Berkeley Wave Carpet

Development of a Submerged Pressure Differential Area Wave Energy Converter

Contact: Marcus Lehmann, M.Sc.

mlehmann@lbl.gov

www.cyclotronroad.org/calwave/

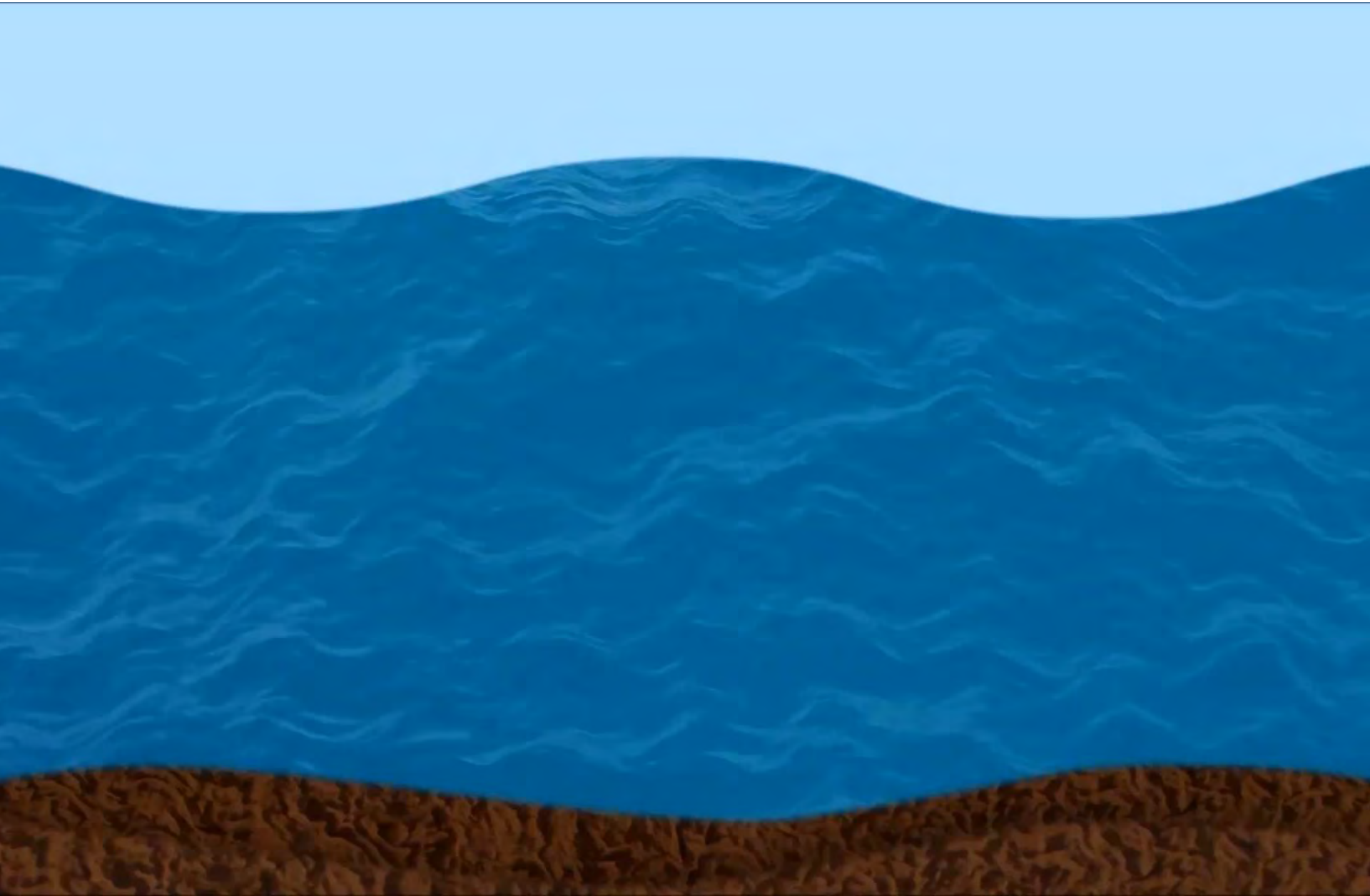
Agenda

1. **Development History**
2. Governing Equations
3. Prototype Development
4. Conducted Experiments
5. Results of the Experiments

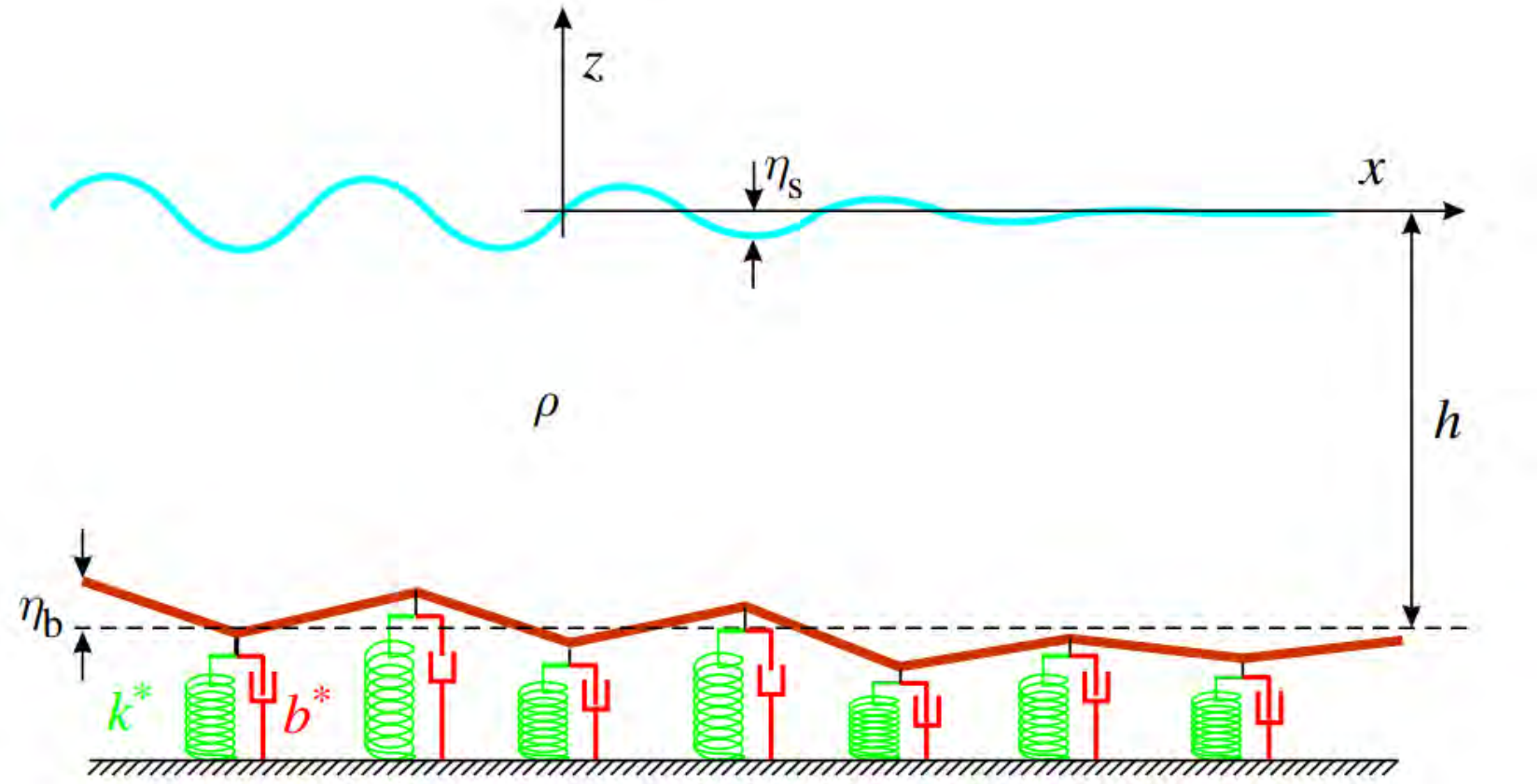
DEVELOPMENT HISTORY – Inspired by Wave Dissipation by Muddy Seafloors

[1] 1998 Airborne Data Acquisition and Registration (ADAR) image showing differential wave breaking due to shallow water mud deposits at the landward location of Cassino beach, Brazil. The experiment origin is signified by the plus sign." (from K.T.Hollandetal./Continental Shelf Research 29 (2009) 503–514)

Video mud vibration



New Wave Energy Converter by Prof. Reza Alam



[2] Alam, M.-R., Nonlinear analysis of an actuated sefloor-mounted carpet for a high-performance wave energy extraction, Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, doi 10.1098/rspa.2012.0193 2012.

