SAND2013-7359C

Optimal Resistive Control Strategy for a Floating OWC

EWTEC 2013: Aalborg Denmark

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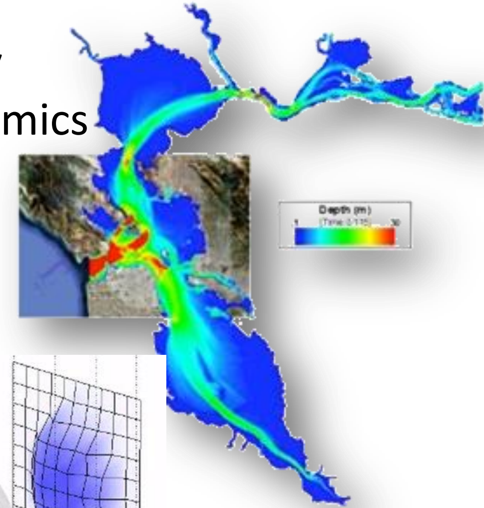
SNL Water Power Program

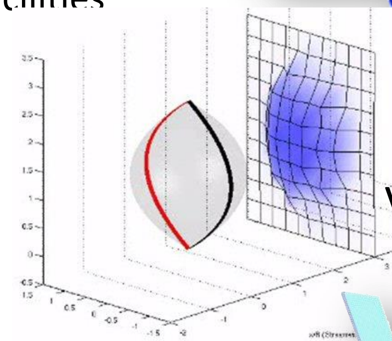
Marine Hydrokinetics, Offshore Wind, Conventional Hydropower



SF-Bay Hydrodynamics

Unique Capabilities

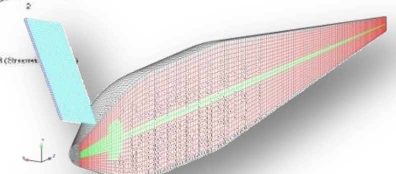
- MHK environmental circulation and performance code (SNL-EFDC)
- Composite structural materials and anti-biofouling coatings test facilities
- Sandia Lake Facility – TRL 6 appropriate for wave testing
- SEAWOLF lab/field oscillatory-flow sediment transport testing
- HydroSCOPE Seasonal Optimization Tool (CH)



VAWT Wake

Collaborative Projects

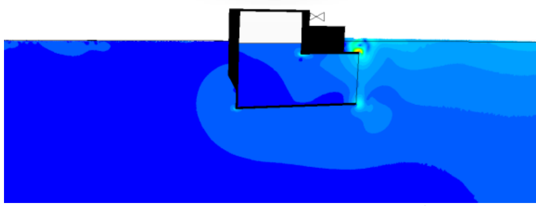
- Technical Industry Support
  - Ocean Renewable Power Company,
  - Ocean Power Technologies,
  - Snohomish PUD
- SNL-EFDC Technology Transfer to
  - Free Flow Power, NOAA, FERC, BOEM, Verdant, ORPC



Whale Strike Analysis

Impact Examples

- Whale strike analysis (collaboration with PNNL) allowing demonstration project to proceed in Puget Sound
- Leading the techno-economic report to Congress detailing what steps need to be taken to ensure the growth of the WEC industry.
- Novel vertical axis wind turbine designs and structural health monitoring for offshore wind devices.



OWC Dynamic Analysis

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Reference Model Project

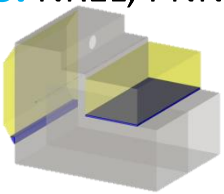
Summary

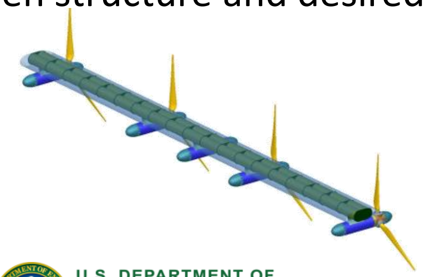
- Multi-Lab effort to obtain **baseline** performance and Cost Of Energy (**COE**) estimates for a variety of Marine Hydro-Kinetic (MHK) devices, sponsored by DOE.
- Method to achieve COE is to develop **public domain designs** incorporating the following:
  - •Power performance models
  - •Structural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

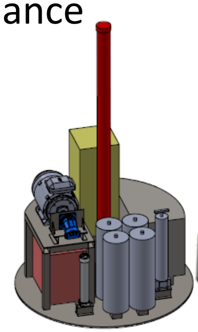
SNL Developed Models/Tools

- **Performance Models** — WEC: 3D model capable of handling 7DOF in Matlab; FEC: CACTUS
- **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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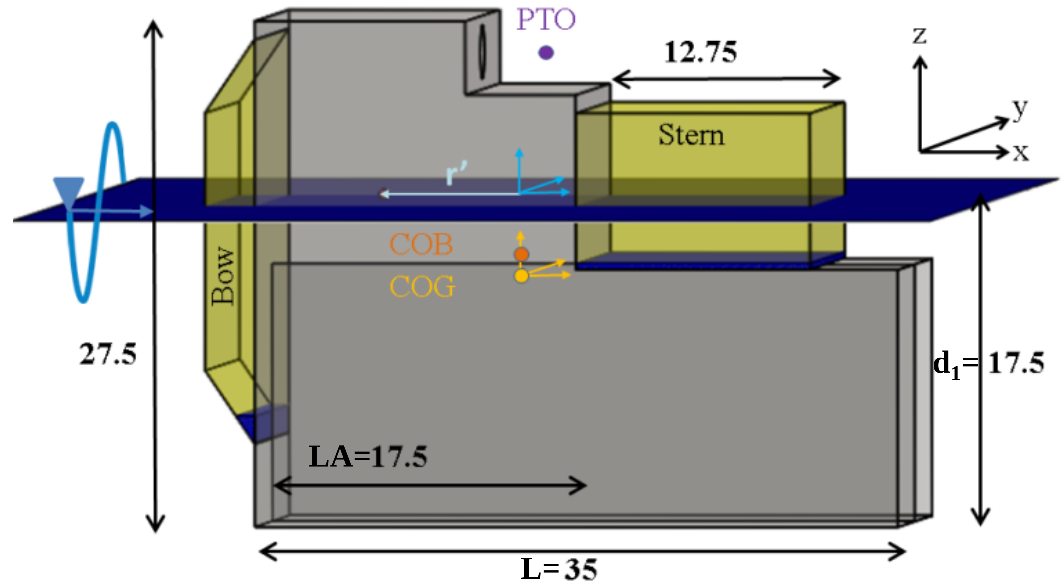
Backward Bent Duct Buoy

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

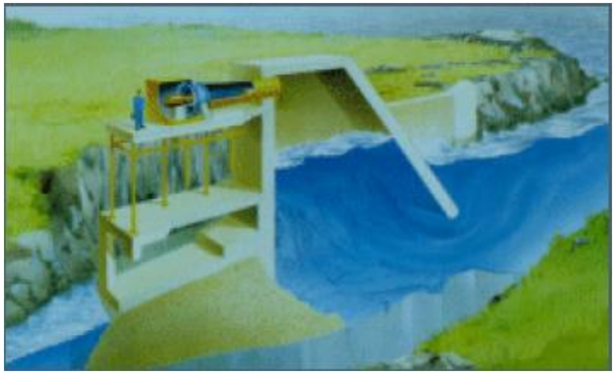


Structural Design

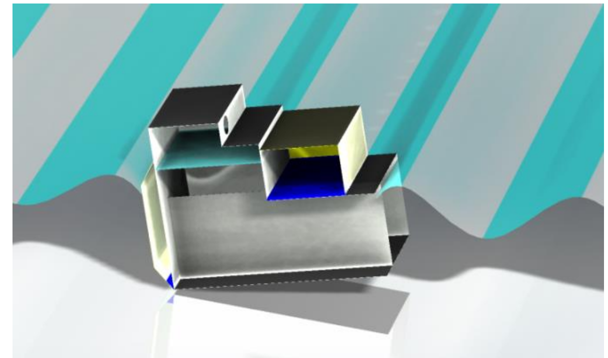
- **Entire structure built to withstand hydrostatic pressure at 23.5 m**
- **Ballast chosen for stability**
- **Buoyancy chambers sized to support weight and obtain desired natural resonances**

