SAND2014-3564C

Pneumatic Performance of a Non-Axisymmetric Floating Oscillating Water Column Wave Energy Conversion Device in Random Waves

METS
MARINE ENERGY TECHNOLOGY SYMPOSIUM

Diana Bull diana.bull@sandia.gov
Sandia National Laboratories.

Presented by Chris Smith css27@arl.psu.edu
Penn State ARL.

April 16th, 2014.

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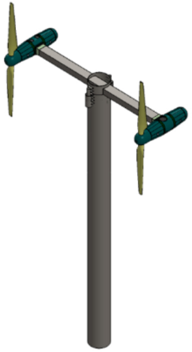
Reference Model Project



http://energy.sandia.gov/rmp

Summary

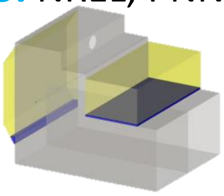
- Multi-Lab effort to obtain **baseline** performance and Cost Of Energy (**COE**) estimates for a variety of Marine Hydro-Kinetic (MHK) devices, sponsored by DOE.
- Method to achieve COE is to develop **public domain designs** incorporating the following:
  - •Power performance models
  - •Structural models
  - •Anchor and mooring design
  - •Economic Model
  - •PTO Design
  - •O&M / Installation
  - •Permitting & Environment

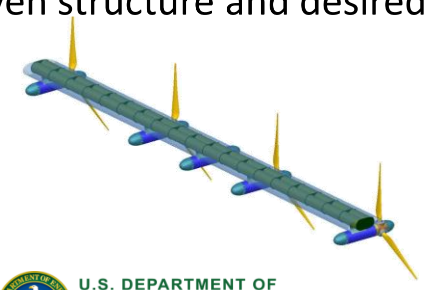
- Designs are intended to be conservative, robust, and **experimentally verified**.

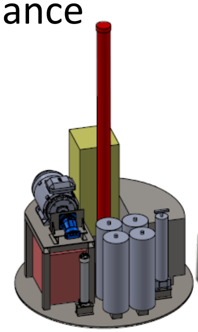
SNL Developed Models/Tools

- **Performance Models** — WEC: 3D model capable of handling 7DOF in Matlab; FEC: CACTUS
- **Mooring Survival Model** — utilize a Morison's Eq. approach to model extreme conditions
- **Structural Sizing Tool** — determination of weight, ballast, COG & COB locations, and natural frequencies
- **PTO Sizing Tool** — Turbine sizing tool for given structure and desired performance

Partners: NREL, PNNL, ARL/PSU, ORNL







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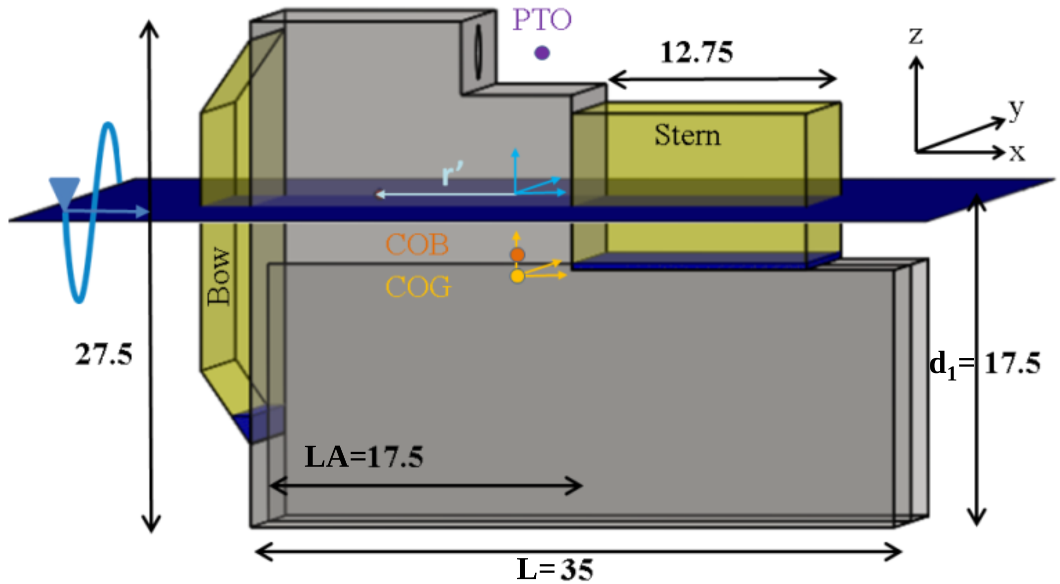
Backward Bent Duct Buoy

Profile

- **Literature survey:**
  - $\lambda/L=4$[1] L=35[m]
    - 9[sec] λ=140[m]
  - L/LA=2.0[2] LA=17.5[m]
  - $d_1/LA=1.0$[2] $d_1=17.5$[m]
  - $d_2/LA=0.2$[2] $d_2=3.5$[m]
  - L/B=1.3[1,3] B=27[m]
    - Selected relationship based on most used in literature



Structural Design

- Entire structure built to withstand hydrostatic pressure at 23.5 m
- Ballast chosen for stability
- Buoyancy chambers sized to support weight and obtain desired natural resonances

Displaced Mass [kg]		2,024,657		
Structural Mass [kg]		1,808,944		
Bow Ballast Mass [kg]		22,072		
Stern Ballast Mass [kg]		123,641		
Power Conversion Mass [kg]		70,000		
COG (x,y,z) [m]		0.00	0.00	-4.29
COB (x,y,z) [m]		0.00	0.00	-3.31
Free Surface Center (x,y,z) [m]		-5.12	0.00	0.00
Radius of Gyration at COG [m]	x	12.53	0.00	0.00
	y	0.00	14.33	0.00
	z	0.00	0.00	14.54

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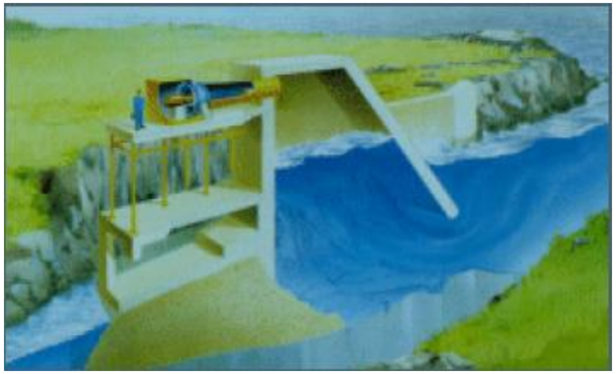
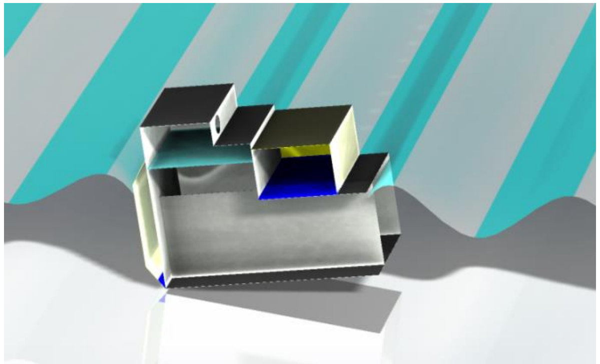
Device Hydrodynamics: Wave Structure Interactions

Modeling OWCs



Grounded



Floating

Power Absorption

- **Wave activated water column**

Coupled Power Absorption

- **Wave activated water column**
- **Wave activated structure**

Power Conversion

- **Pressure and volume in the air chamber**
  – Wave activated motions linked through power conversion chain.