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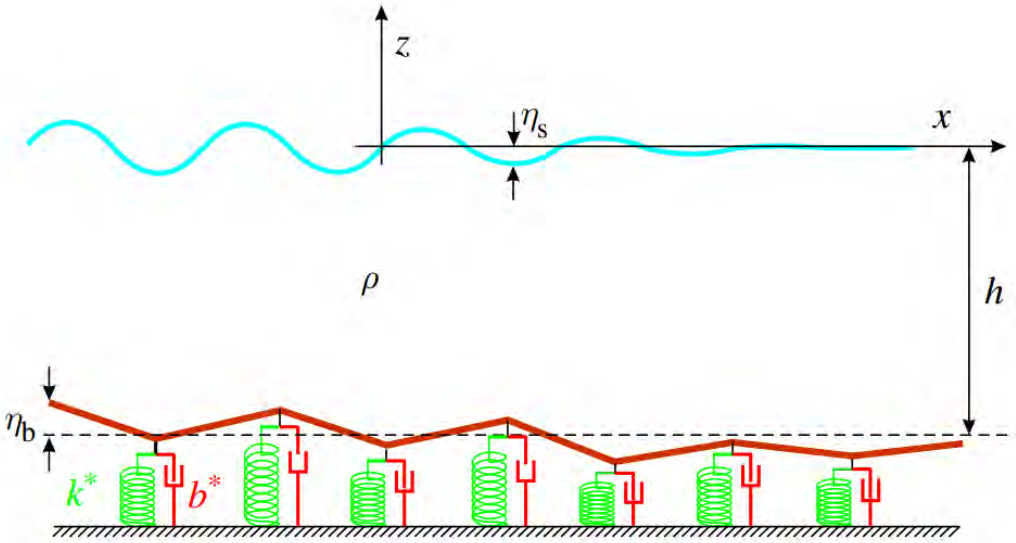
FUNDAMENTALS - Governing Equations

Assumptions:

Incompressible & Irrotational (Potential)

Inviscid, No surface tension



$$\nabla^2\phi = 0, \qquad -h + \eta_b < z < \eta_s$$

$$\eta_{s,t} + \eta_{s,x}\phi_x = \phi_z \qquad z = \eta_s$$

$$\phi_t + \frac{1}{2}(\phi_x^2 + \phi_z^2) + g\eta_s = 0 \qquad z = \eta_s$$

$$\eta_{b,t} + \eta_{b,x}\phi_x = \phi_z \qquad z = -h + \eta_b$$

$$\phi_t + \frac{1}{2}(\phi_x^2 + \phi_z^2) + g\eta_b + \frac{P_b}{\rho} = 0 \qquad z = -h + \eta_b$$

$$b^*\eta_{b,t} + k^*\eta_b + P_b = 0 \qquad z = -h + \eta_b$$

ENERGY EXTRACTION RATE – E0~carpet properties

$$\omega^2 = g\ k \tanh(kh)$$

$$\gamma\Omega^4 \tanh\mu + \mathrm{i}\mu\gamma\zeta\Omega^3 - \mu\Omega^2 - \mathrm{i}\mu^2\gamma\zeta\Omega \tanh\mu + \mu^2(1-\gamma)\tanh\mu = 0$$

$$\mu = kh \qquad \zeta = \frac{b^*}{\rho\sqrt{gh}} \qquad \gamma = \frac{\rho g}{k^*} \qquad \Omega = \omega\sqrt{h/g}$$

Energy Extraction Rate

$$E = \text{kinetic energy} + \text{potential energy} = 1/2\rho g a_s^2 D$$

$$\text{kinetic energy} = \frac{1}{4}\rho g a_s^2 \left[\frac{\sinh 2kh}{2}\left(\frac{\omega^2}{gk} + \frac{gk}{\omega^2}\right) - 2\sinh^2 kh\right]$$

$$\text{potential energy} = \frac{1}{4}\rho g(a_s^2 - a_b^2) + \frac{1}{4}k^* a_b^2$$

D is a (dimensionless) constant and a function of water depth, wavenumber and the carpet properties

$$\eta_s = (a_{s0}\, e^{\omega_i t})\, e^{i(kx-\omega_r t)} = a_s(t)\, e^{i(kx-\omega_r t)}$$

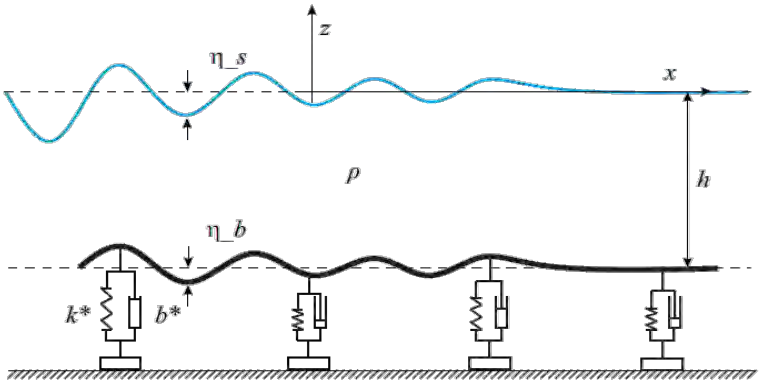
$$\frac{dE}{dt} = \rho g D a_s(t)\frac{da_s(t)}{dt} = \rho g D \omega_i a_{s0}^2\, e^{2\omega_i t}$$

$$\mathcal{E} = E/E_0$$

$$E_0 = 1/2\rho g a_{s0}^2$$

$$\dot{\mathcal{E}}_0 = 2D\Omega_i$$

TRANSFER – Effective Absorption Principle for WEC



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WEC

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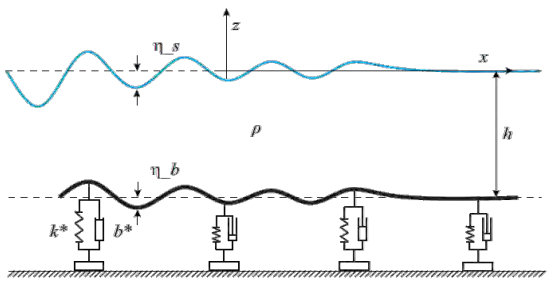
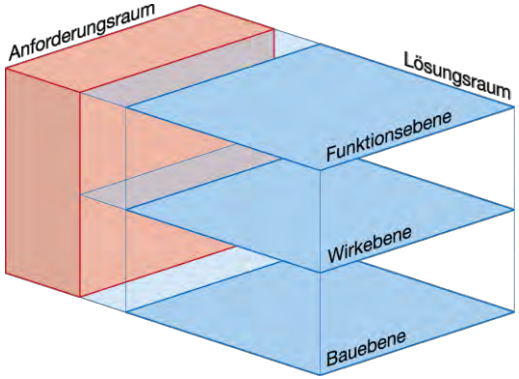
SYSTEM ENGINEERING – Prototype Development