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

Optimal Resistive Control of OWCs



Grounded



Floating

Power Absorption

- **Wave activated water column**

Power Conversion

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

Coupled Power Absorption

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

Power Conversion

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

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Modeling the Pressure Distribution of a Floating OWC

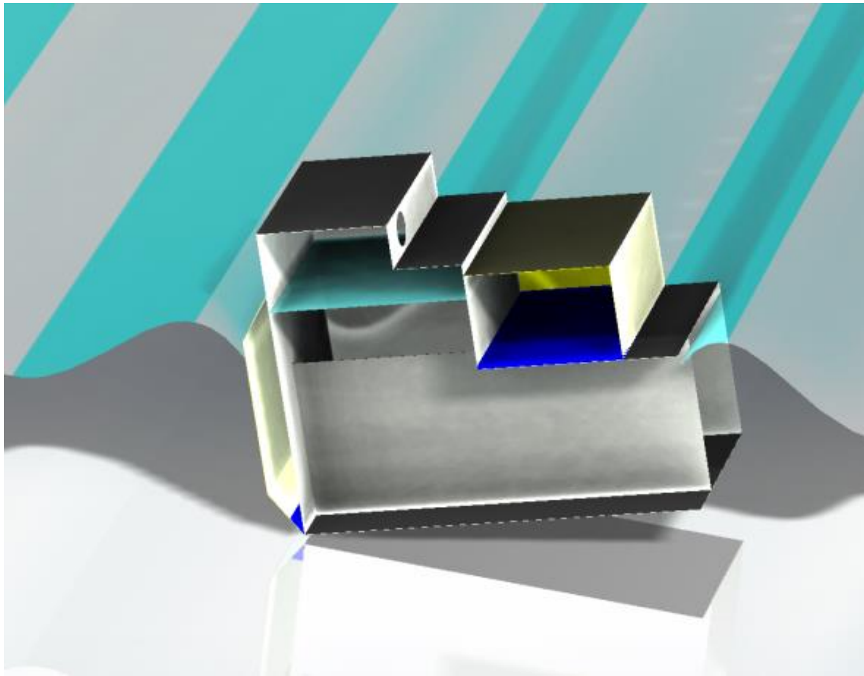
Approximation

- **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

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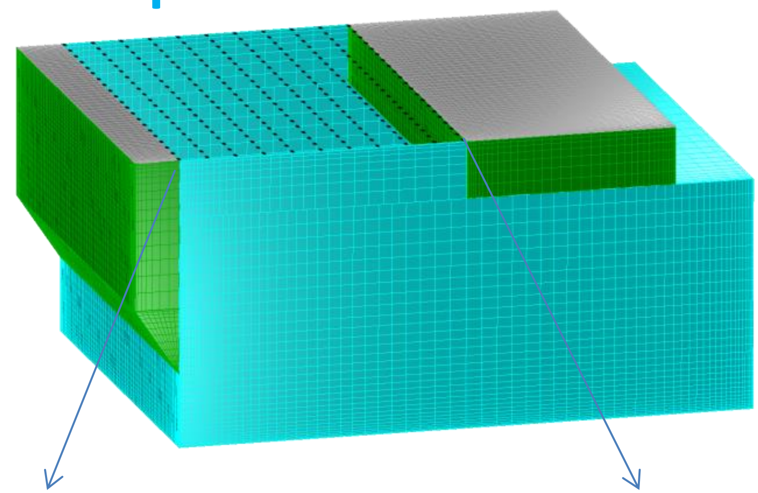
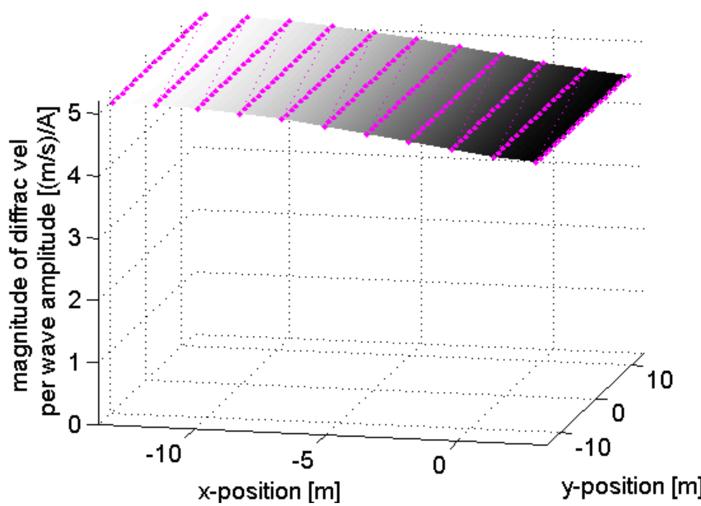
Device Representation in WAMIT



OWC free surface diffraction velocity values for ω=0.46.



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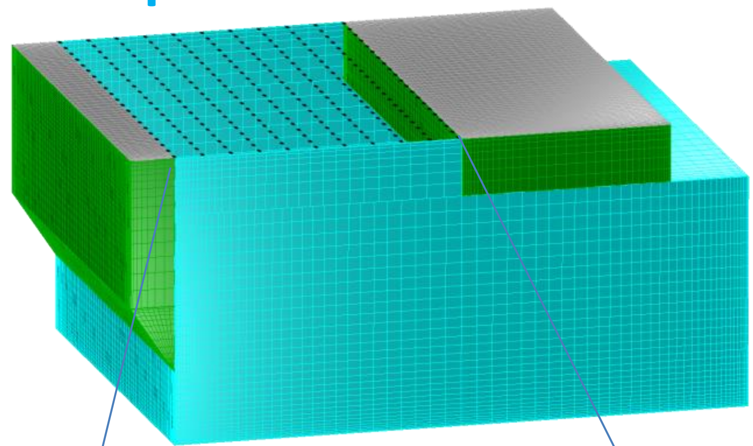

