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# BBDB OWC Reference Model 6

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Prepared for a webinar with HMRC and WavEC

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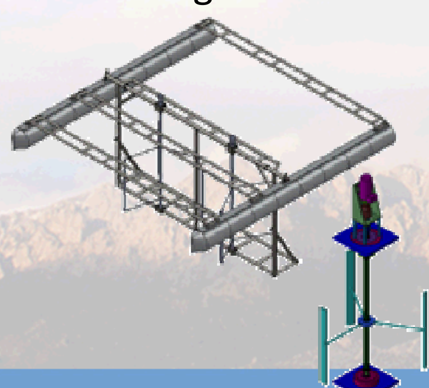
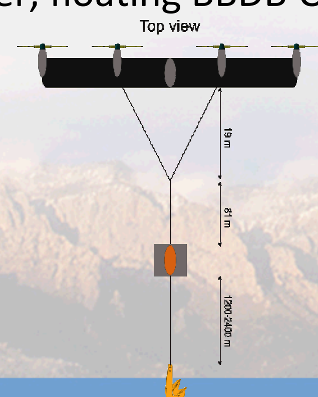
# Acknowledgements.

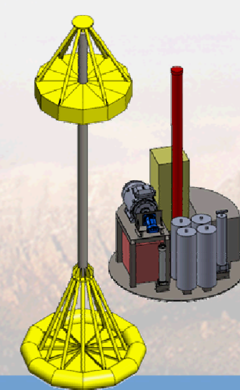
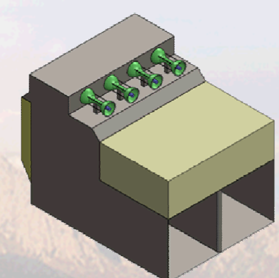
Many helpful conversations were had regarding the development of the frequency domain model. Conversations with Erick Johnson, Kelley Ruehl, John Berg, Dave Wilson, Adi Kurniawan, C.H. Lee, and Nick Newman all helped to shape my understanding of the system. The development of this model is based off of the work of Falnes and off of the paper 'Modelling and Simulation of a Floating Oscillating Water Column' by Kurniawan, A., Hals, J., and Moan, T.

Continued collaboration with ARL employees--Steve Willits, Bill Zierke, Jim Mikey, Mike Beam, and Arnie Fontaine--on the PTO design has shaped my understanding of the Wells Turbine.

# Reference Model Project

- **Project goal is to obtain baseline Cost Of Energy (COE) estimates for a variety of Marine Hydro-Kinetic (MHK) devices.**
- **Method to achieve cost of energy estimates 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 models.
  - Environmental considerations.
- **Designs are intended to be conservative and robust.**
- **Project initiated in May 2010.**
  - 3 current devices:  vertical axis tidal turbine, cross flow river turbine, open ocean current
  - 2 WEC devices:  floating dual absorber, floating BBDB OWC

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# Purpose of Webinar

- **RM 6: BBDB OWC.**
  - Initiated in October 2011.
  - First iteration on all design aspects complete: power performance (frequency domain), structural, anchor & mooring, PTO, and environmental.
  - A second design iteration is needed before COE will be computed.
- **Webinar will familiarize attendees with:**
  - Physical design
  - Theoretical framework being pursued
  - Power performance results
  - PTO decisions
- **Purpose of the webinar is to obtain feedback for the next design iteration.**
  - To obtain feedback from experts in the field regarding technical issues including:
    - Viscous damping
    - Average Annual Power
    - Capture length control methodologies
    - Wells Turbine integration
  - To gain experientially derived knowledge from experts who have gone through the design process and deployed systems.

# Floating OWC Operation

**General Velocity Potential** $\hat{\varphi} = \hat{\varphi}_o + \hat{\varphi}_s + \hat{\varphi}_r$

Excitation Potential

Excitation Potential: sum of the incident and scattered potentials $\hat{\varphi}_d = \hat{\varphi}_o + \hat{\varphi}_s$

Radiation Potentials

- Rigid body moving in water $\hat{\varphi}_{r_{RigidBody}} = \sum_{i,j} \varphi_{ij} \hat{u}_{ij}$
- Oscillating air pressure at a contained interface $\hat{\varphi}_{r_{OWC}} = \sum_{k} \varphi_k \hat{p}_k$

**Velocity Potential of a moving body with an internal free surface**

$$\hat{\varphi} = \hat{\varphi}_o + \hat{\varphi}_d + \sum_{i,j} \varphi_{ij} \hat{u}_{ij} + \sum_{k} \varphi_k \hat{p}_k$$

- **3 ways to solve this problem[1,2,3]:**
  - Solve for the OWC velocity potential explicitly
  - Approximate the internal surface using generalized modes
  - Use reciprocity relations to obtain all necessary information

[1] "Analysis of oscillating-water-column device using a panel method." Lee, C.H., and Nielson, F.G.. In Proceedings of the 11th International Workshop on Water waves and Floating Bodies. 1996. pp. 1-4.