Power Conversion

- **Pressure and volume in the air chamber**
  – Coupled wave activated motions linked through power conversion chain.

Modeling the Pressure Distribution of a Floating OWC

Approximation

- **Generalized Modes**
  - Approximates full solution with user defined number of higher order modes

Explicit Solution

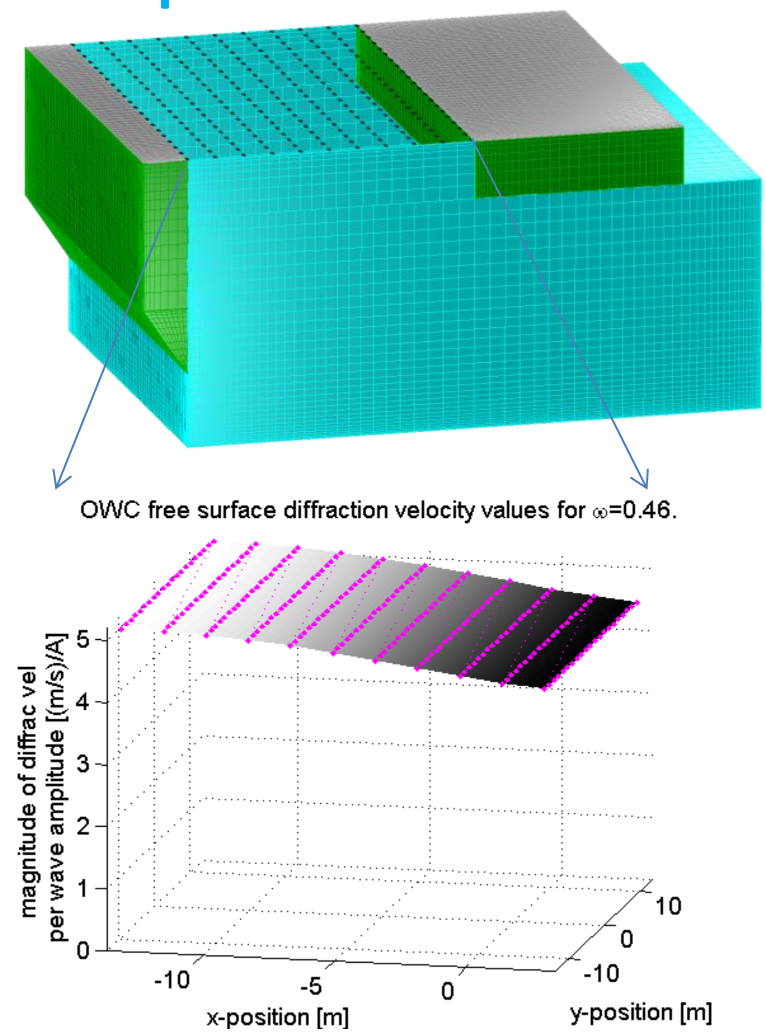
- **Free Surface Radiation Potential**
  - Solves explicitly for the full velocity potential of i oscillating structures with k internal free surfaces.

$$\hat{\phi} = \hat{\phi}_o + \hat{\phi}_d + \sum_{ij} \varphi_{ij}\hat{u}_{ij} + \sum_{k} \varphi_k \hat{p}_k$$

Implicit Solution

- **Reciprocity Relations**
  - Derive all of the free surface parameters from the oscillating structure potential
    - Requires an array of field points to define the internal free surface

Device Representation in WAMIT



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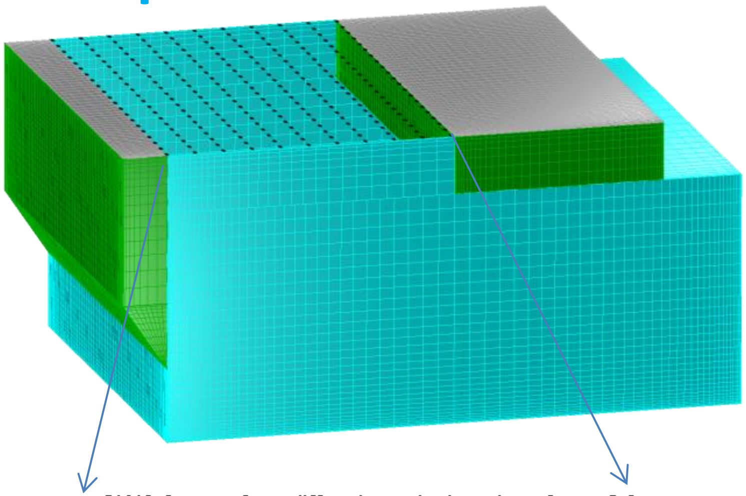
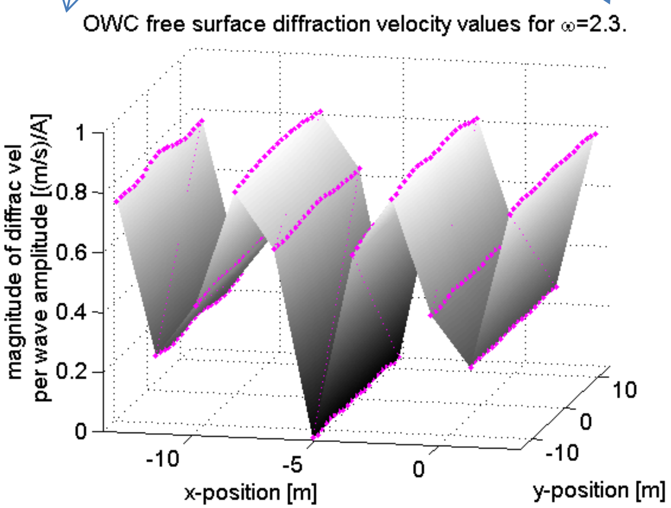




