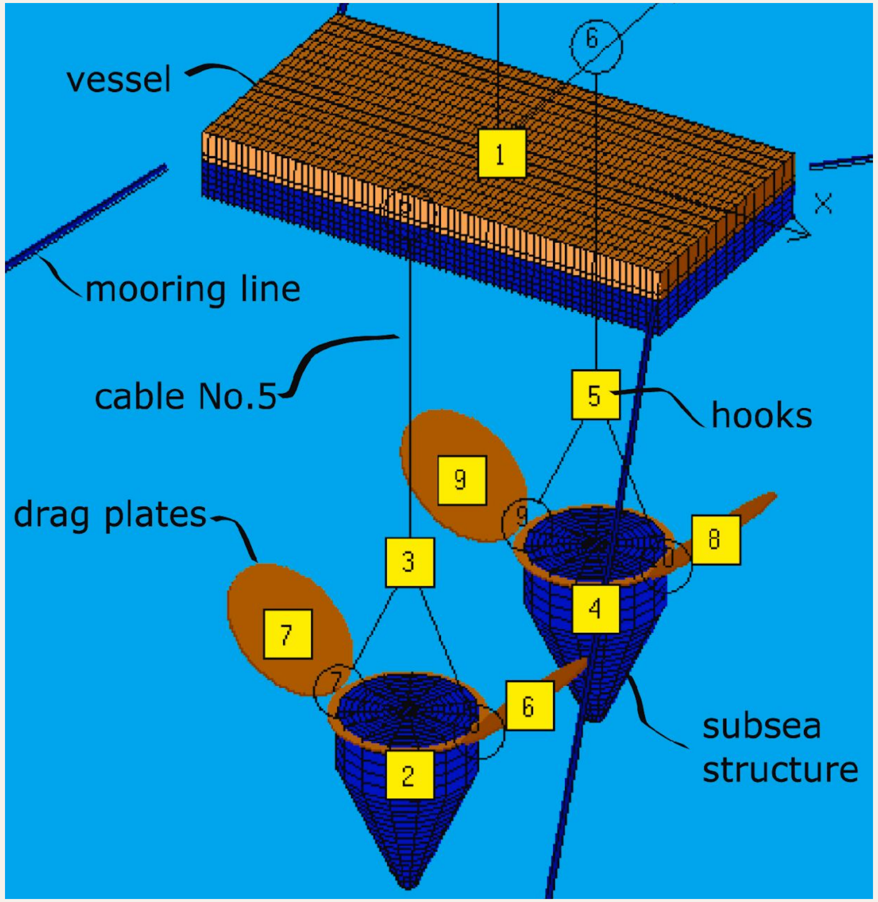


1st generation barge WEC



2nd generation ship WEC

Motivations



Schematics of passive-tuning WEC system with cones

Source: *Guachamin-Acero et al, Feasibility study of a method for tuning wave energy converters, 2024,* https://doi.org/10.1016/j.seta.2024.103702

Why Passive-Tuning Wave Energy Converter (WEC) Matters

- **Naturally Resonant**
  No need for active systems or external tuning mechanisms
- **Adaptable Across Sites**
  Effective in tropical and long-period swell regions (e.g., Galápagos, Pacific)
- **Quick Deployment & Low Maintenance**
  Lightweight, simple structure with minimal anchoring needs
- **Modular & Scalable**
  Suitable for off-grid, remote, or developing areas
- **Unlocks New Use Cases**
  Blue Economy: aquaculture, desalination, isolated grids