[2] "Wave interactions with an oscillating water column." Lee, C.H., Newman, J.N. and Nielsen, F.G. In Proceedings of the 6th International Offshore and Polar engineering Conference. 1996. pp. 82-90

[3] "Modelling and Simulation of a Floating Oscillating Water Column." Kurniawan, A., Hals, J., Moan, T. Proceedings of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering. 2011. OMAE2011-49263.

# Floating OWC Hydrodynamic Equations

- **The state of system must be specified by two parameters**
  - The velocity of the moving body
  - The pressure in the air chamber

$$\hat{F}_{t,j} = f_j A - \sum_{j'} Z_{jj'} \hat{u}_{j'} - H_j^p \hat{p}$$

**Total Force =**

Excitation Force from $\hat{\varphi}_o + \hat{\varphi}_d$; body held fixed ( $\hat{u} = 0$ )

Radiated Force from $\sum_{i,j} \varphi_{ij} \hat{u}_{ij}$; body oscillated and $\hat{p} = 0$

Coupling Force. Oscillating air pressures inducing body movements.

$$\hat{Q}_t = qA - Y\hat{p} - \sum_j H_j^u \hat{u}_j$$

**Total Volume Flow=**

Excitation Volume Flow; internal surface held fixed ( $\hat{p} = 0$ )

Radiated Volume Flow; internal surface oscillated and $\hat{u} = 0$

Coupling Force. Body movements inducing oscillating air pressures.

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- Formalism developed in: Ocean Waves and Oscillating Systems. J. Falnes. 2002. Cambridge University Press. Chapter 7

# Floating OWC
# Hydrodynamic Terms: Free Surface

$$q = \frac{1}{A}\iint_{S_k} \frac{\partial \varphi_d}{\partial z} dS$$

The integral of the "diffraction velocity" of the free surface in the heave direction over the free surface

$$Y = -\iint_{S_k} \frac{\partial \varphi_k}{\partial z} dS = G + iB$$

The integral of the "radiation velocity" of the free surface in the heave direction over the free surface. Do not have radiation potential of free surface, hence must find G & B independently.

$$G = \frac{2\omega}{4\pi\rho g v_g} \int_0^\pi |q(\beta)|^2 d\beta$$

'Radiation Conductance.' Related to the excitation volume flow through reciprocity.

$$B(\omega) = -\frac{2\omega}{\pi} \int_0^\infty \frac{G(y)}{\omega^2 - y^2} dy$$

'Radiation Susceptance.' Related to the radiation conductance through Kramers-Kronig Relationship.

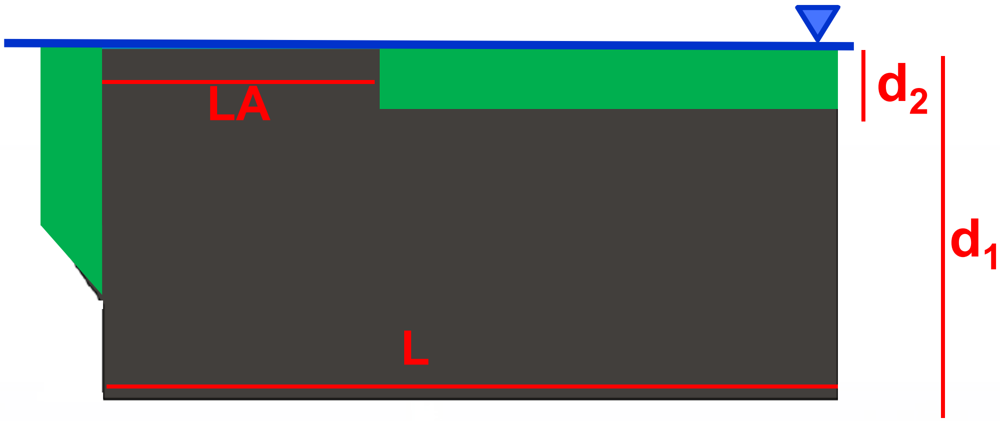
$$H_j^u = -\iint_{S_k} \frac{\partial \varphi_j}{\partial z} dS = C + iJ$$