Coupled Wave-Structure-OWC Governing Equations[4]

Total Hydrodynamic Force: $$F_{TH,j} = f_j A - \sum_{j'} Z_{jj'} u_{j'} - H_j^p p \quad j = 1, \dots, 6.$$

- Excitation Force $$f_j = -i\omega\rho \frac{1}{A} \iint_{S_b} (\phi_o + \phi_d) n_j dS$$
- Radiation Impedance $$Z_{jj'} = i\omega\rho \iint_{S_b} \varphi_j \frac{\partial \varphi_{j'}}{\partial n} dS = b_{jj'} + i\omega a_{jj'}$$
- Hydrodynamic Coupling $$H_j^p = i\omega\rho \iint_{S_b} \varphi n_j \, dS$$

Total Hydrodynamic Volume Flow: $$Q_{TH} = qA - Yp - \sum_j H_j^u u_j$$

- Excitation Volume Flow $$q = \frac{1}{A} \iint_S \frac{\partial(\phi_o + \phi_d)}{\partial z} dS$$
- Radiation Admittance $$Y = -\iint_S \frac{\partial \varphi}{\partial z} dS = G + iB$$
- Hydrodynamic Coupling $$H_j^u = -\iint_S \frac{\partial \varphi_j}{\partial z} dS = C_j + iJ_j$$

Coupled Wave-Structure-OWC Governing Equations[4]

Total Hydrodynamic Force: $F_{TH,j} = f_j A - \sum_{j'} Z_{jj'} u_{j'} - H_j^p p \quad j = 1, \dots, 6.$

Direct WAMIT Output

- Excitation Force $f_j = -i\omega\rho \frac{1}{A} \iint_{S_b} (\phi_o + \phi_d) n_j dS$
- Radiation Impedance $Z_{jj'} = i\omega\rho \iint_{S_b} \varphi_j \frac{\partial \varphi_{j'}}{\partial n} dS = b_{jj'} + i\omega a_{jj'}$
- Hydrodynamic Coupling $H_j^p = i\omega\rho \iint_{S_b} \varphi n_j \, dS$

Total Hydrodynamic Volume Flow: $Q_{TH} = qA - Yp - \sum_j H_j^u u_j$

Implicit Solution

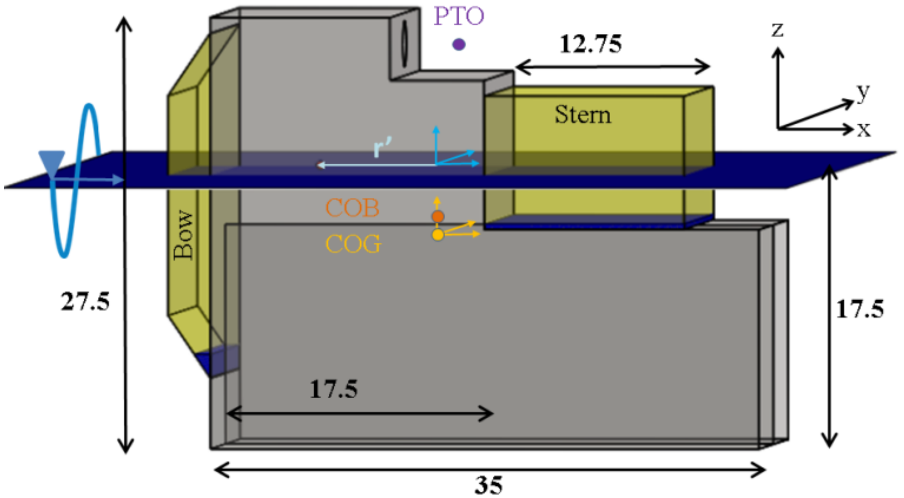
- Excitation Volume Flow $q = \frac{1}{A} \iint_S \frac{\partial(\phi_o + \phi_d)}{\partial z} dS$
- Radiation Admittance $G = \frac{2k}{8\pi\rho g v_g} \int_0^{\pi} |q(\beta)|^2 \, d\beta \quad B(\omega) = -\frac{2\omega}{\pi} \int_0^{\infty} \frac{G(y)}{\omega^2 - y^2} dy$
- Hydrodynamic Coupling $-H_j^p = H_j^u = -\iint_S \frac{\partial \varphi_j}{\partial z} dS = C_j + iJ_j$

Hydrodynamically Coupled Water Column Resonance

Relativizing the pressure

- Apply transformation vector to account for body oscillations

$$\boldsymbol{T} = [0 \quad 0 \quad 1 \quad 0 \quad -r' \quad 0]^{\mathrm{T}}$$

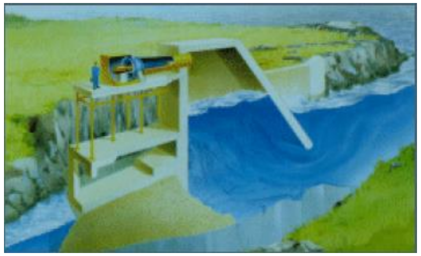


Coupled Hydrodynamic Volume Flow in an *unlinked, fully vented device* (i.e. no PCC, pure wave-structure-OWC without any pressure) :

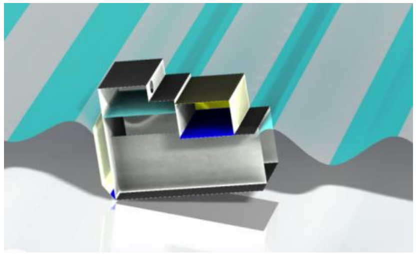
$$Q_{TH} = qA - \sum_{j} (H_j^u + T_j S) u_j$$

Hydrodynamically Coupled Water Column Resonance[4]

Grounded



Floating



Hydrodynamic Volume Flow:

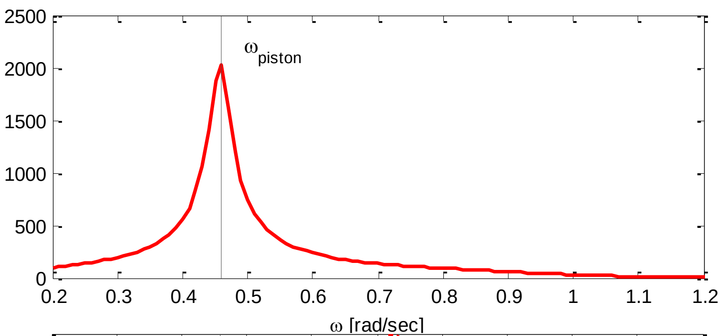
$$qA$$

Coupled Hydrodynamic Volume Flow:

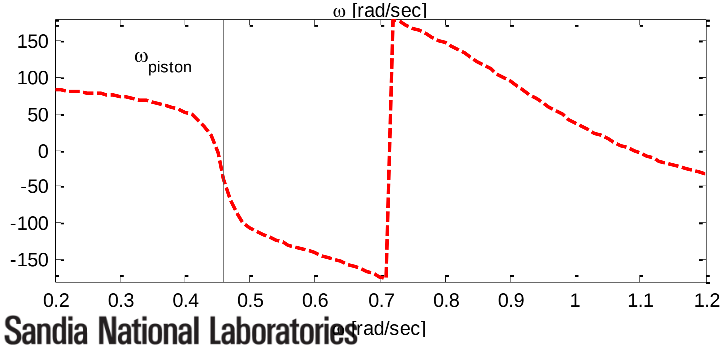
$$qA - \sum_j (H_j^u + T_j S) u_j$$

Determining Resonances:

Magnitude

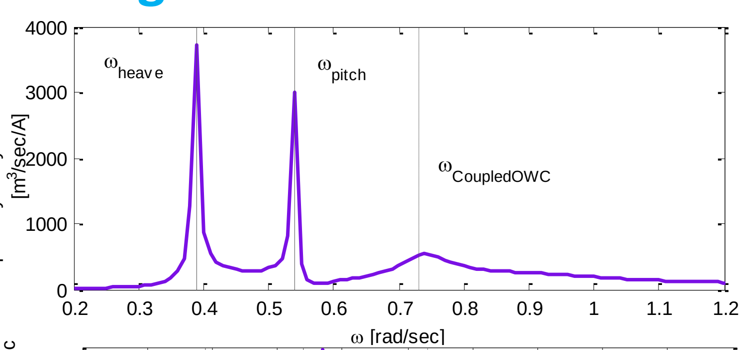


Phase

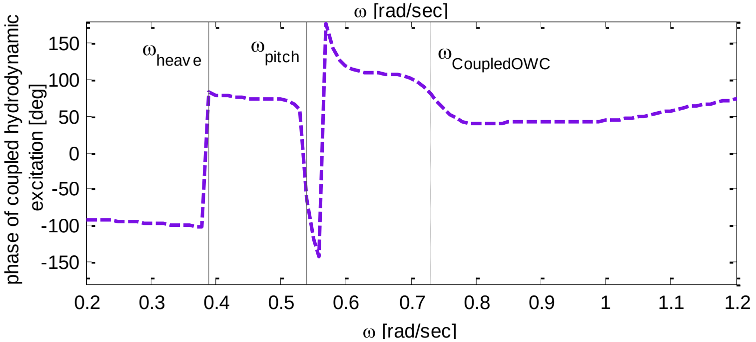


Determining Resonances:

Magnitude



Phase



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Device Performance:
Linear Wells Turbine Linking the Structures Oscillations to the OWC

Linked Governing Equations

Linked Matrix Representation

- Structure velocity
- Relative Pressure in the Air Column

$$\begin{pmatrix} \boldsymbol{f} \\ q \end{pmatrix} A = \begin{pmatrix} \boldsymbol{Z}_i & -\boldsymbol{H}_i \\ \boldsymbol{H}_i^T & Y_i + \dfrac{1}{R_{load}} \end{pmatrix} \begin{pmatrix} \boldsymbol{u} \\ p \end{pmatrix}$$

- Radiation Impedance of the Structure

$$\boldsymbol{Z}_i = \boldsymbol{b} + \boldsymbol{b}_{vis} + i\omega \left(\boldsymbol{m} + \boldsymbol{a} - \frac{(\boldsymbol{C} + \boldsymbol{K})}{\omega^2} \right)$$

- Relative Coupling Term

$$\boldsymbol{H}_i = \boldsymbol{H} + \boldsymbol{TS}$$

- Radiation Admittance of the Compressible Air Column

$$Y_i = \left(G + \frac{1}{R_{vis}} \right) + i \left(B + \frac{\omega \forall_o}{\gamma p_{atm}} \right)$$

Linked Total Volume Flow

$$Q_T = qA - Y_i p - \boldsymbol{H}_i^T \boldsymbol{u} = \frac{p}{R_{load}}$$

Externally Applied Forces: Viscous Damping and Mooring

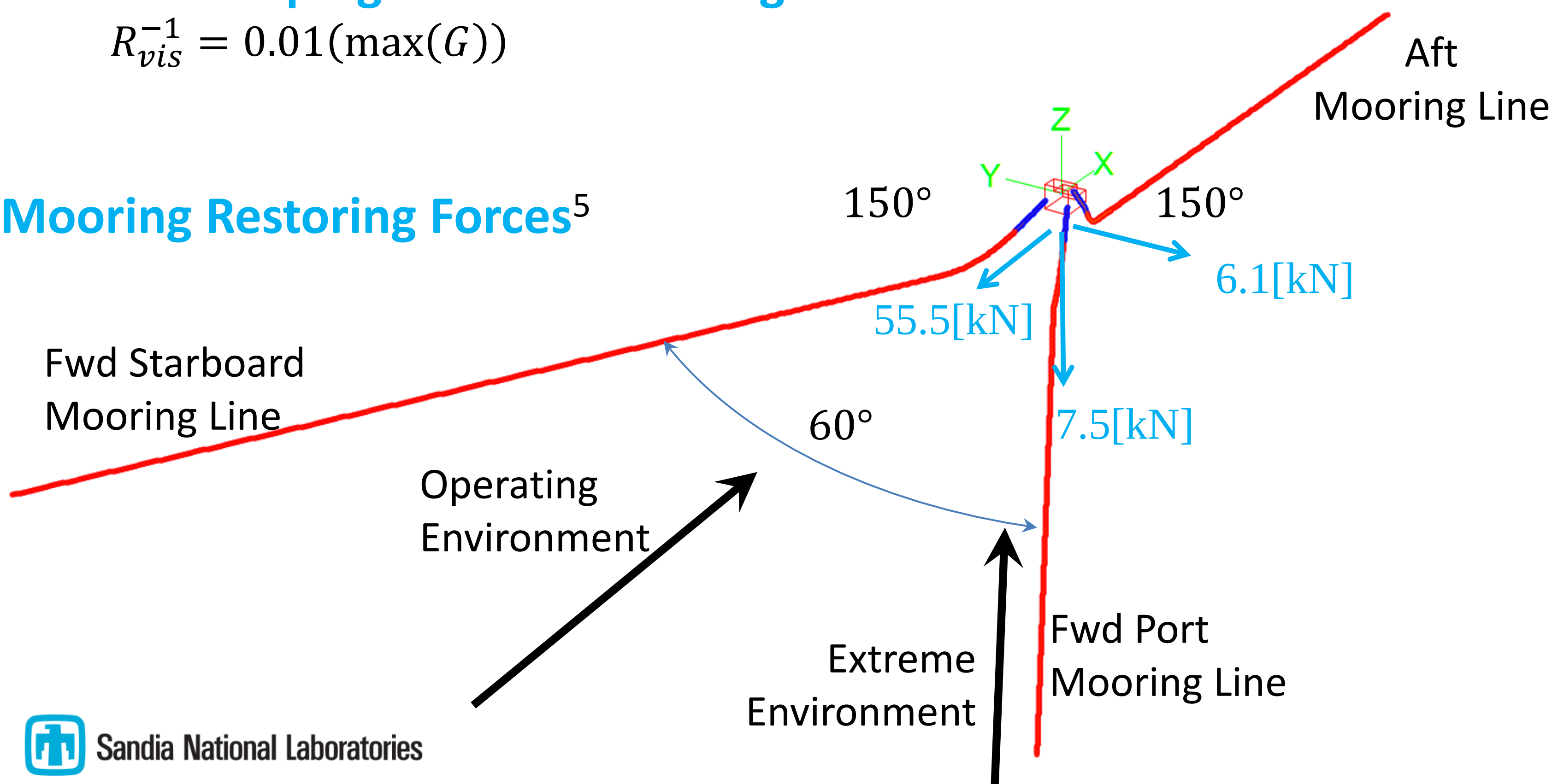
Viscous Damping on the Floating Structure