1st Generation model

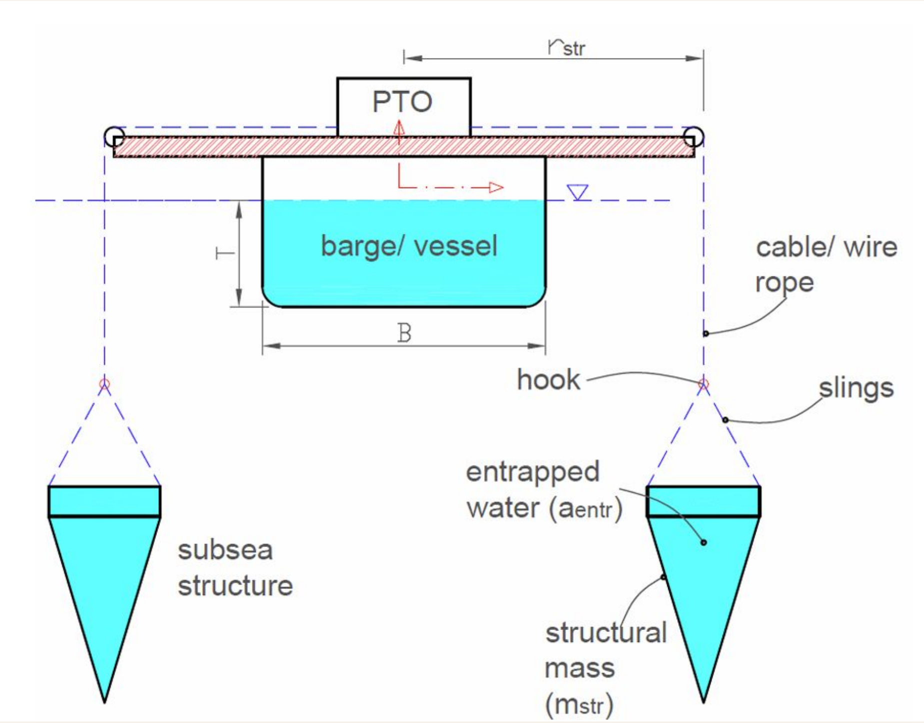
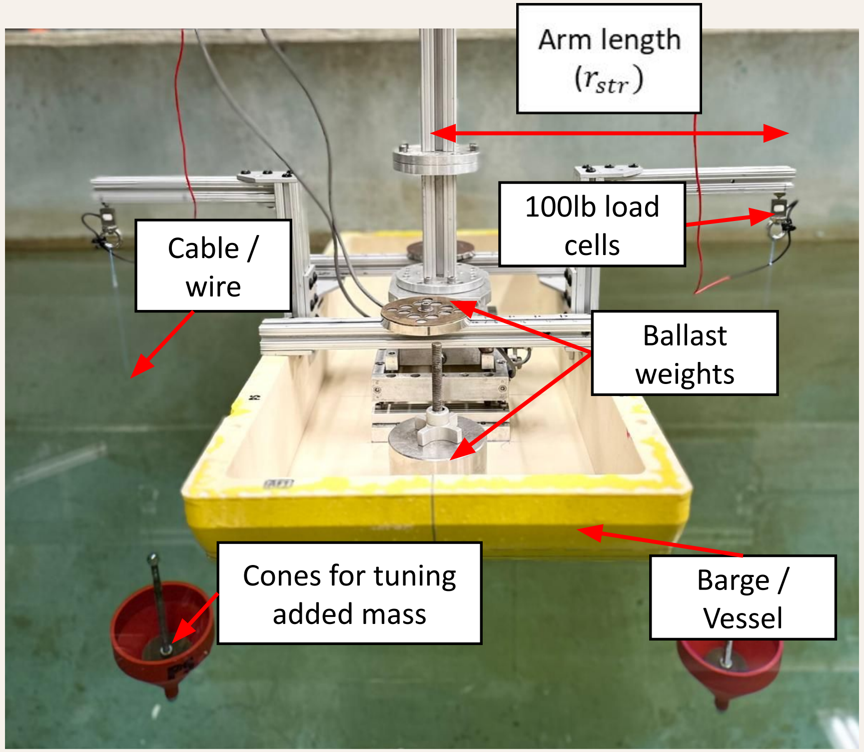


Diagram of 1st generation passive tuning WEC system



Actual WEC model with two cones in the water tank

B: length of the barge
T: Draft
r_{str}: Arm length, from center to the end of arm
m_{str}: Structural mass of cones

Characteristics

- 1:40 scaled WEC model
- Barge-based WEC system with two cones.
- Cones work as supporting added mass effect to WEC system, reducing the natural frequency.
- Operating environment: long and slow waves regions (low natural frequency)

1:40 Model parameters

Condition	Full scale	Barge only	Barge+Cone	Units
Length Overall, LOA	30	0.8	0.8	[m]
Beam, B	14	0.35	0.35	[m]
Draft, T	2.4	0.075	0.075	[m]
Displacement, Δ	890	17.71	17.76	[kg]
r_{str}	10	-	0.28	[m]
Metacentric Height, GM	4.8	0.088	0.087	[m]
Vertical center of gravity, KG	3.9	0.106	0.107	[m]
Mass moment of inertia, I_{44}	27,910	0.157	0.217	

$B: length\ of\ the\ barge$
$T: Draft$
$r_{str}: Arm\ length, from\ center\ to\ the\ end\ of\ arm$
$m_{str}: Structural\ mass\ of\ cones$