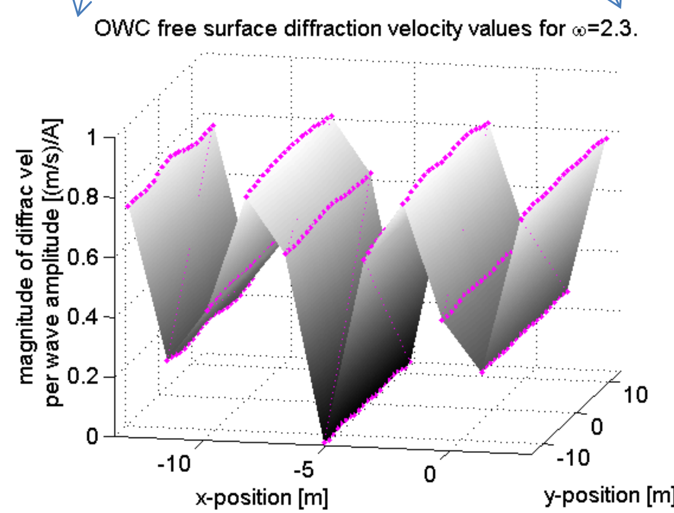

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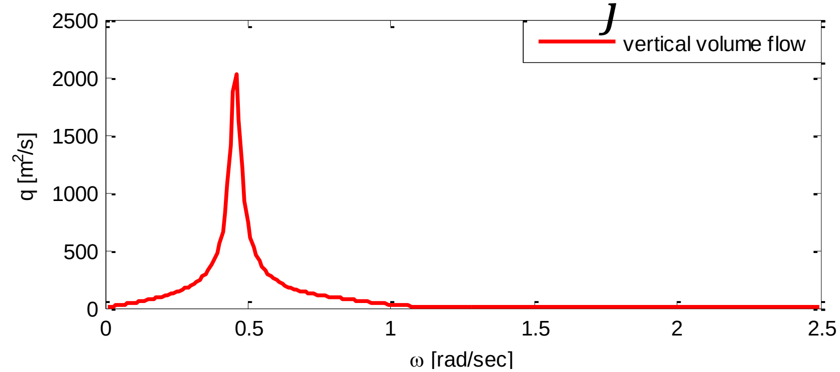
Device Hydrodynamics: Wave Structure Interactions

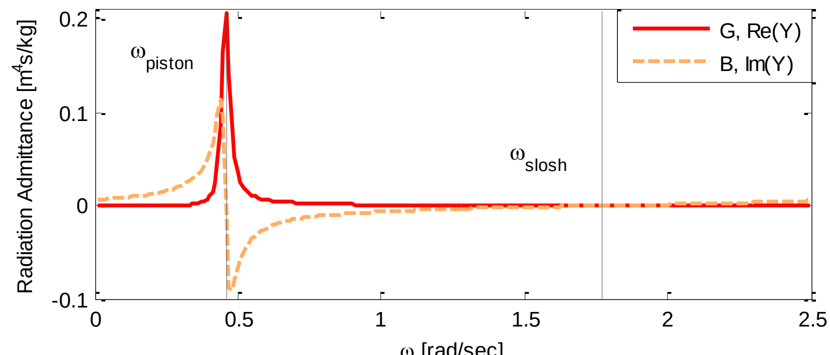
Free Surface Hydrodynamics

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



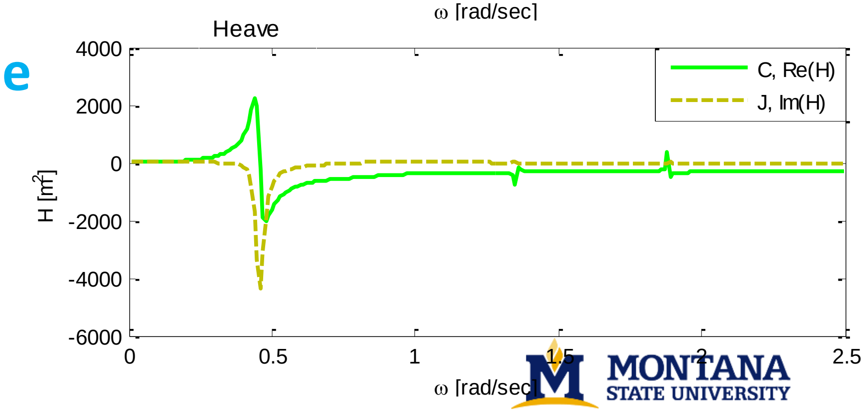
Excitation Volume Flow

$$q = \frac{1}{A} \iint_S \frac{\partial(\phi_o + \phi_d)}{\partial z} dS$$



Radiation Admittance

$$Y = -\iint_S \frac{\partial \varphi}{\partial z} dS = G + iB$$



Coupling of the Oscillating Structure to the Oscillating Water Column

$$H_j^u = -\iint_S \frac{\partial \varphi_j}{\partial z} dS = C_j + iJ_j$$

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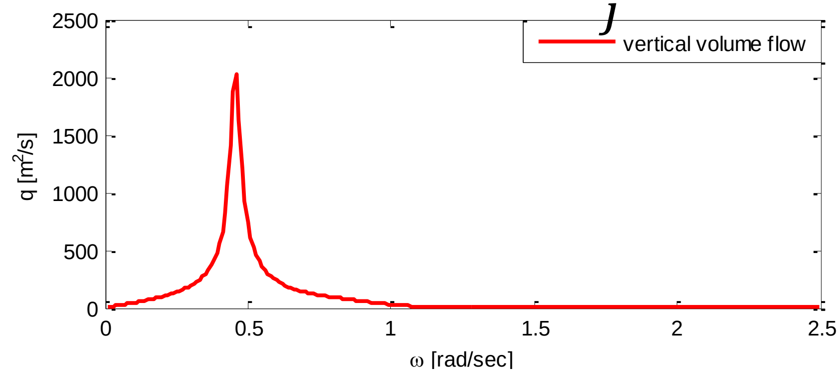

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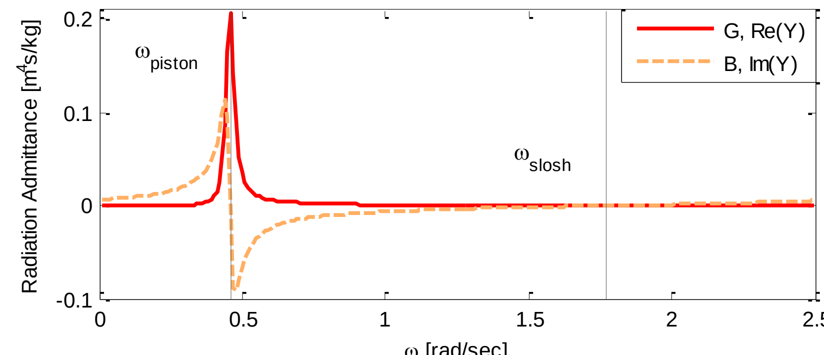
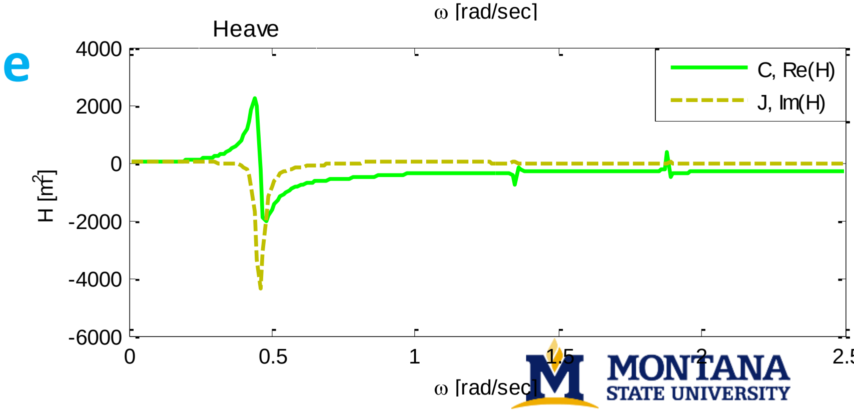