$$b_{vis} = 0.02(2\sqrt{M_{tot}c_{tot}})$$

Viscous Damping on the Oscillating Water Column

$$R_{vis}^{-1} = 0.01(\max(G))$$

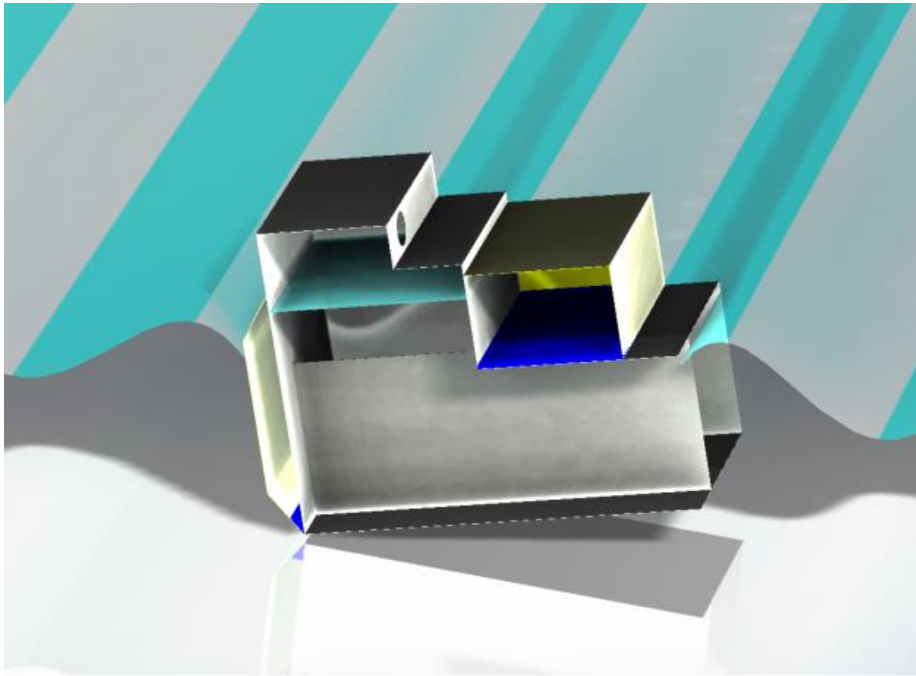
Mooring Restoring Forces[5]



Pneumatic Power

Pneumatic Power

$$\langle P\rangle = \overline{p(t)Q_T(t)} = \frac{1}{2}Re\{pQ_T^*\}$$



Monochromatic Waves[4]

Pneumatic Power

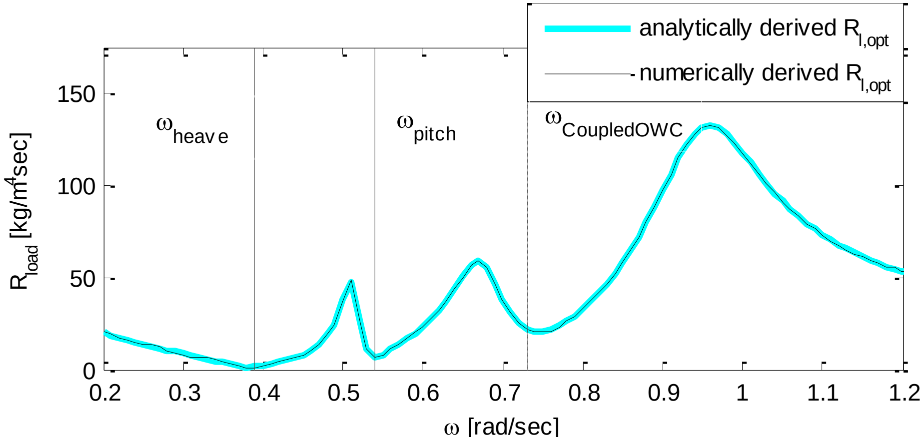
- $\langle \mathrm{P}\rangle = \frac{1}{2}\frac{1}{R_{load}}|p|^2$

Optimization Condition

- $\frac{\partial\langle \mathrm{P}\rangle}{\partial R_{load}} = 0$

Optimal Resistive Damping for Hydrodynamically Coupled OWC

- $R_{l_{opt}} = \left(\left|Y_i + \boldsymbol{H}_i^T\boldsymbol{Z}_i^{-1}\boldsymbol{H}_i\right|^2\right)^{-\frac{1}{2}}$



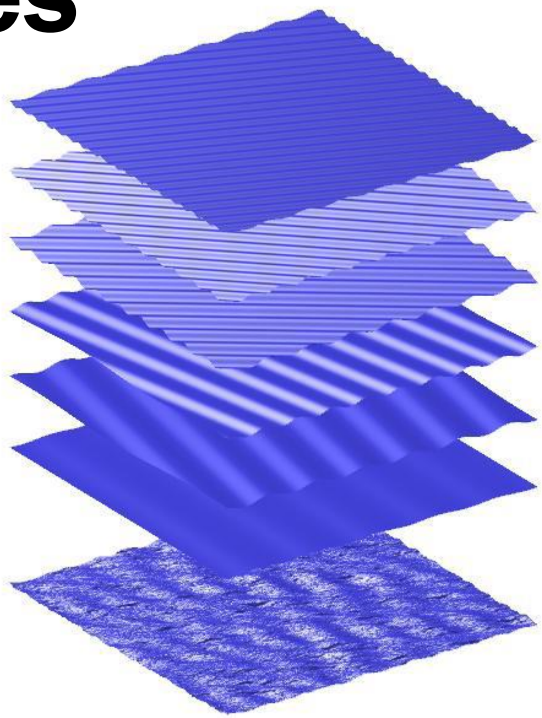
Device Performance in Random Waves.