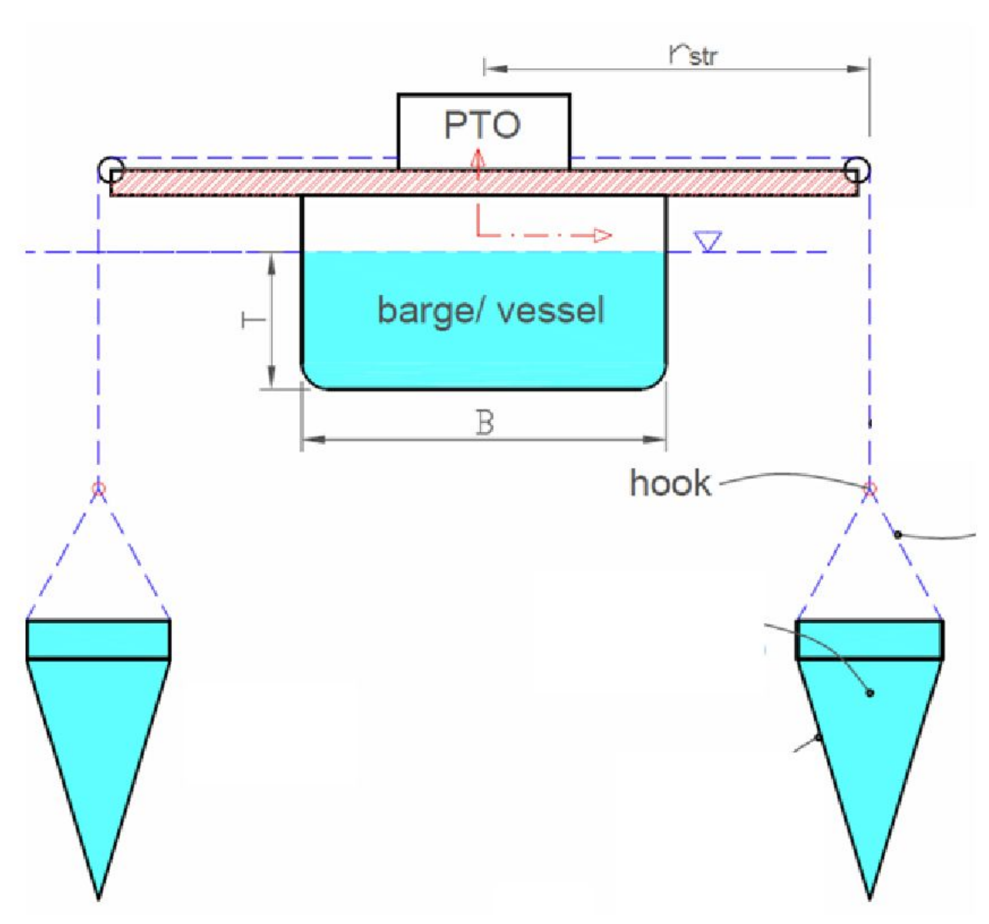
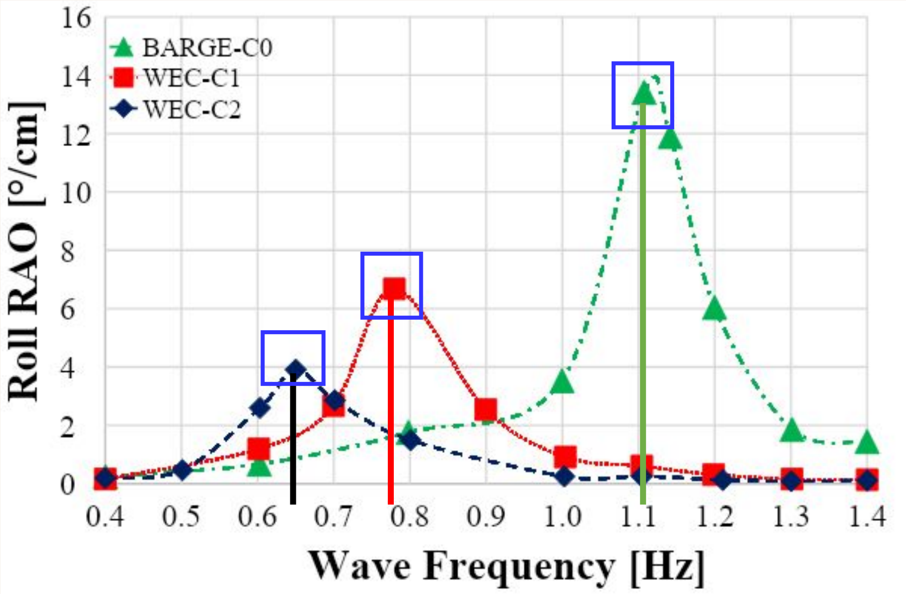