- **Reciprocity Relation** $G = \frac{2k}{8\pi\rho g v_g} \int_0^\pi |q(\beta)|^2 \, d\beta$
- **Kramers-Kronig** $B(\omega) = -\frac{2\omega}{\pi} \int_0^\infty \frac{G(y)}{\omega^2 - y^2} dy$

Coupling of the Oscillating Structure to the Oscillating Water Column



$$H_j^u = -\iint_S \frac{\partial \varphi_j}{\partial z} dS = C_j + iJ_j$$

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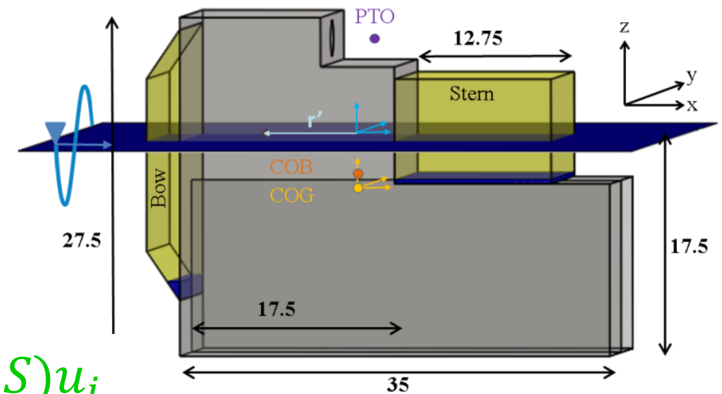
Hydrodynamically Coupled Relative Pressure



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 relative pressure

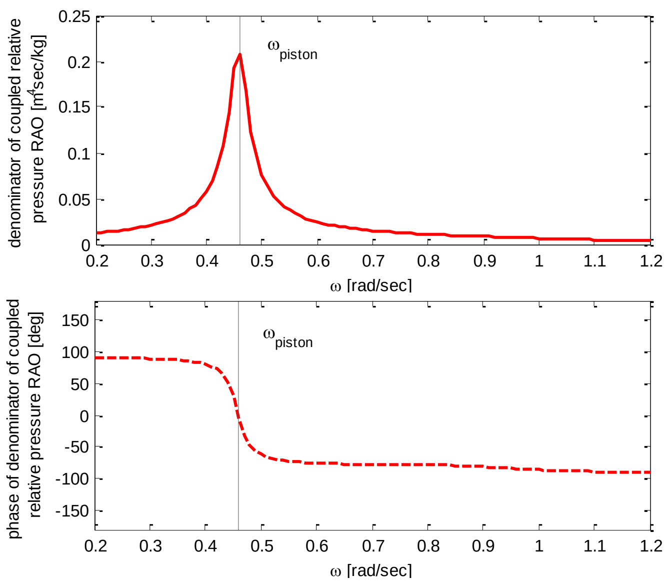
$$\frac{p}{A} = \frac{q - \sum_j (H_j^u + T_j S) u_j}{Y}$$

Determining Resonances: Couple Relative Pressure

Denominator

Magnitude

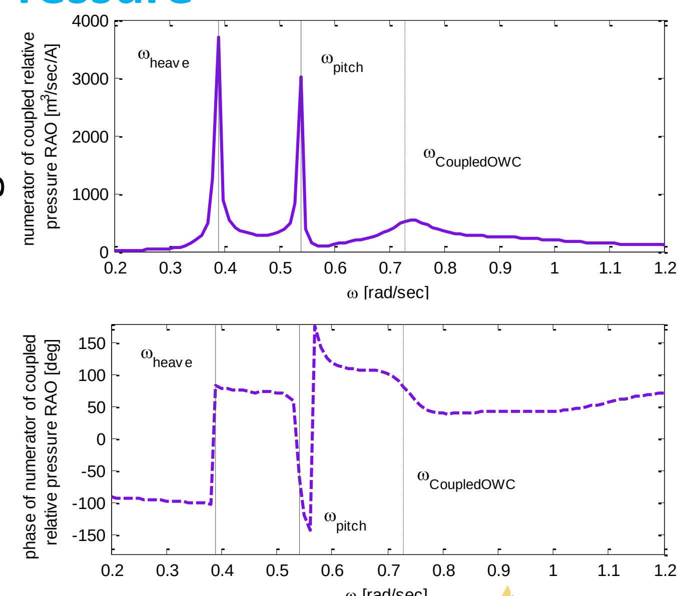
Phase



Numerator

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**

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

- **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**

$$\boldsymbol{H}_i = \boldsymbol{H} + \boldsymbol{T}S$$

- **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

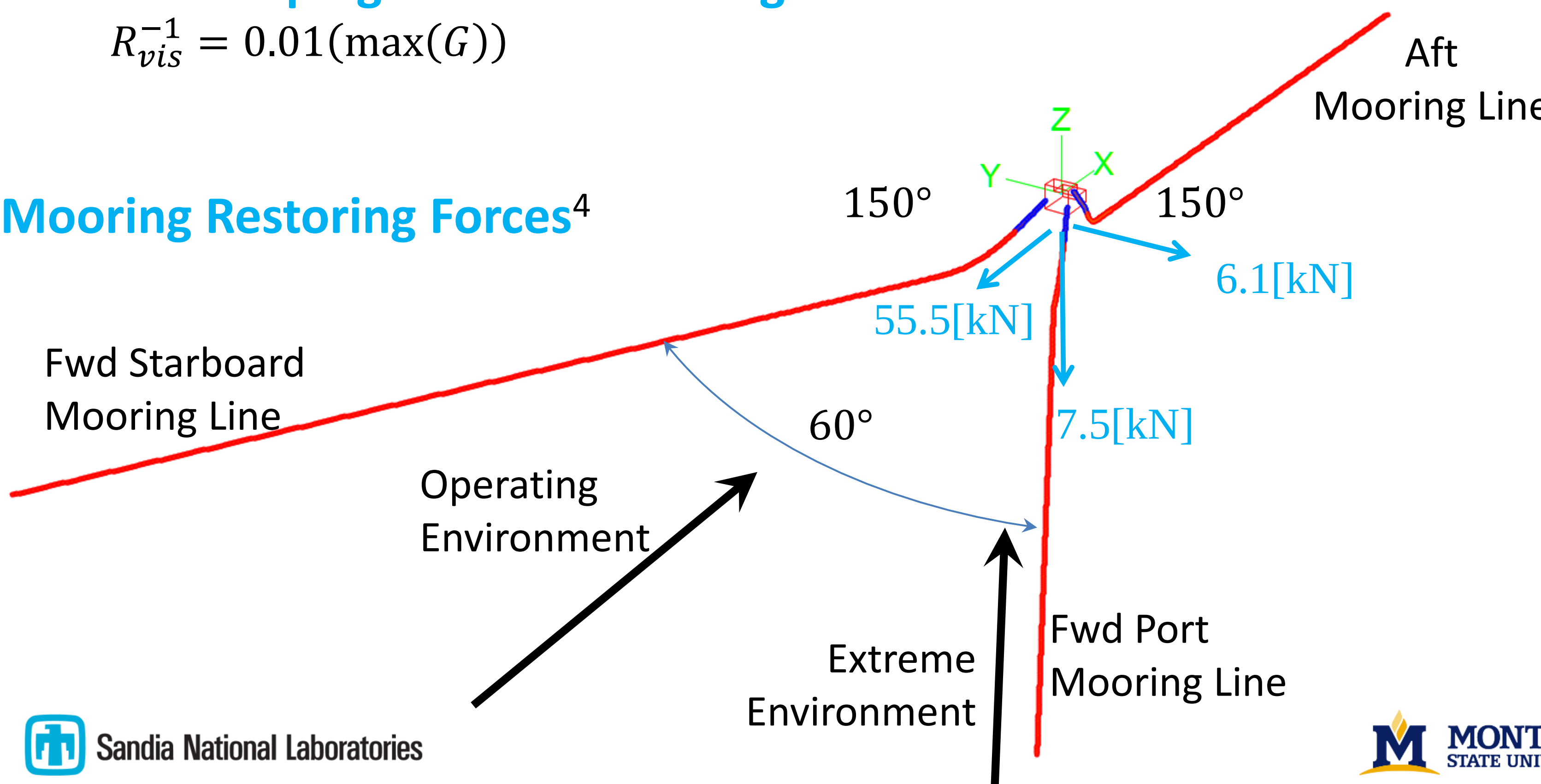
Viscous Damping on the Floating Structure