Random Waves

[6]

Modeling Ocean Waves

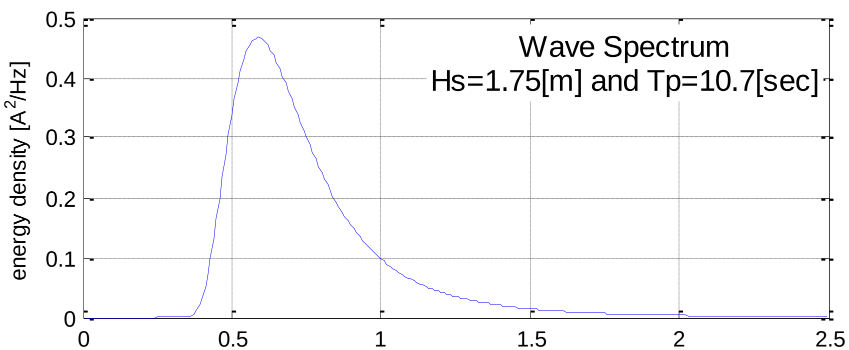
- Superposition of harmonic waves
  - Distinct frequencies, amplitudes, and incident directions.
- Gaussian random process
- Wave Spectra $S(\omega)$
  - Represent distribution of energy content as a function of frequency and direction.
  - Use standard distributions to describe waves in different parts of the world.



$$\eta(x,y,t) = \sum_i a_i \cos(k_i(x\cos\theta_i + y\sin\theta_i) - 2\pi f_i t + \phi_i)$$

Power In Unidirectional Waves

- $$J(T_p, H_s) = J_{ij} = \sum_k \rho g c_{g,k} S_{ij}(\omega_k)\Delta\omega_k$$



Spectral Density

Response Spectrum for variable R:

- $S_R(\omega) = [\mathrm{RAO}(\omega)]^2 S(\omega)$

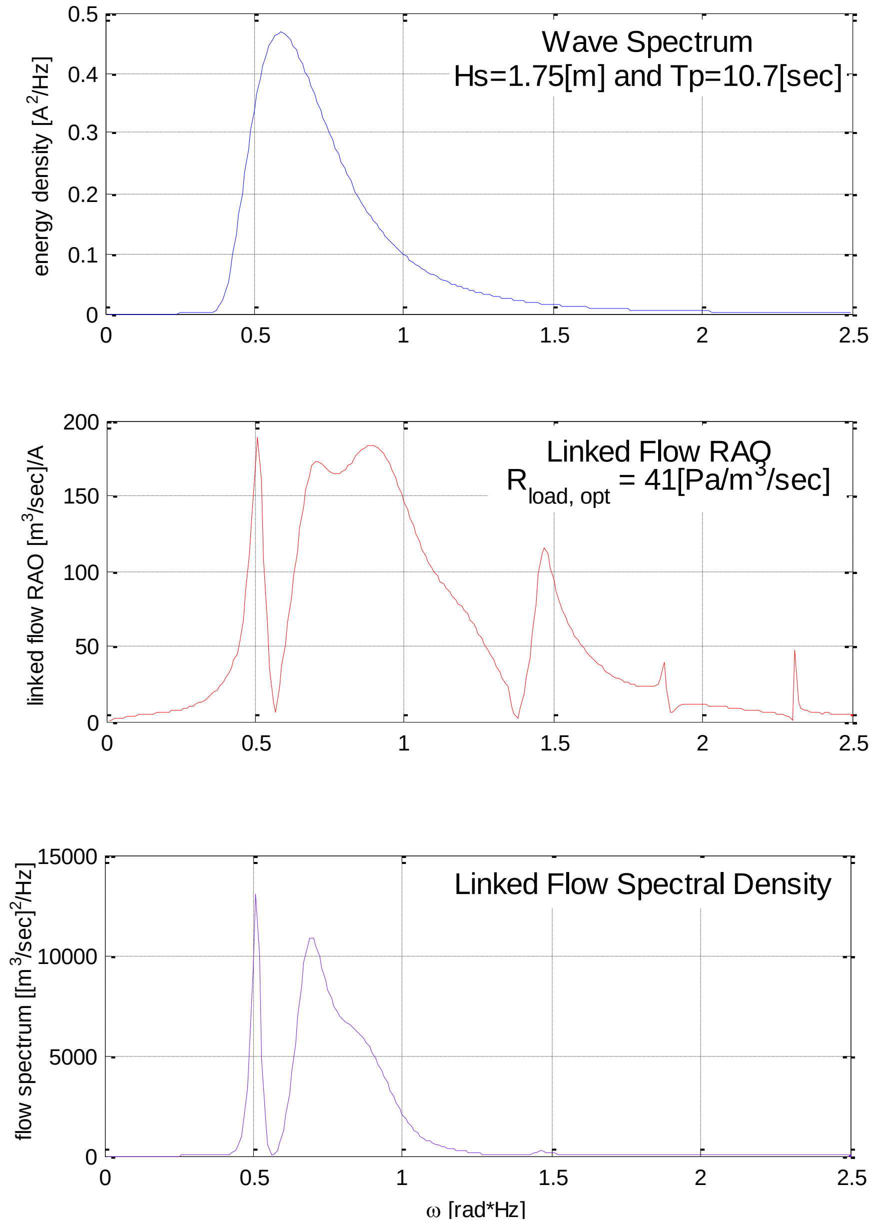
Statistical Properties

- **Root-mean square**

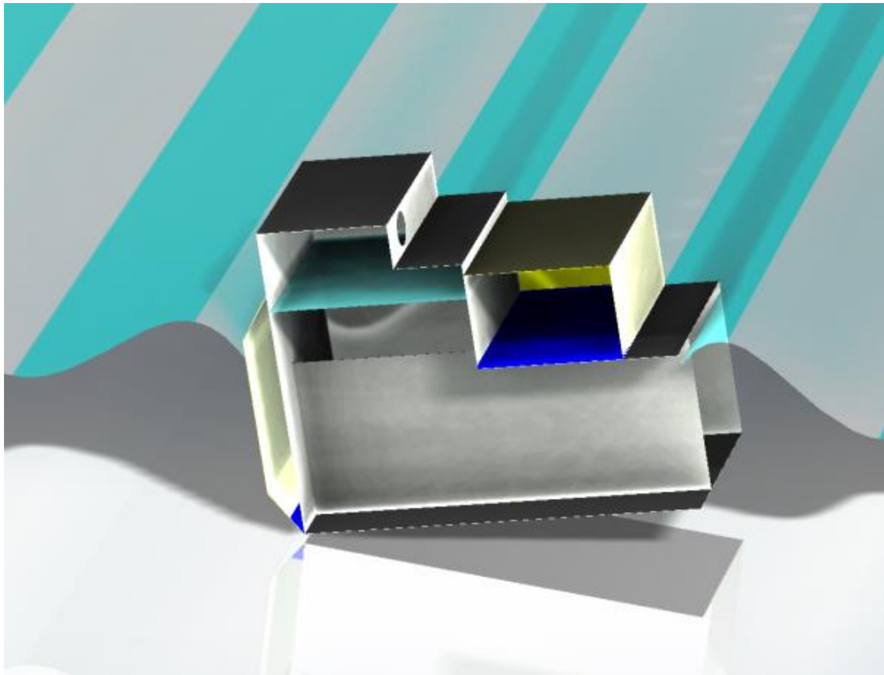
$$R_{RMS} = \sqrt{\int S_R(\omega)d\omega} = \sqrt{m_0}$$

- **Significant**

$$R_s = 2\sqrt{\int S_R(\omega)d\omega} = 2\sqrt{m_0}$$



Optimization of Pneumatic Power In Random Waves



Pneumatic Power In Random Waves

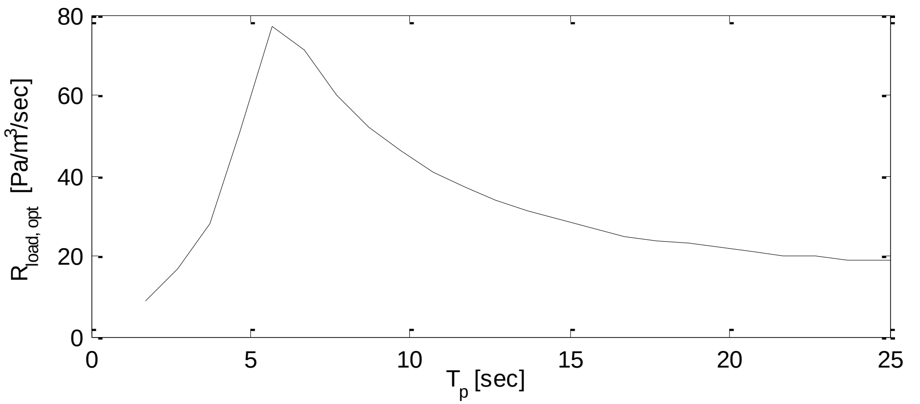
- $\langle P_{ij} \rangle = R_{load,i} \int Q_{T,ij}(\omega)^2 S_{ij}(\omega) d\omega$

- Must apply a constant R_{load} across all frequencies to match the linear properties of the Wells Turbine and the Resistive Control Strategy

Optimization

- Run performance model with constant R_{load}'s and select the R_{load} that gives the largest pneumatic power

Optimal Resistive Damping for Hydrodynamically Coupled OWC in Random Waves



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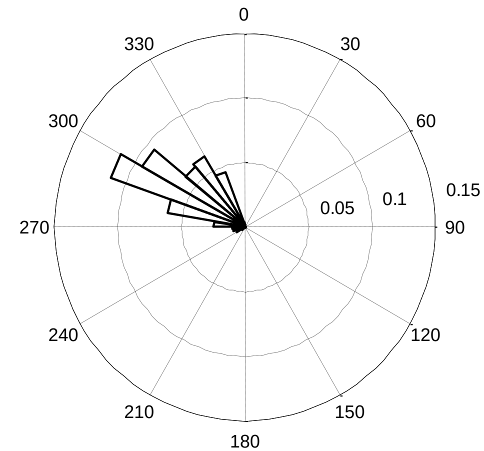
Annual Pneumatic Performance at Northern CA Deployment Location.

Northern CA Characteristics

NDBC 46212 data (2004-2011)

- Assume unidirectional Bretschneider spectrum.



Wave direction rose

Joint-Probability Distribution

- likelihood of a particular significant wave height, H_s, occurring with peak period T_p
- Power 31.5 kW/m

Peak Period, Tp [sec]

Significant Wave Height, Hs [m]	4.7	5.7	6.7	7.7	8.7	9.7	10.7	11.7	12.7	13.7	14.7	15.7	16.7	17.7	18.7
0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.75	0.0	0.004	0.011	0.011	0.013	0.004	0.006	0.003	0.0	0.0	0.003	0.004	0.005	0.0	0.0
1.25	0.0	0.010	0.028	0.024	**0.046**	0.018	0.022	0.011	0.009	0.007	0.005	0.004	0.004	0.002	0.0
1.75	0.0	0.002	0.025	0.027	0.036	0.021	0.035	0.019	0.014	0.012	0.010	0.005	0.005	0.003	0.0
2.25	0.0	0.0	0.006	0.023	0.036	0.017	0.033	0.024	0.019	0.015	0.010	0.006	0.005	0.003	0.0
2.75	0.0	0.0	0.0	0.009	0.027	0.010	0.022	0.020	0.015	0.013	0.009	0.005	0.005	0.003	0.0
3.25	0.0	0.0	0.0	0.0	0.011	0.007	0.012	0.013	0.012	0.011	0.008	0.005	0.004	0.0	0.0
3.75	0.0	0.0	0.0	0.0	0.003	0.003	0.005	0.007	0.007	0.007	0.006	0.003	0.003	0.0	0.0
4.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.003	0.003	0.004	0.004	0.0	0.002	0.0	0.0
4.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.002	0.0	0.0	0.0	0.0
5.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4.0	**4.9**	**5.7**	**6.6**	**7.5**	**8.3**	**9.2**	**10.0**	**10.9**	**11.7**	**12.6**	**13.5**	**14.3**	**15.2**	**16.0**