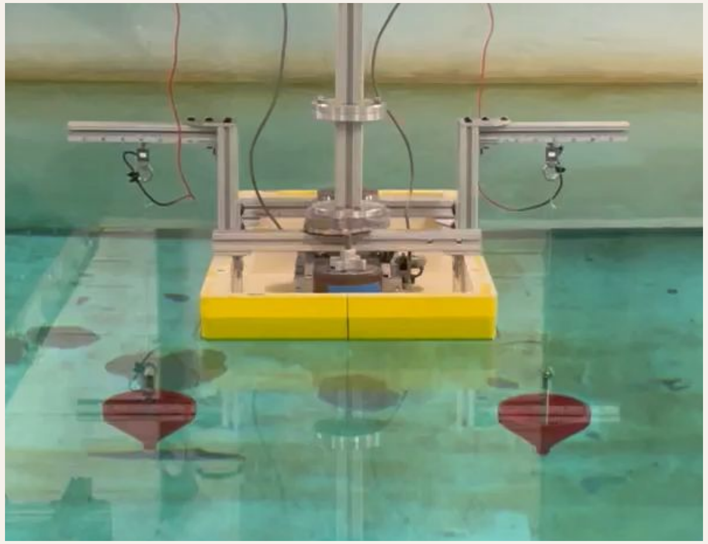
Diagram of 1st generation passive tuning WEC system

Tests with Barge-WEC model

1. Response Amplitude of Operators (RAO) in Roll direction

- Objectives
- Compare natural frequency between without cones (BARGE-C0) and with cones (WEC-C1 and WEC-C2)
- Measure the efficiency of wave energy convergence.





Low frequency wave test with Barge WEC
f_w : 0.78 Hz (=1.28 s)
Aw : 1.2 cm

Config.	**Natural frequency**	**Angular Velocity**	Tension Difference	Harvested Power	Wave Power	Effic.
	[Hz]	[rad/s]	[kg]	[mW]	[mW]	[%]
WEC-1	0.78	0.47	0.313	284.6	545.5	52.2
WEC-2	0.64	0.28	0.198	137.9	977.4	14.1

2. Parametric roll test

- Objectives
- Identify the parametric roll frequency condition of Barge WEC with cones.
- Verify the validities of restoring moment in evaluating natural frequency.

- Barge WEC model dynamics

$$\ddot{\phi} + d(\dot{\phi}) + \omega_{cw}^2 \cdot \frac{\overline{GZ_{wave}(\phi, t)}}{\overline{GM_{cw}}} = 0$$

$d(\dot{\phi})$: *nonlinear damping coefficient*
w_{cw}: *Natural frequency of WEC with cones*
GZ_{wave}: *Nonlinear righting arm* length
GM_{CW}: *Metacentric height*