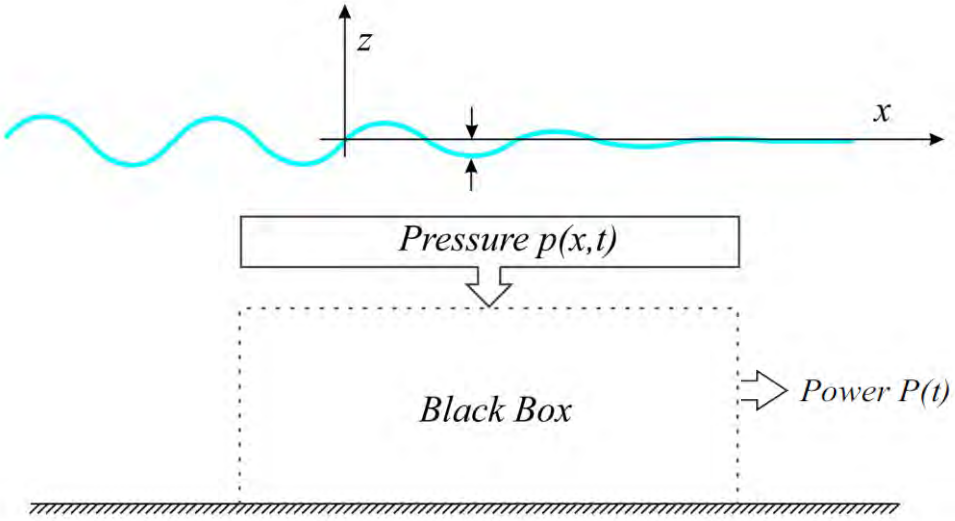
WEC

1) Specification model
2) Function model
3) Solution model
4) Physical model

[3] J. Ponn, U. Lindemann. Konzeptentwicklung und Gestaltung technischer Produkte, Berlin Heidelberg: Springer-Verlag, 2007

DEVELOPMENT HISTORY – Prototype Development

1) **Specification model**
2) Function model
3) Solution model
4) Physical Model



DEVELOPMENT HISTORY – Prototype Development

1) Specification model
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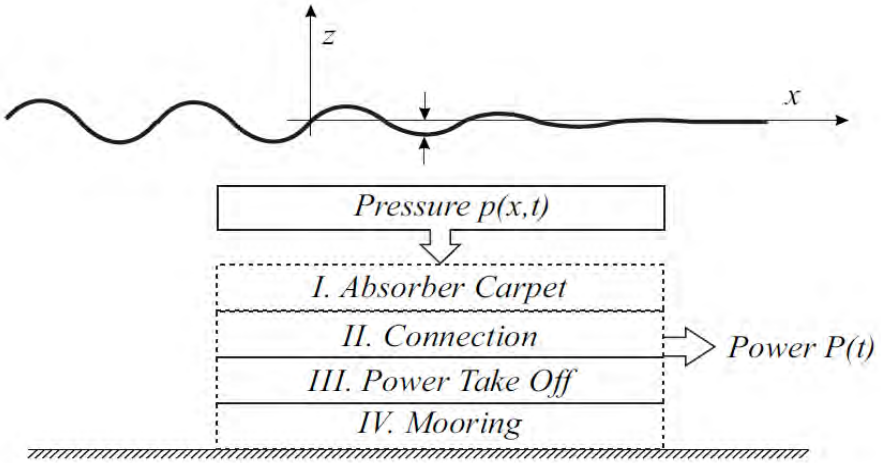
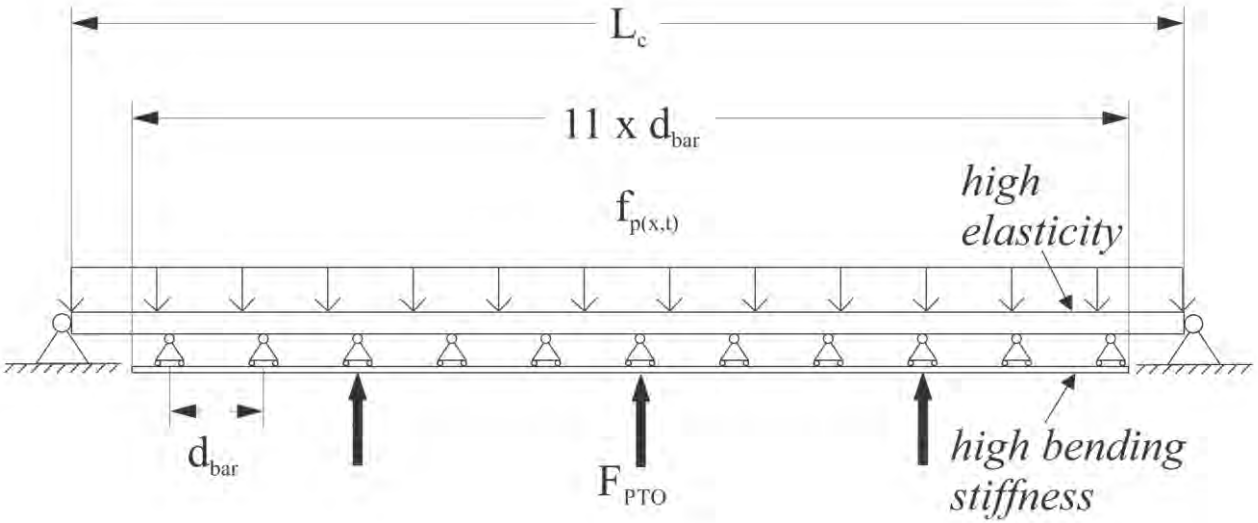
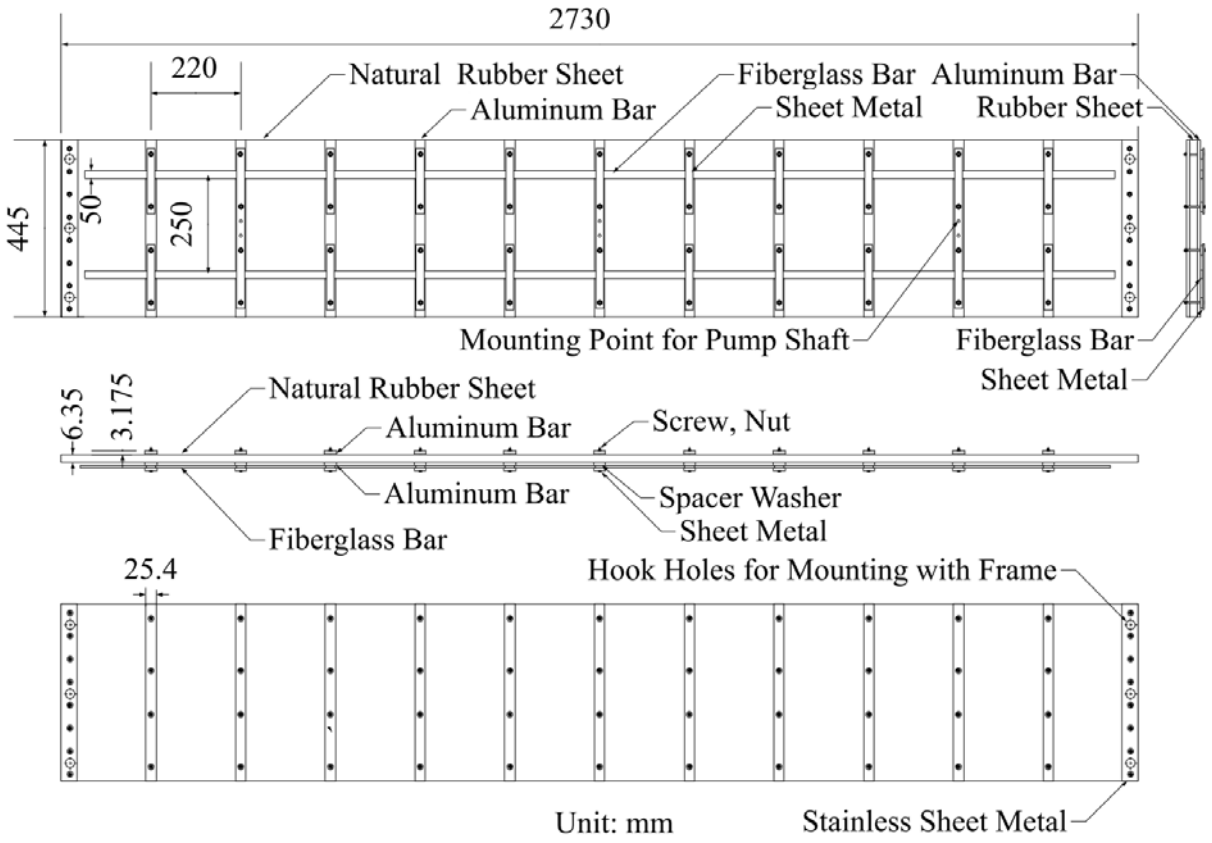
4) Physical Model