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

Viscous Damping on the Oscillating Water Column

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

Mooring Restoring Forces[4]



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Optimal Resistive Damping: Derivation

Pneumatic Power

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

Pneumatic Power In Monochromatic Waves

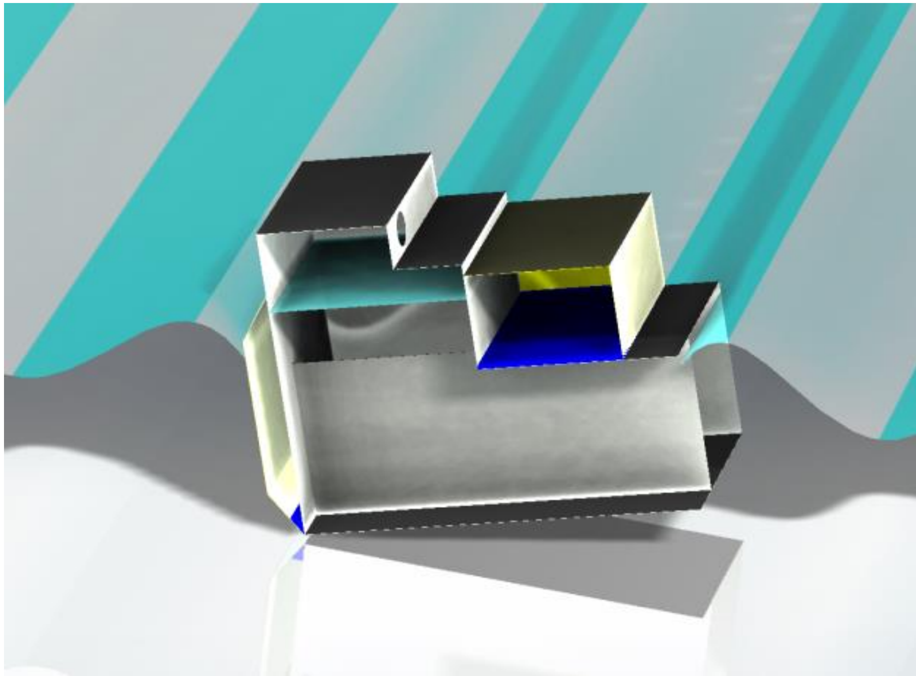
- $\langle \mathrm{P} \rangle = \frac{1}{2} \frac{1}{R_{load}} |p|^2$

Optimization Condition

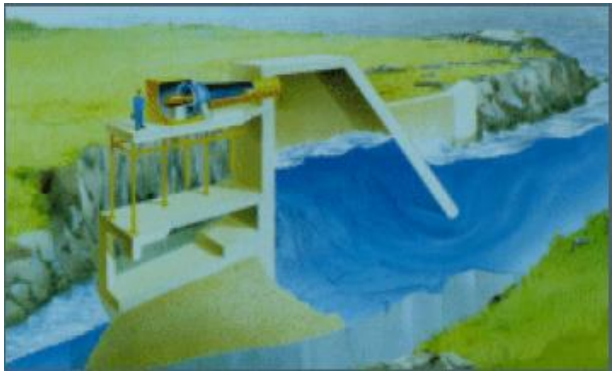
- $\frac{\partial \langle \mathrm{P} \rangle}{\partial R_{load}} = 0$

Optimal Resistive Damping for Hydrodynamically Coupled OWC

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



Optimal Resistive Damping: with Wells Turbine



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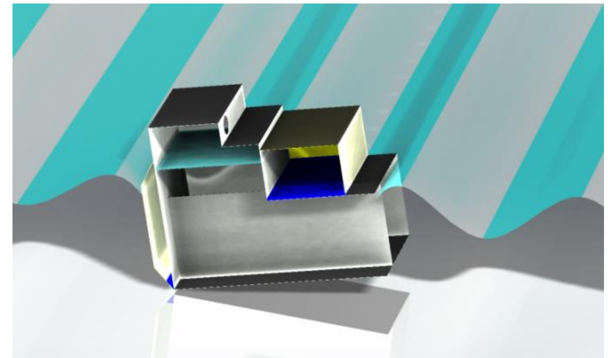
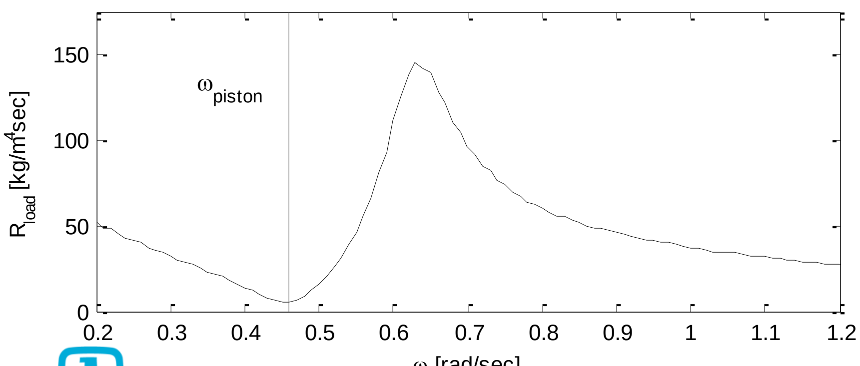