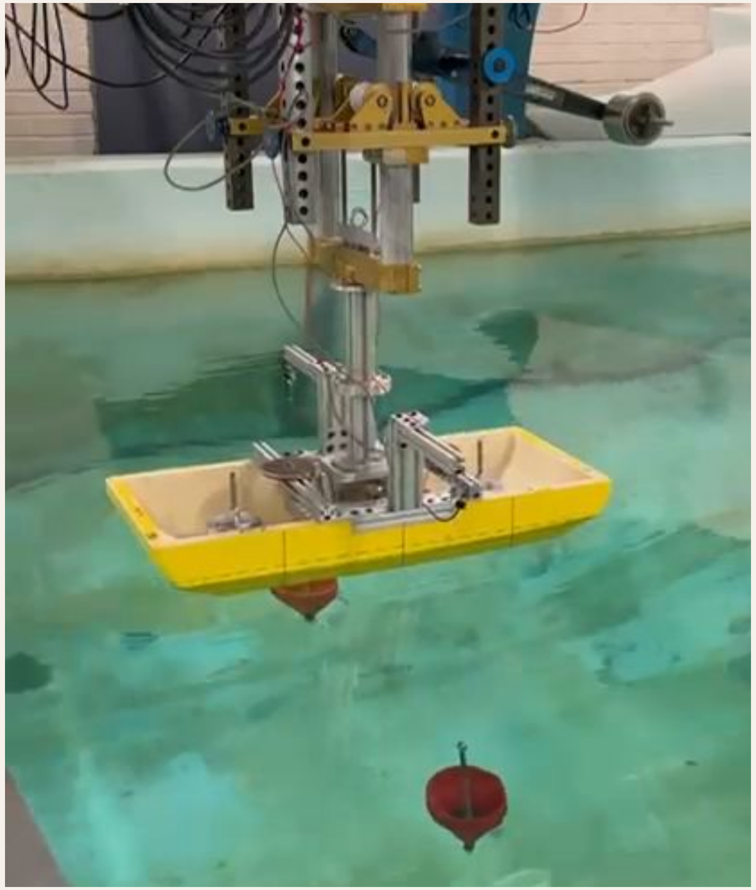
In linearized model

$$\ddot{\phi} + 2 \cdot \mu \cdot \dot{\phi} + \omega_{cw}^2 \cdot \frac{\overline{GM_{wave}(t)}}{\overline{GM_{cw}}} \cdot \phi = 0$$

μ: *linearized damping coefficient*

Barge WEC's natural frequency can be written as:

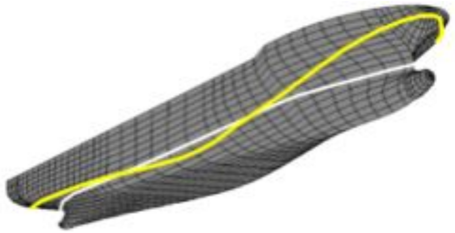
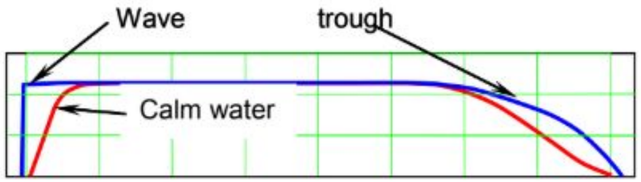
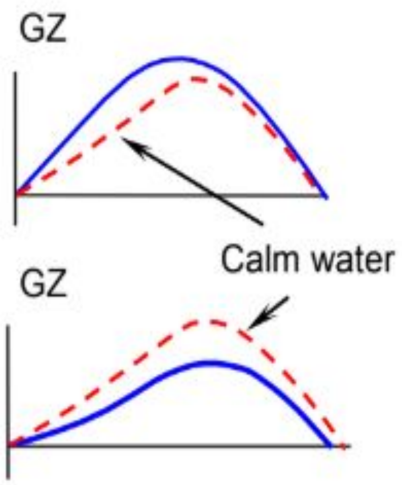
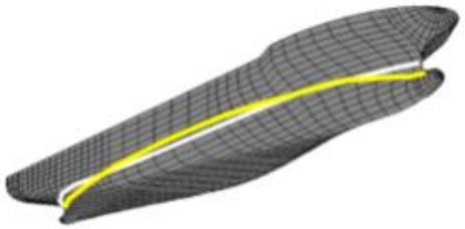
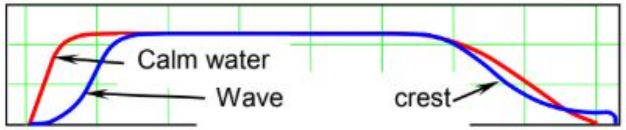
$$|\omega_e| \approx 2 \cdot \omega_{cw}$$



Parametric roll test

Limitation of the barge on parametric roll

Restoring Moment $\overline{GZ} = \frac{\overline{GM_{wave}(t)}}{\overline{GM_{cw}}}$ **Calm Water** → $GM = \frac{I_{WP}}{\nabla} + KB - KG$

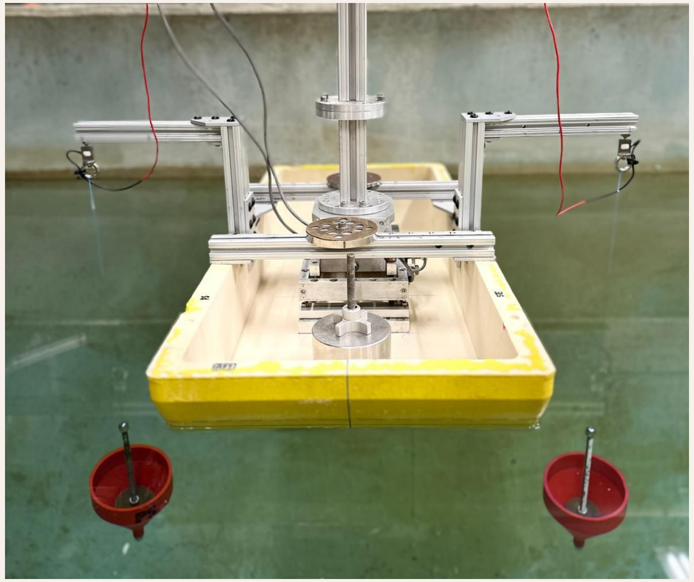
Wave profile condition	Ship model with area	Projected area in wave and calm water conditions	Change of GZ
High projected water plain area			
Low projected water plain area			