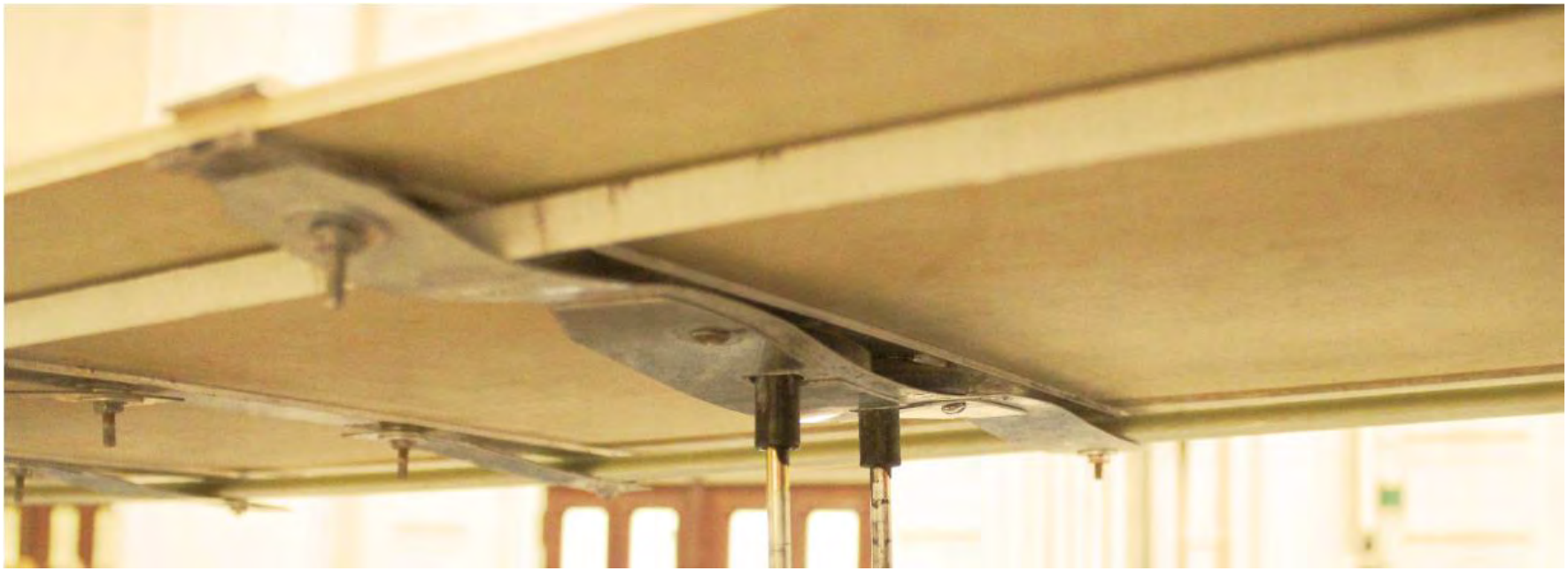
DEVELOPMENT HISTORY – Prototype Development

1) Specification model
2) Function model
3) **Solution model**
4) Physical Model



Composite material (rubber & fiberglass)

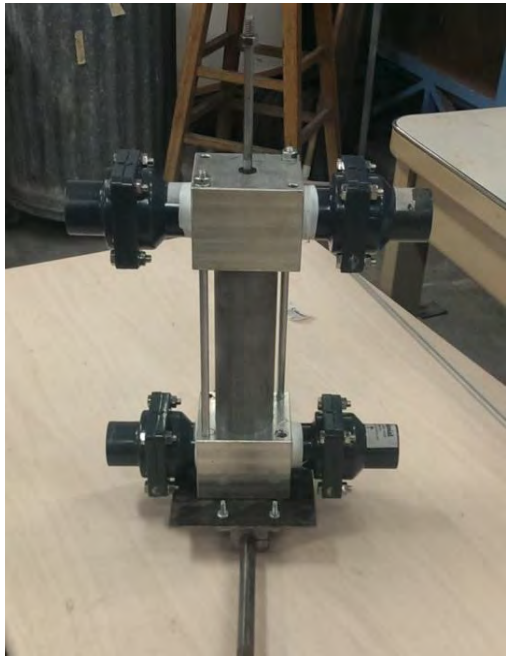
1) Specification model
2) Function model
3) Solution model
4) **Physical Model**

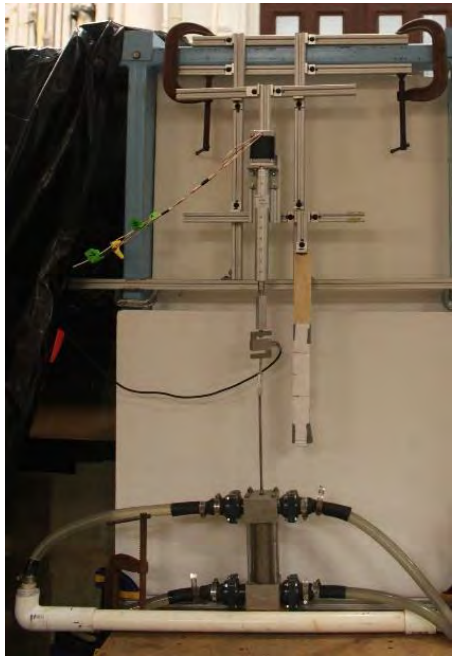


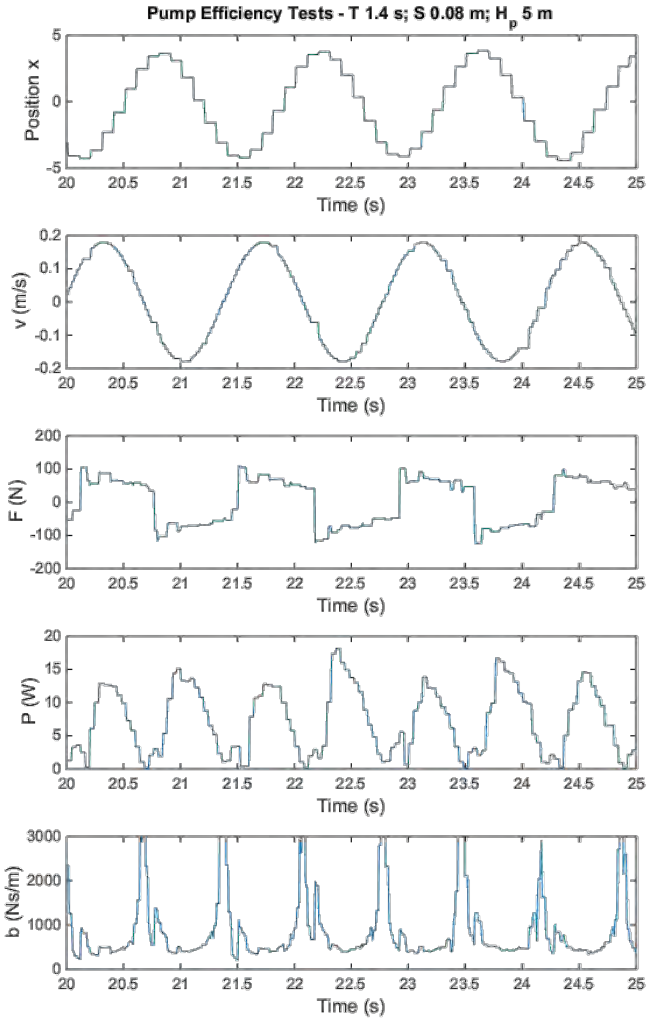
DEVELOPMENT HISTORY – Prototype Development