Floating

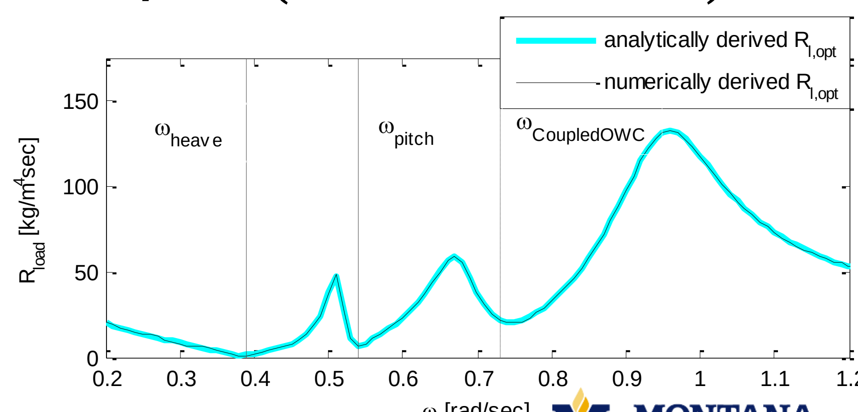
Optimal Resistive Damping

- $R_{l_{opt}} = \left(|Y_i|^2\right)^{-\frac{1}{2}}$



Optimal Coupled Resistive Damping

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



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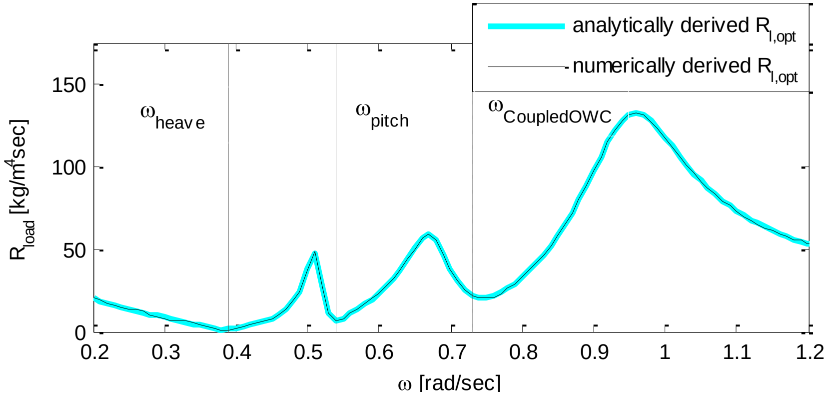
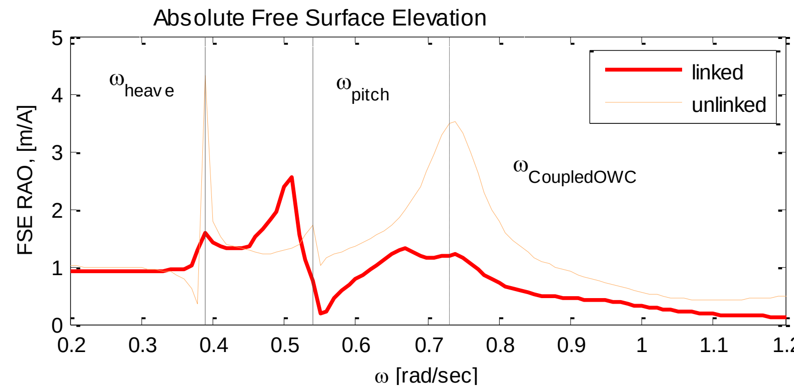
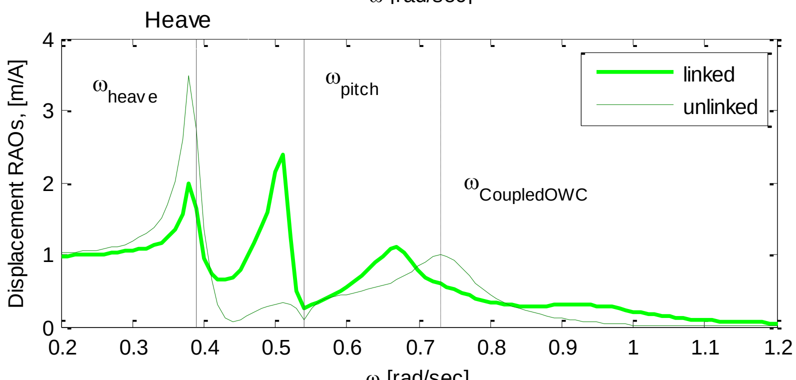
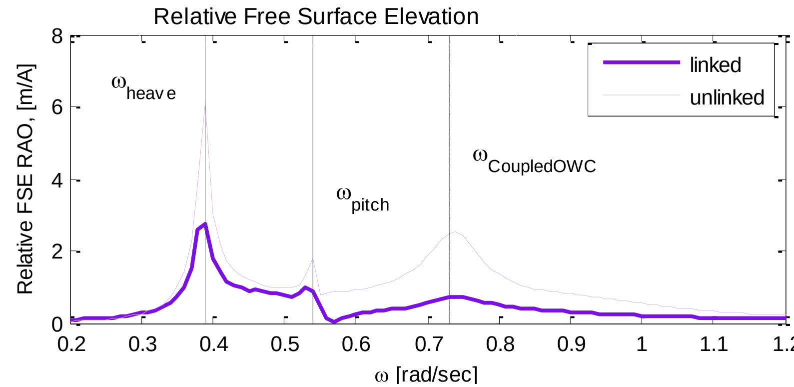
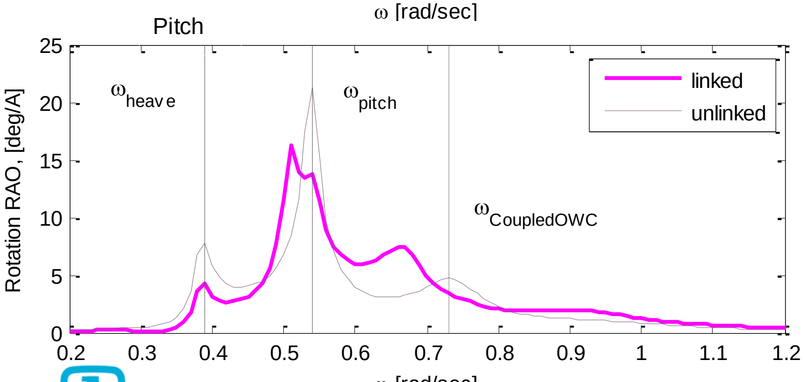
Influence of Wells Turbine on Device Motion: Troughs