Source: IMO SDC 3/WP.5 (2016), Finalization of Second Generation Intact Stability Criteria

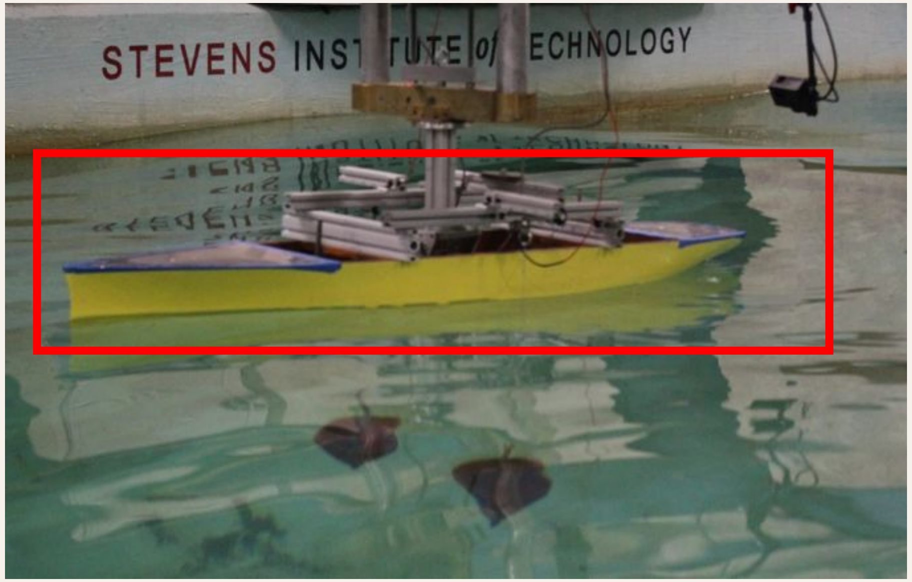
Restoring moment changes based on the projected water plain area on Barge

-> Parametric roll depends on the restoring moment which is not constant.

2nd generation model setup



Barge-WEC



Ship-based WEC

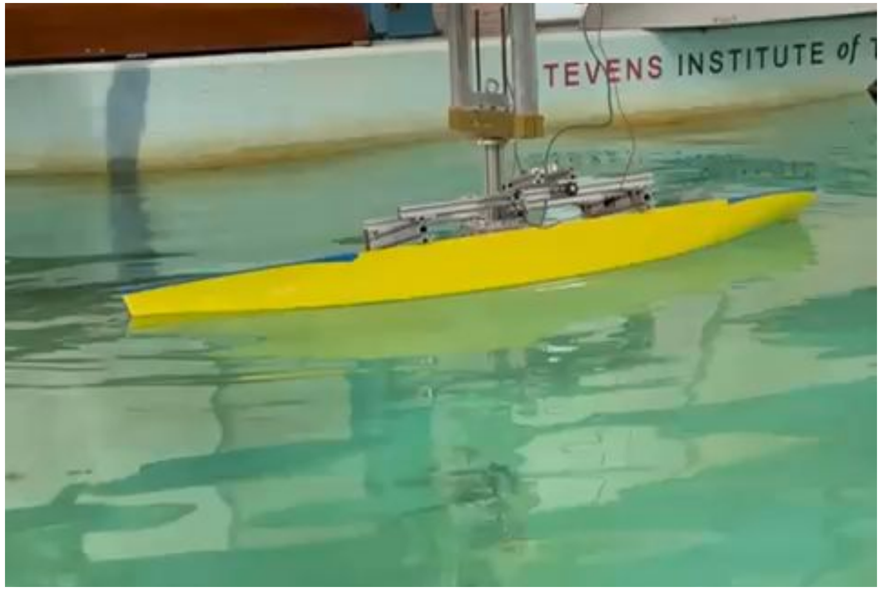
Parameter	Barge	Ship	Units
Length Overall, LOA	0.8	1.63	[m]
Beam, B	0.35	0.24	[m]
Displacement, Δ	17.76	14.71	[kg]
Roll natural frequency	1.13	0.43	[Hz]