1) Specification model
2) Function model
3) Solution model
4) **Physical Model**

POWER TAKE OFF – Performance Test Stand







h_{head}			5.5					3.69					1.82	
			T					T					T	
d_{st}	1.4	1.43	1.67	1.94	2.43	1.4	1.43	1.67	1.94	2.43	1.4	1.43	1.67	1.94
0.01	0.52	0.56	0.56	0.44	NaN	0.59	0.54	0.19	0.27	NaN	0.59	0.69	0.44	0.36
0.02	0.82	0.86	0.82	0.79	0.71	0.75	0.76	0.74	0.71	0.65	0.80	0.76	0.76	0.76
0.04	0.88	0.89	0.87	0.87	0.83	0.75	0.75	0.76	0.82	0.91	0.73	0.77	0.81	0.78
0.06	0.91	0.89	0.82	0.78	0.77	0.75	0.74	0.76	0.79	0.80	0.70	0.70	0.74	0.71
0.08	0.84	0.81	0.82	0.81	0.85	0.74	0.75	0.73	0.75	0.79	0.69	0.67	0.70	0.69
0.1	0.81	0.79	0.81	0.84	0.83	0.69	0.72	0.73	0.75	0.82	0.62	0.65	0.65	0.63
0.12	0.77	0.76	0.81	0.84	0.83	0.64	0.66	0.71	0.74	0.79	0.57	0.55	0.56	0.63

Table 1: PTO efficiency (-) for different strokes d_{st} (m), periods T (s) and pump heads h_{head} (m).

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Experimental scheme

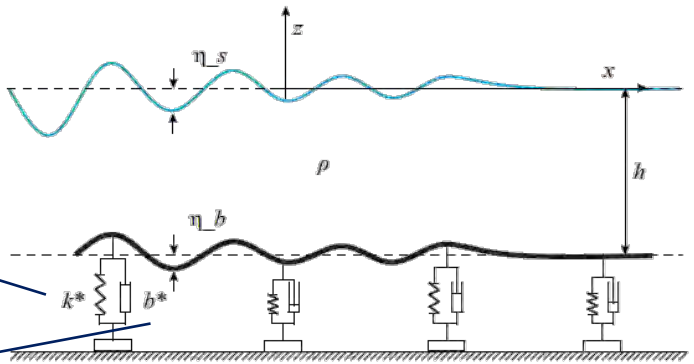
Two carpet stiffness's were investigated:

Stiffness 1 < Stiffness 2

For three different damping coefficients:

h_head = 1:82, 3:69, and 5:5 m

p_head= 0.18, 0.36, and 0.54 bar



Absorption and PTO efficiency was measured:

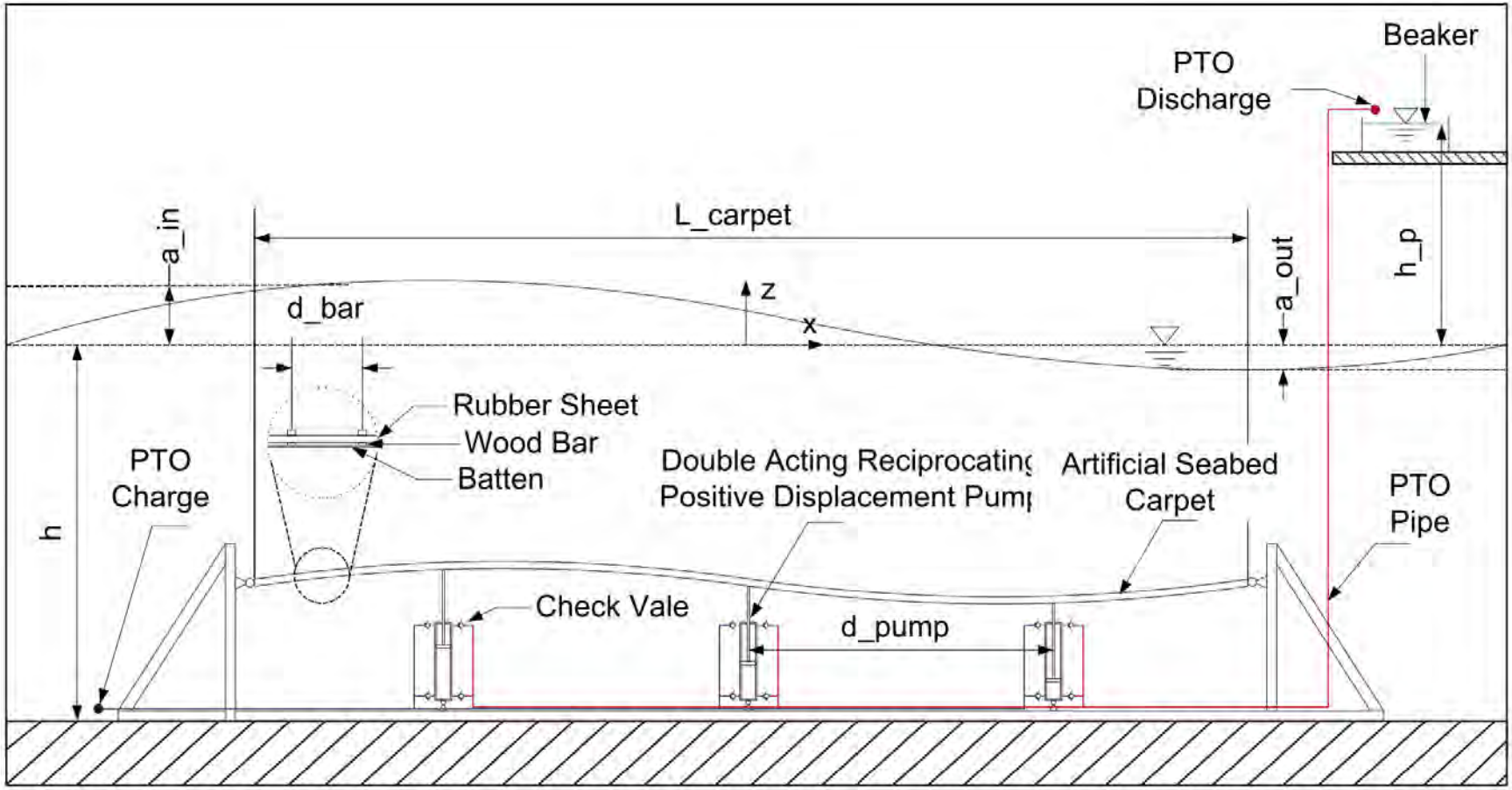
$$\eta_{prim} = \frac{P_{Prim}}{P_{wave}}$$

$$P_{Prim} = P_{pot} + P_{kin} = \rho \dot{V} g h_p + \frac{1}{2}\rho \dot{V} v_{free}^2$$

$$P_{wave} = \frac{1}{2}\rho g C_g a_{in}^2 W$$

$$\eta_{ABS} = \frac{E_{in} - E_{out}}{E_{in}} = \frac{a_{in}^2 - a_{out}^2}{a_{in}^2}$$