Energy Period, Te [sec] $2\pi(m_{-1}/m_0)$

Energy Weighted Characteristics

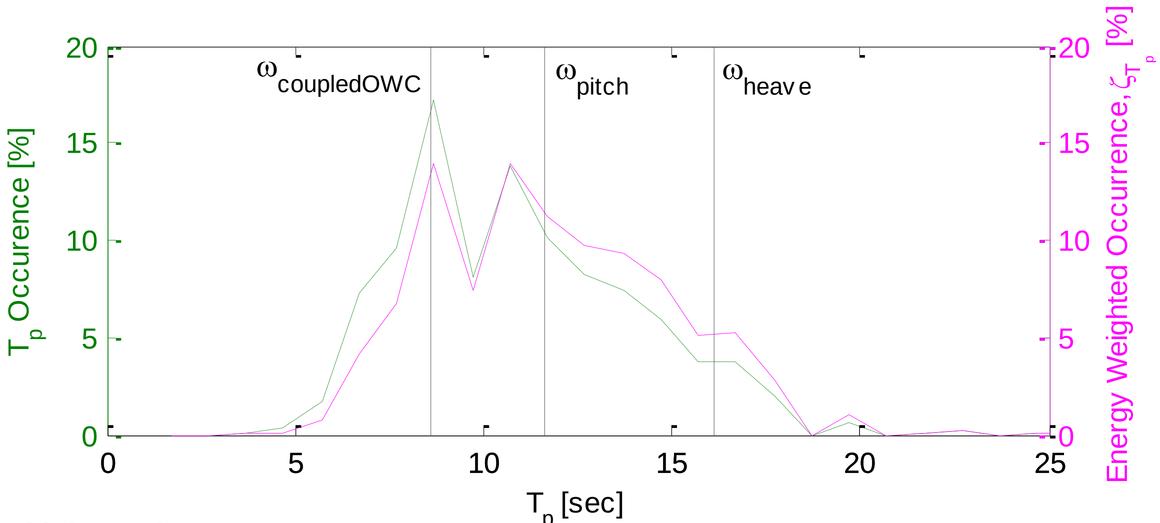
Energy Weighted Occurrence

- $\zeta_i = \frac{(\sum_j JPD_{ij})(\sum_j J_{ij})}{\sum_{ij} JPD_{ij} J_{ij}}$

- Focus on the period energy weighted occurrence—resonant devices respond to frequencies!

Structural Design Match

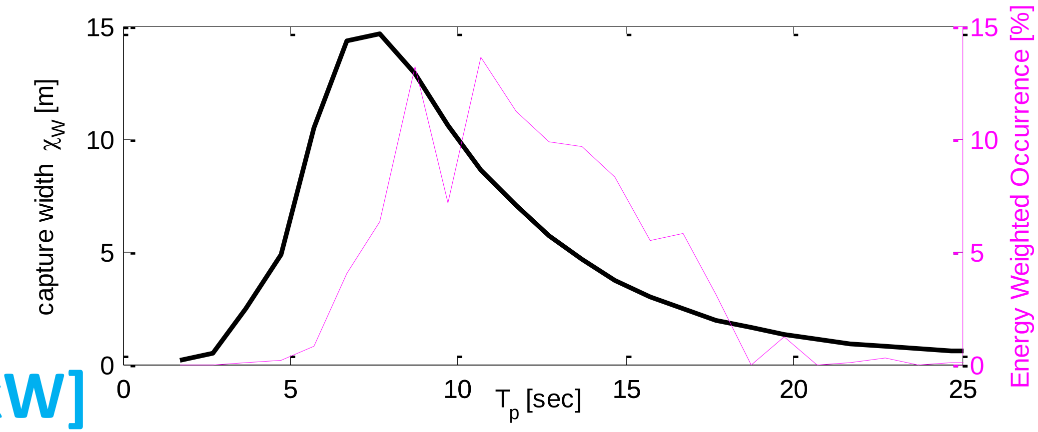
- Ensure that the structural resonances of the device align with the energy weighted deployment climate



Annual Performance

Spectral Capture Width

- $\chi_{w,i} = \frac{\langle P_i \rangle}{J_i}$



Pneumatic Power Matrix [kW]

Peak Period, Tp [sec]

Significant Wave Height, Hs [m]	4.7	5.7	6.7	7.7	8.7	9.7	10.7	11.7	12.7	13.7	14.7	15.7	16.7	17.7	18.7
0.25	1	2	3	3	3	3	3	2	2	2	2	1	1	1	1
0.75	5	14	23	28	28	27	24	22	20	17	15	13	11	9	8
1.25	14	39	64	77	**78**	74	68	61	55	48	41	35	30	25	21
1.75	28	76	125	150	153	144	133	120	107	93	80	69	58	49	42
2.25	46	126	207	249	253	239	219	199	177	154	133	113	96	82	69
2.75	69	188	309	371	378	356	328	297	264	231	199	170	144	122	103
3.25	96	262	431	519	528	498	458	414	369	322	277	237	201	170	144
3.75	128	349	574	691	703	663	609	552	491	429	369	315	268	227	192
4.25	164	448	737	887	903	851	783	709	630	551	474	405	344	291	247
4.75	205	560	921	1108	1128	1063	978	885	787	688	593	506	429	364	309
5.25	251	684	1125	1354	1378	1299	1194	1082	962	840	724	618	525	445	377
Energy Period, Te [sec] $2\pi(m_{-1}/m_0)$	**4.0**	**4.9**	**5.7**	**6.6**	**7.5**	**8.3**	**9.2**	**10.0**	**10.9**	**11.7**	**12.6**	**13.5**	**14.3**	**15.2**	**16.0**

Energy Period, Te [sec] $2\pi(m_{-1}/m_0)$

Annual Performance Metrics

	Variable		RMS Eq. 13	Significant Eq. 14
Power Performance	Pneumatic Power	kW	207.8	--
	Pneumatic Energy Production	MW-hr	1820	--
	Capture Width	m	8.89	--
Device Dynamics	Pressure	Pa	2728	5456
	Flow	m^3/sec	66.2	132.5
	Heave	m	0.43	0.87
	Pitch	deg	2.9	5.7

Cost of Energy Proxy's

Variable		RMS			
Capture Width Ratio	%	33	Length used	m	27
Energy Capture per Displaced Mass	MW-hr / tonne	0.90	Displaced Mass	tonne	2025
Energy Capture per Structural Mass	MW-hr / tonne	1.01	Structural Mass	tonne	1809
Energy Capture per Surface Area	MW-hr / m^2	0.43	Surface Area	m2	4251

Next Steps

Incorporation of Wells Turbine

- **ARL at Penn State is working with SNL to size the Wells Turbine and power electronics that should be associated with this design**
  - Incorporation will include sea state – by – sea state derived efficiencies
    - This model is being completed in 2 stages:
      - Stochastic treatment of pneumatic power only[7]
      - Full stochastic treatment all the way through the generator.

Economic Model

- **NREL will be working to determine the LCOE of this device**
  - The cost model will incorporate sensitivity analysis on some of the estimates.

Thank you.

Chris Smith agreed to present this for me requiring a special acknowledgement—Thank you!

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Diana Bull diana.bull@sandia.gov

Sandia National Laboratories

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