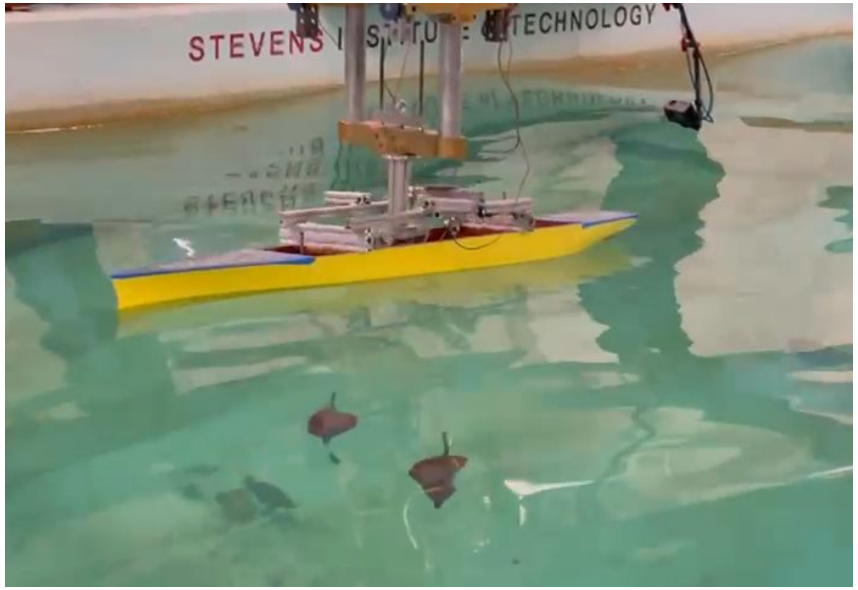
Parameters changes of wave capture device.
In this case, barge and ship model are compared

Ship-based WEC model test

1. Parametric roll test with ship-based WEC

- Two wave conditions are applied to the ship-based WEC

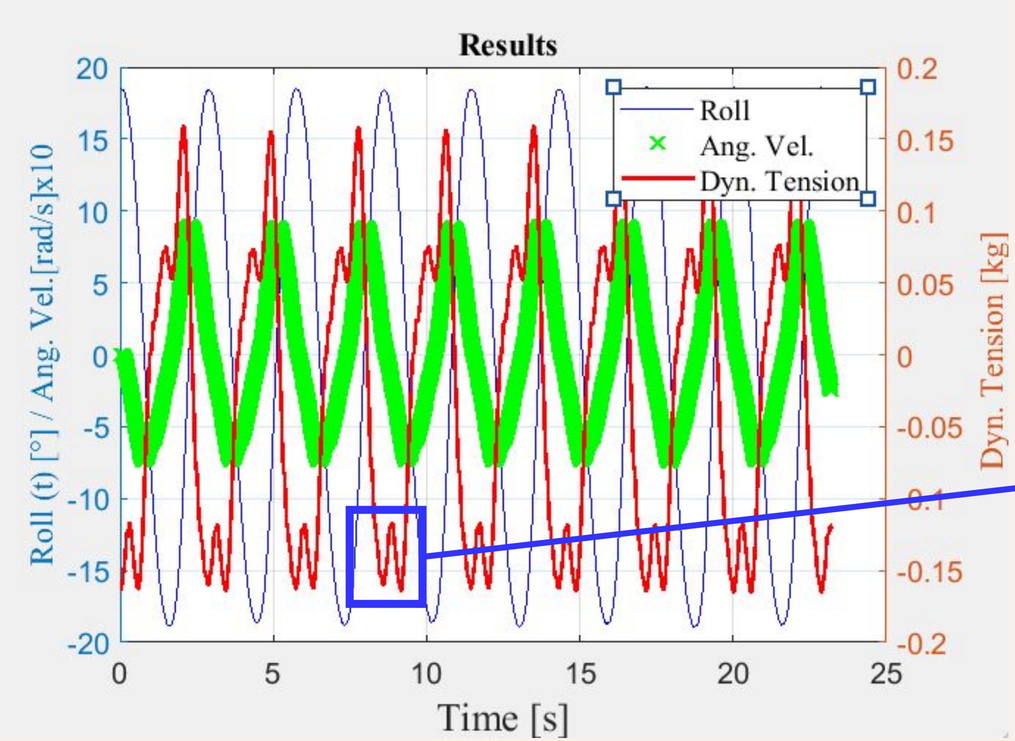
<table>
<tr><td>Wave conditions</td><td>Frequency: 0.85 Hz
Amplitude: 2 cm</td><td>Frequency: 0.7 Hz
Amplitude: 3 cm</td></tr>
<tr><td>Response of WEC</td><td>