Setup of the Experiment

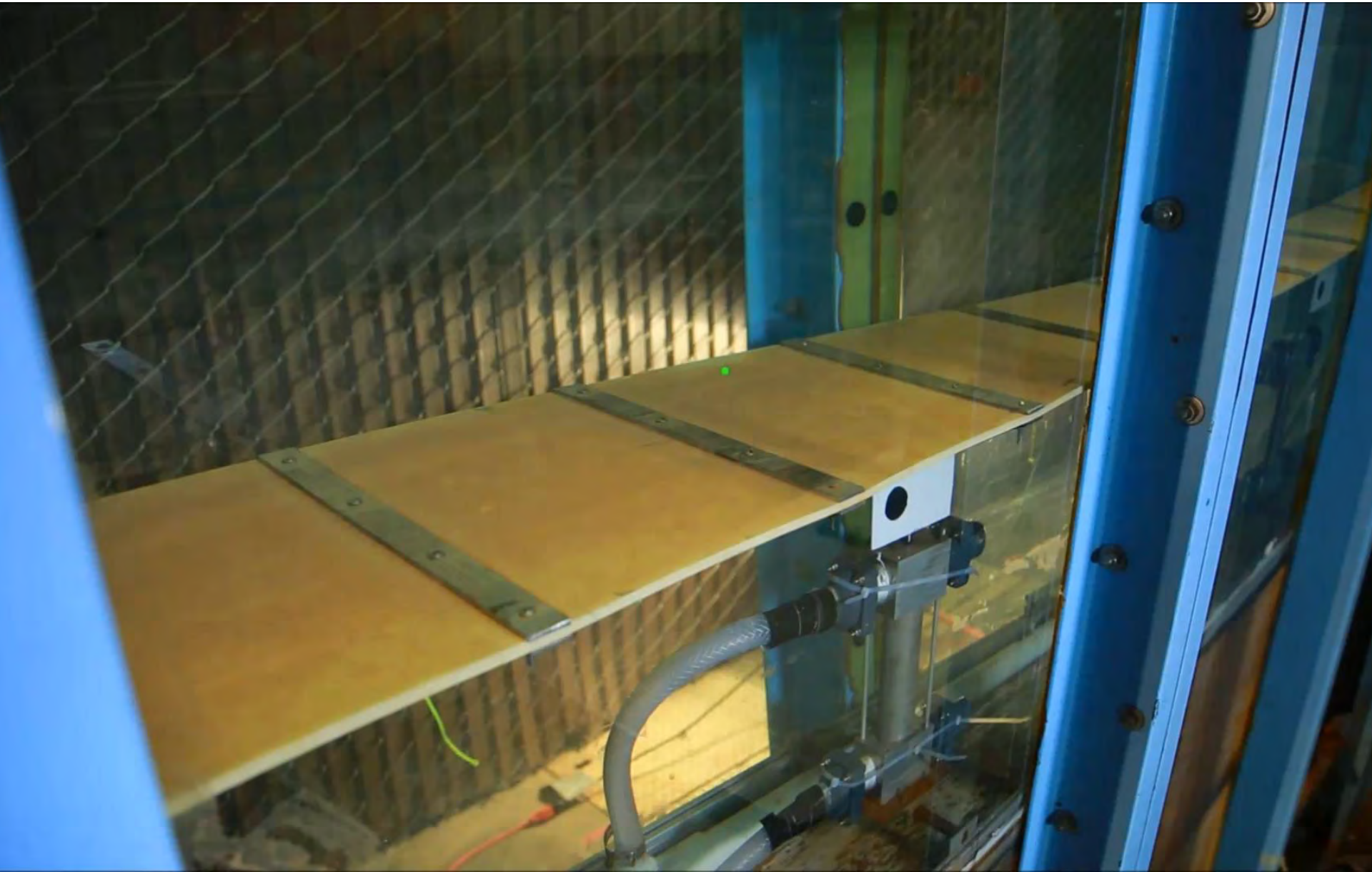


$$\eta_{prim} = \frac{P_{Prim}}{P_{wave}}$$

$$P_{Prim} = P_{pot} + P_{kin} = \rho \dot{V} g h_p + \frac{1}{2} \rho \dot{V} v_{free}^2$$

$$\eta_{ABS} = \frac{E_{in} - E_{out}}{E_{in}} = \frac{a_{in}^2 - a_{out}^2}{a_{in}^2}$$