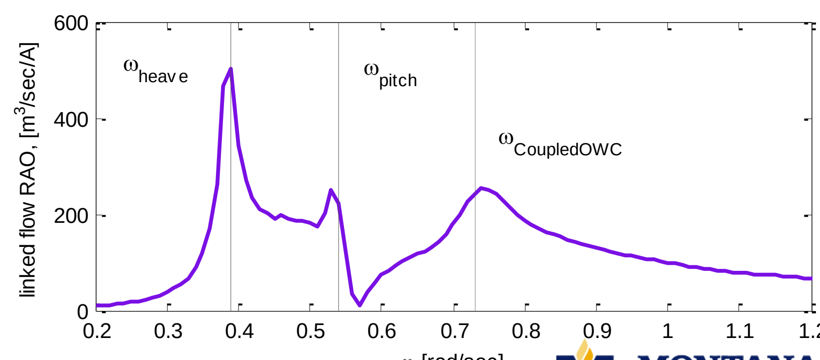












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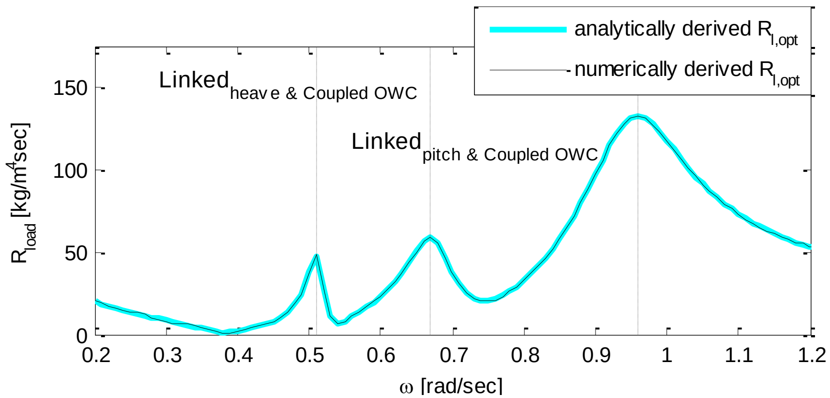
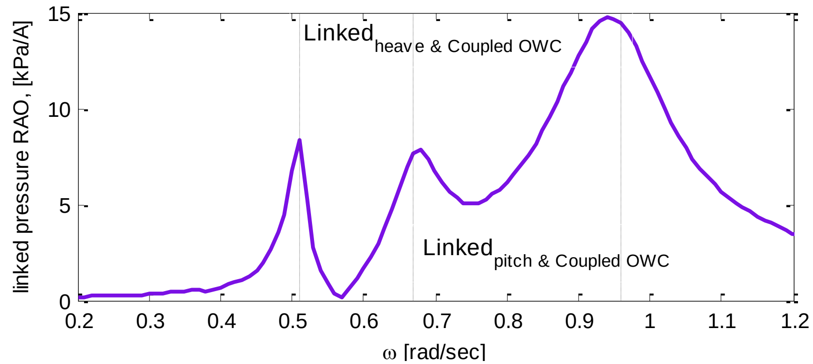
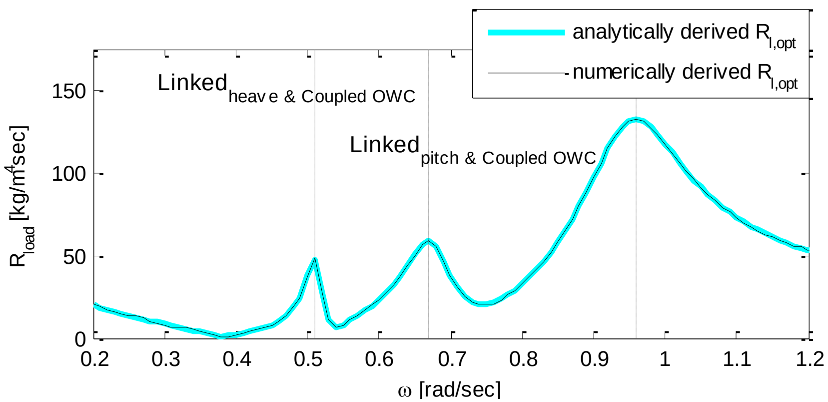
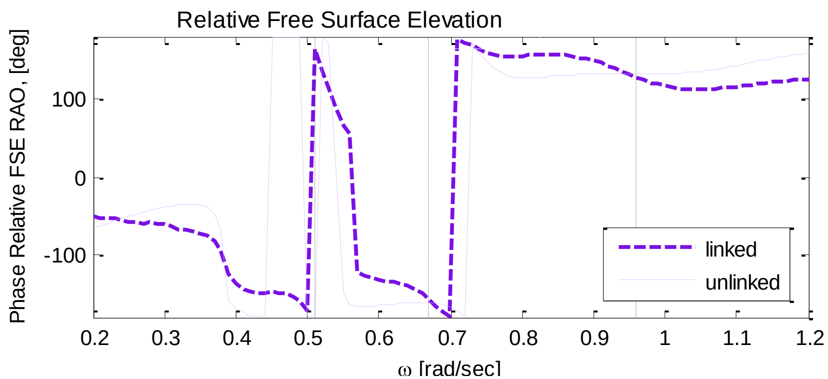
Influence of Wells Turbine on Device Motion: Peaks

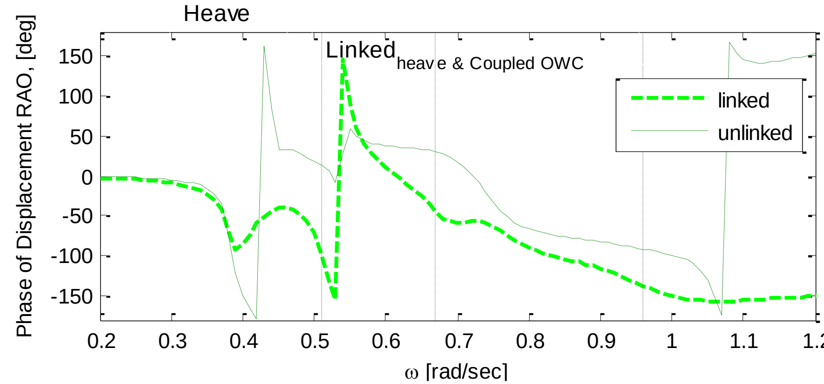


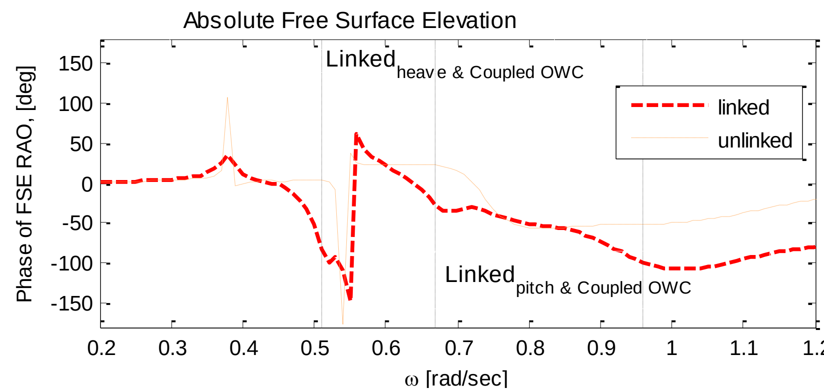


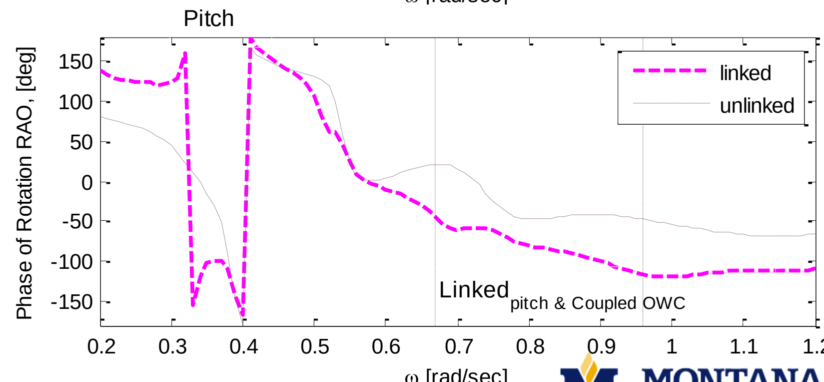
Influence of Wells Turbine on Device Motion: Understanding Peaks