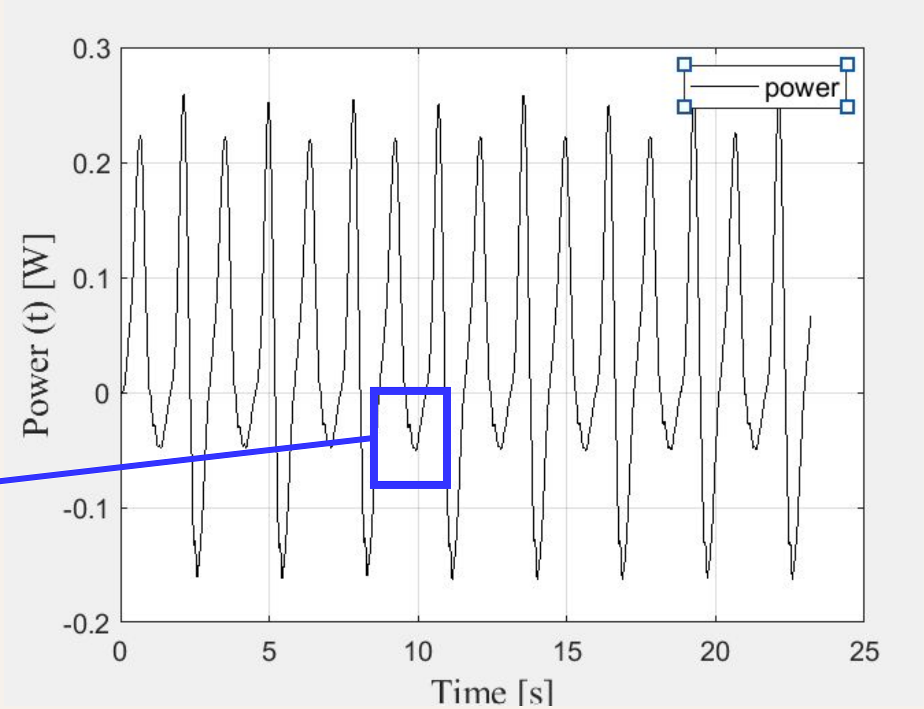
Without cones</td><td>

With cones</td></tr>
</table>

2. Response analysis of Ship-based WEC

- Analysis of the response – Angular displacement and velocity in Roll direction and tension by cones.
- Wave condition (Regular wave)
- Wave frequency: *0.7 Hz*
- Amplitude: *3 cm*





- Results
- In regular wave conditions, rolling displacement and angular velocity have regular changes in sinusoidal forms.
- Bouncing of the tension in cables is observed, which can cause the reduction of the absorbed power. (Blue rectangular on the graph)

3. Comparison of performance between Barge-WEC and Ship-based WEC

Configuration	Wave Amp.	Wave Period	Roll amp.	Angular Velocity	Tension Difference	Wave Power	Harvested Power	Effic.
	[cm]	[s]	[deg]	[rad/s]	[kg]	[mW]	[mW]	[%]
Barge (Beam Seas)	1.43	1.54	5.5	0.28	0.198	994.1	137.9	14.1
Ship (Head Seas)	2.4	1.66	13.0	0.35	0.07	845	31.8	3.76
Ship (Head Seas)	2.9	1.66	17.6	0.48	0.10	1268	60.4	4.70
Ship (Head Seas)	3.4	1.66	20.1	0.54	0.11	1798	70.2	3.90

- Key observations

- In ship model, the roll amplitude is increased compared to the barge model, which also increased the angular velocity of the model.
- Average tension difference in ship model was lower than barge due to a less efficient energy transfer mechanism between ship and the cone.
- Harvested power was lower than the barge-based model. Further investigation on improvement is needed.

Conclusion

- **Passive tuning with conical devices** successfully shifted the roll resonance frequency without adding structural mass, validating the proposed concept.
- **Parametric roll motion was clearly observed**, indicating effective coupling between pitch and roll dynamics in the tuned configuration.
- **While energy conversion efficiency remains modest**, the experiments revealed critical insights into the system's dynamic behavior.
- **The system's compact and modular design** highlights its potential for scalable, low-cost WEC applications in remote or island environments.