EXPERIMENTS – Prototype being tested in Wave Tank



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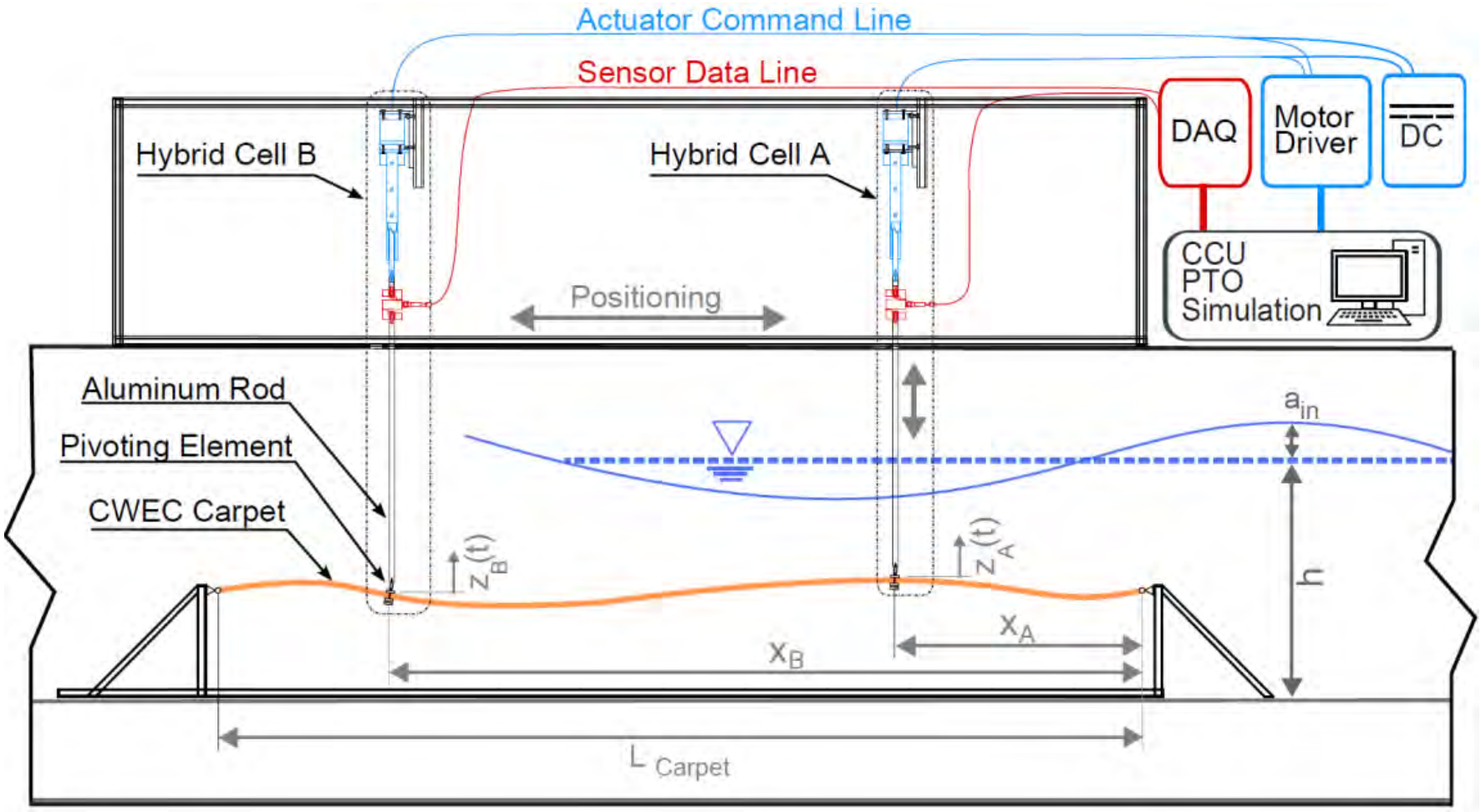
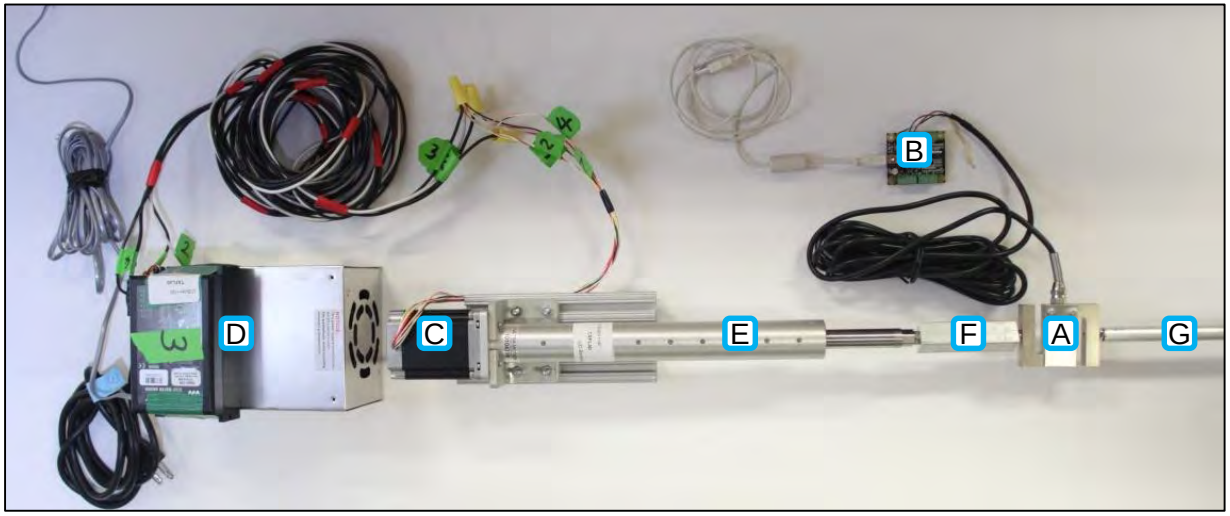
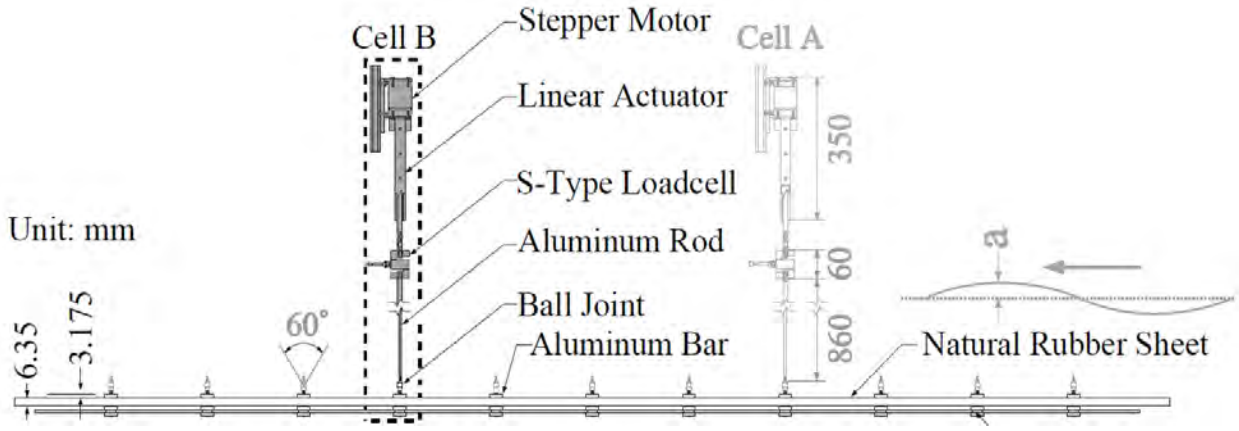
MODELING - Hybrid Simulation