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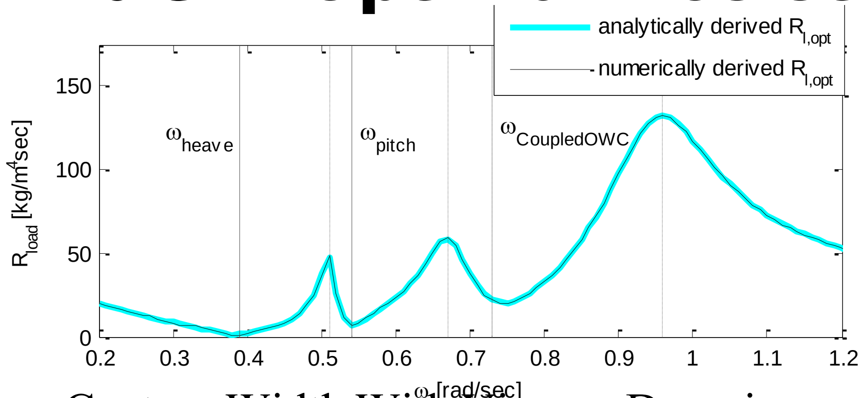
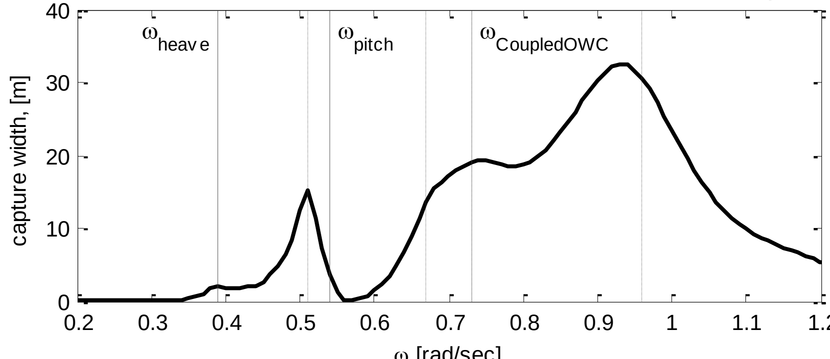
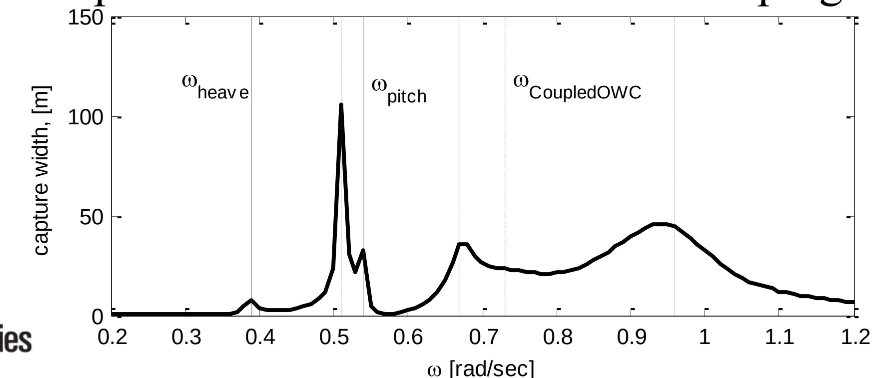
Influence of Wells Turbine on Device Capture Width: Optimal Resistive Damping



Capture Width With Viscous Damping



Capture Width *Without* Viscous Damping



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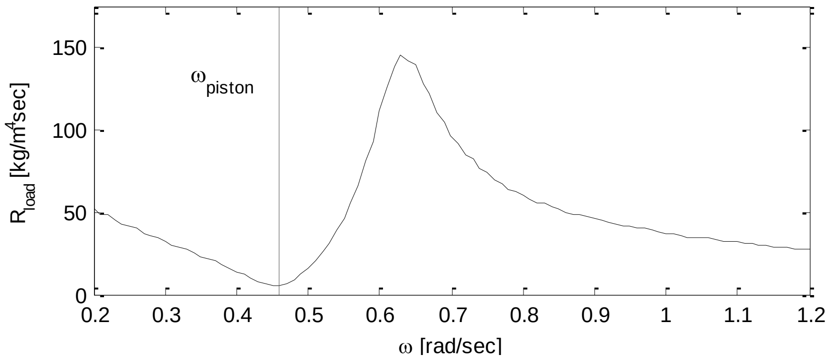
Comparison of Damping

Applying Grounded $R_{l,opt}$ to Floating Device



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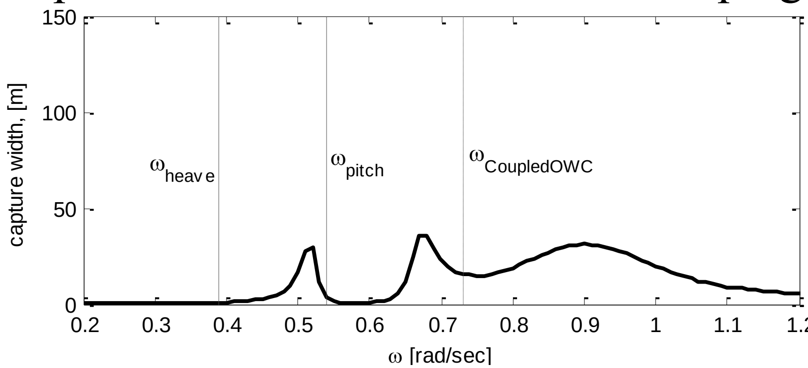
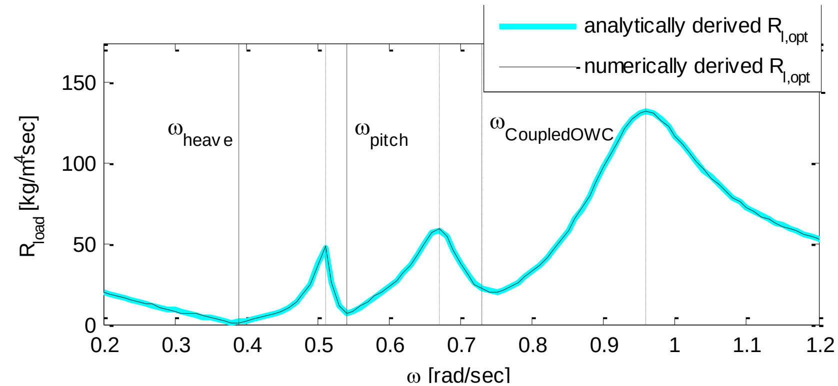


Applying Coupled $R_{l,opt}$ to Floating Device



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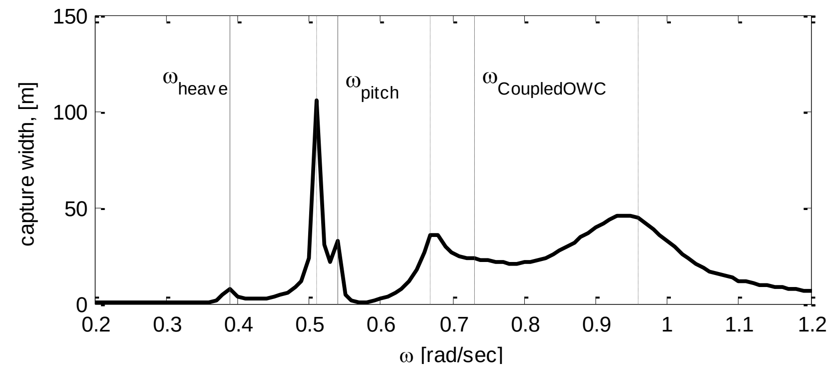

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Conclusions

Grounded vs. Floating OWCs

- Floating OWCs must be modeled such that BOTH the wave activated water column and the wave activated structure are included

Coupled Water Column Resonance for Floating OWCs

- Floating OWCs are coupled between the wave activated column and the wave activated structure.
- This coupling results in a new resonance location for the coupled relative free surface in the device.

Optimal Resistive Control for Floating OWCs

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

Controls' Influence on Device Motion and Power

- Applying $R_{l,opt}$ to the floating OWC will preserve the natural resonances of the coupled system.
- This optimization clearly takes advantage of the coupling between the OWC and the structure.

Next Steps

Experimental Verification at HMRC

- **Determine realistic viscous damping values**
- **Verify the shape of the optimal R_{load} curve in monochromatic waves**
  - A linear scaled PTO has been designed
- **Verify the predicted power absorption of the device in Northern California**

Incorporation of Wells Turbine

- **ARL at PennState 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

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.

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Thank you.

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