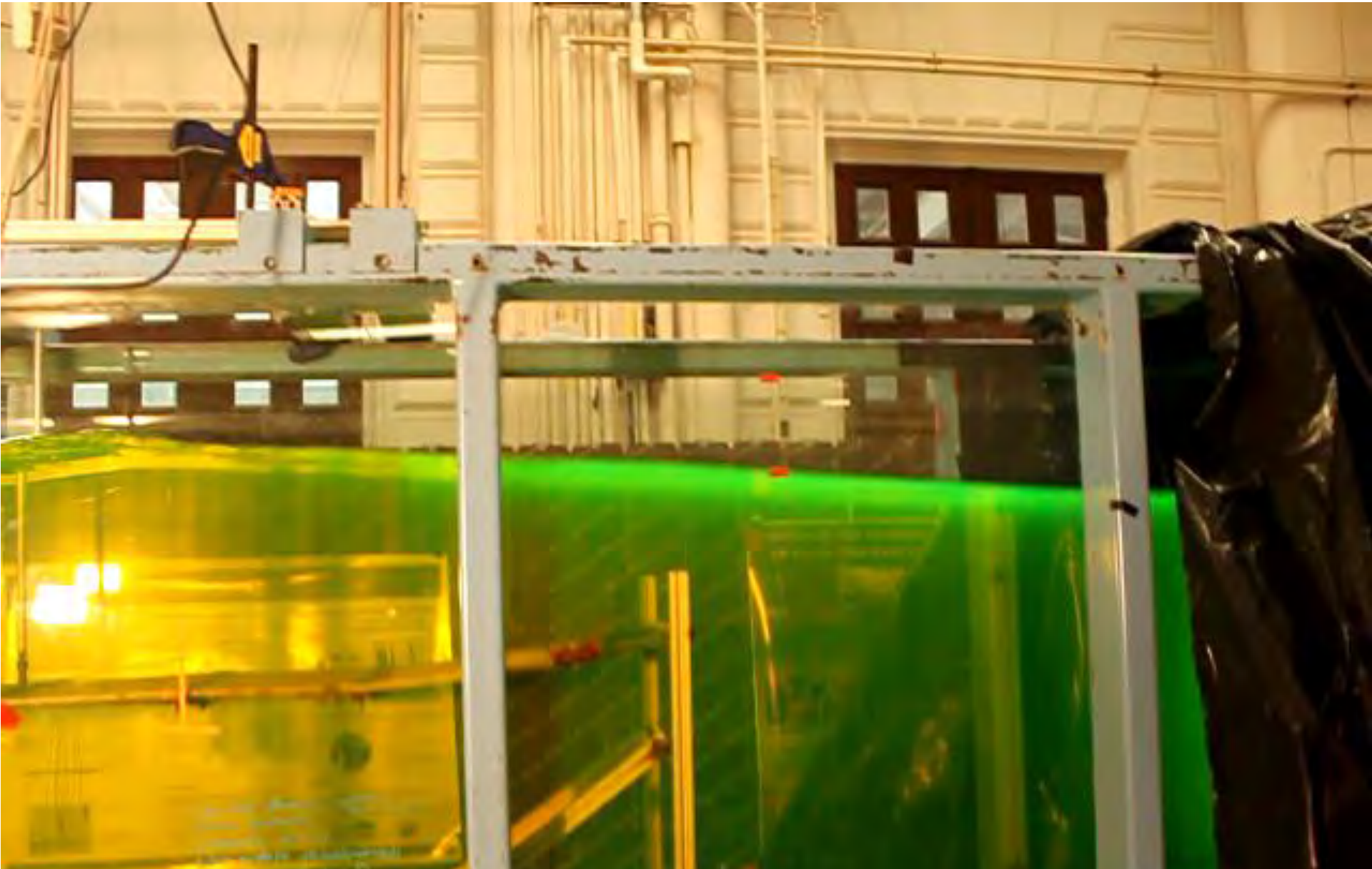
OUTLOOK - Hybrid Framework



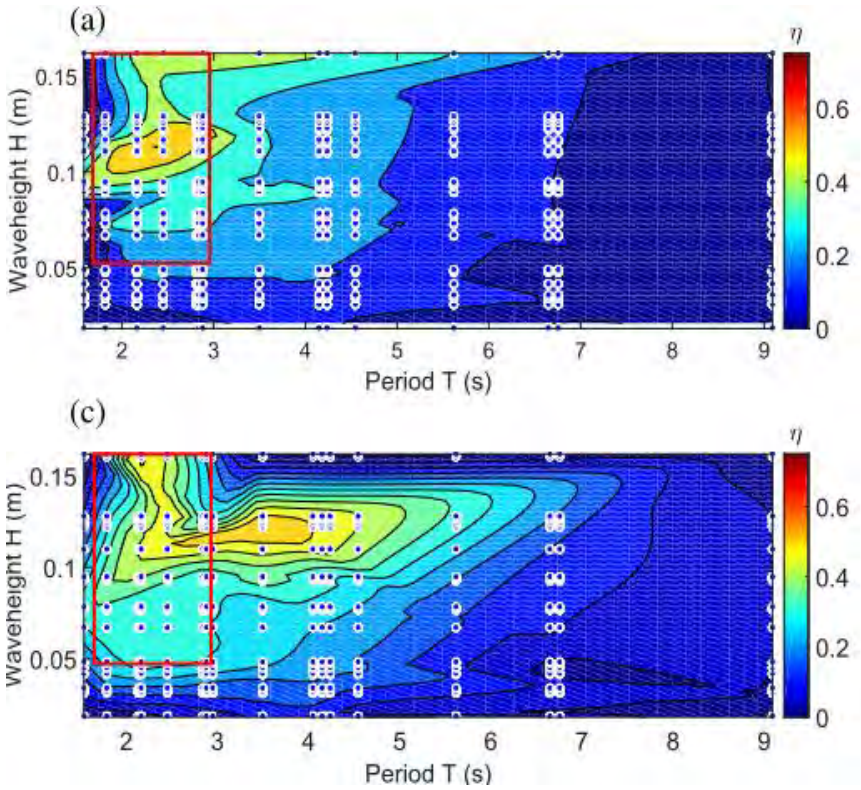


Drawing of two Hybrid Cells connected to the absorber mat of the CWEC

OUTLOOK – Hybrid Simulation



MODELING - Hybrid Simulation predicts up to 60% efficiency

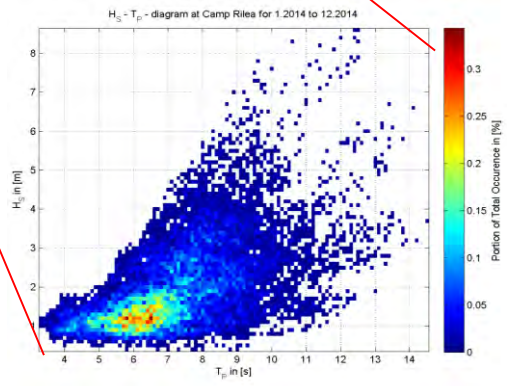
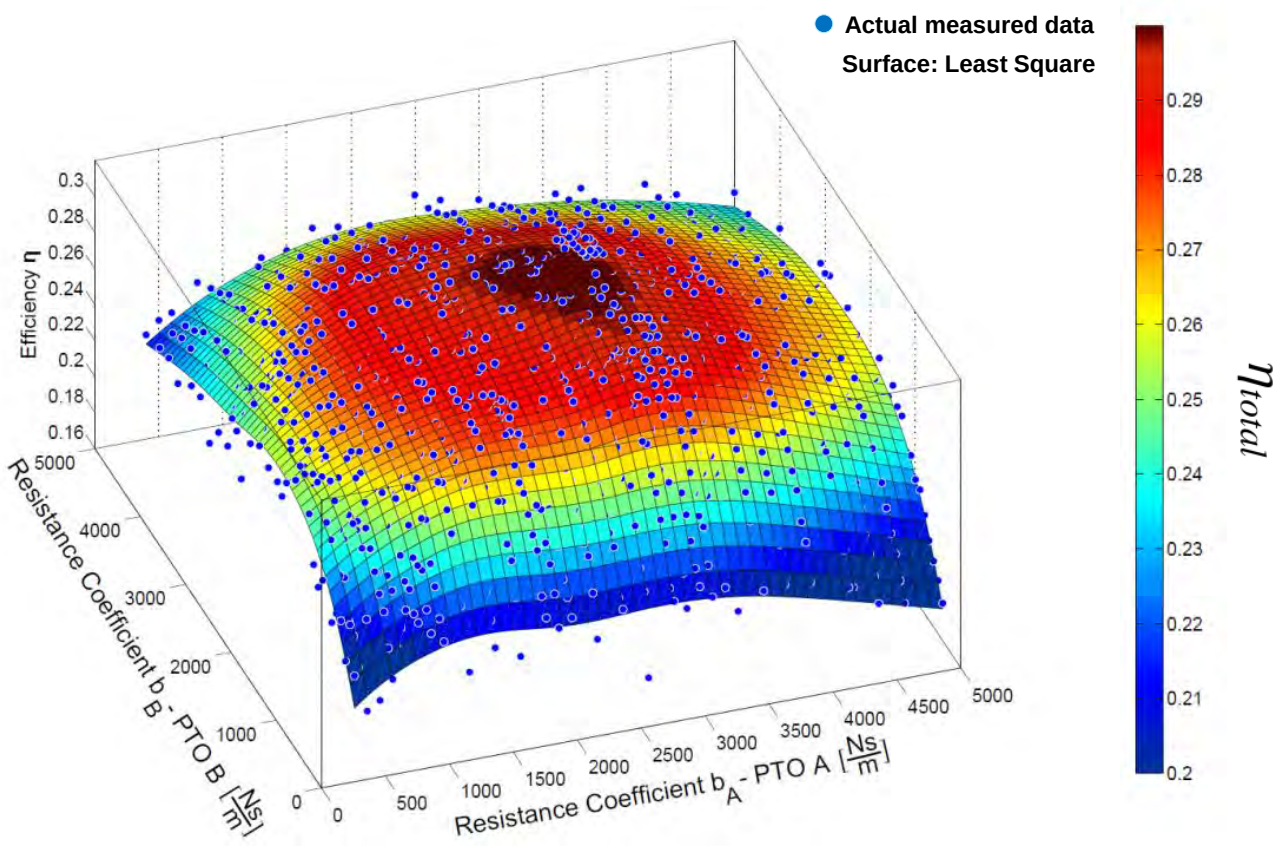


Damping coefficient:

a) – d)

b=1000, 2000, 3000, 4000 Ns/m

Natural pectrum of Pacific West Coast



Wave Carpet Optimization via Hybrid Modeling – PTO Resistance Coefficient