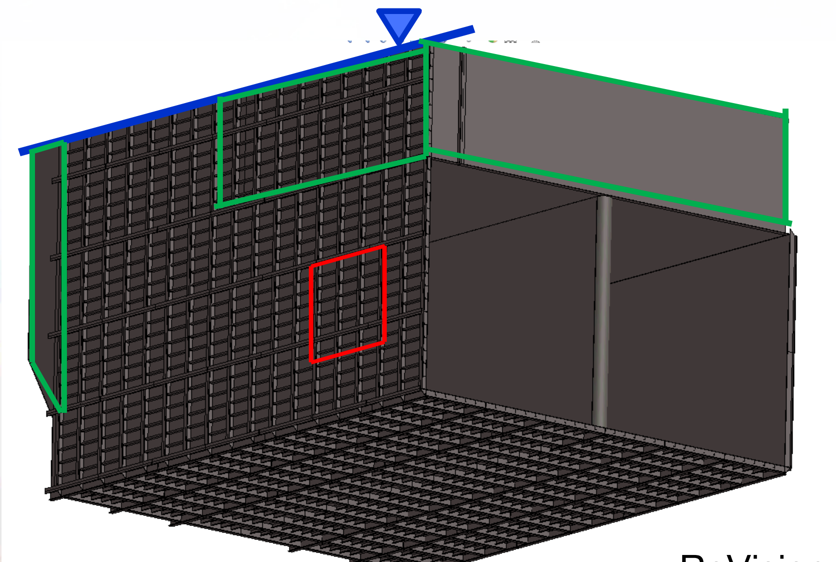
The integral of the "radiation velocity" of the *body* in heave direction over the free surface

- Formalism developed in: Ocean Waves and Oscillating Systems. J. Falnes. 2002. Cambridge University Press. Chapter 7

# BBDB Baseline Design

- Profile of design set from literature search:
  - $\lambda/L=4$[1] $\longrightarrow$ L=35[m]
    - 9[sec] $\longrightarrow \lambda=140$[m]
  - L/LA=2.0[2] $\longrightarrow$ 17.5[m]
  - $d_1/LA=1.0$[2] $\longrightarrow$ 17.5[m]
  - $d_2/LA=0.2$[2] $\longrightarrow$ 3.5[m]
  - L/B=1.3[1,3] $\longrightarrow$ 27[m]
    - Selected relationship based on most used in literature
- Structural design based on hydrostatic 23.5[m] submersion load




[1]An Experimental Study on Generating Efficiency of a Wave Energy Converter “Backward Bent Duct Buoy.” Imai, Y., Toyota, K., Nagata, S., Setoguchi, T., Takao, M. EWTEC 2011.

[2]Numerical Investigation of 2D Optimal Profile of Backward-Bent Duct Type Wave Energy Converter. Suzuki, M., Kuboki, T., Nagata, S., Setoguchi, T. Journal of Offshore Mechanics and Arctic Engineering. V133, 4. 2011.

[3]Numerical study on the reverse drift force of floating BBDB wave energy absorbers. Hong, DC, Hong, SY, Hong, SW. Ocean Engineering. V31. 10. 1257-1294. 2004.

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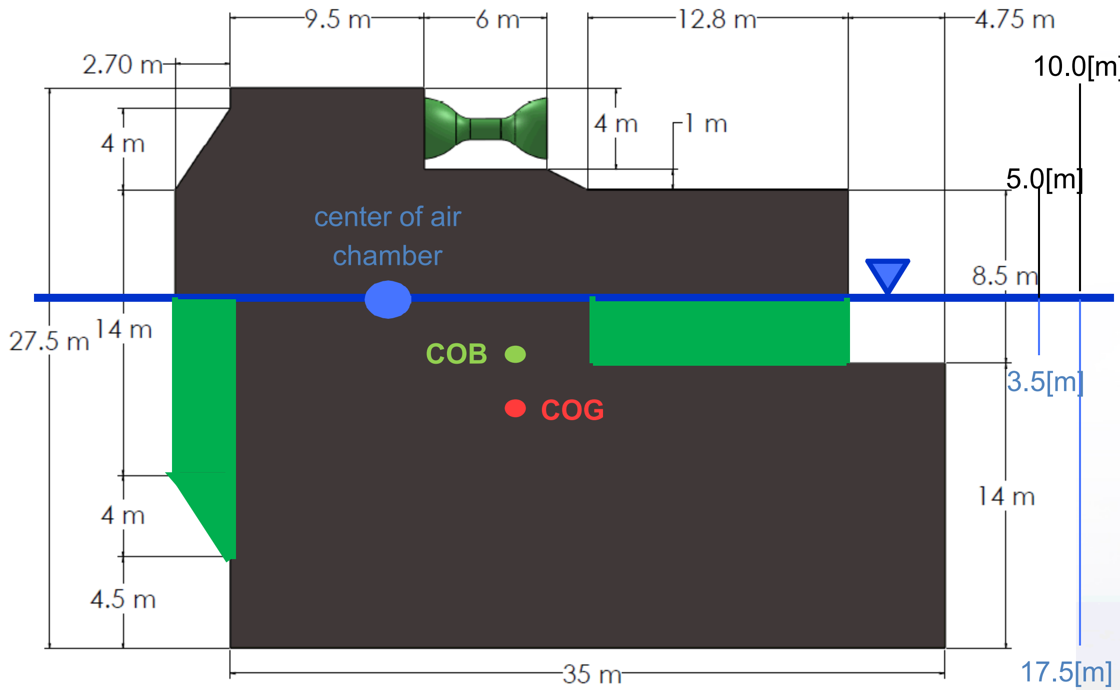
# BBDB Baseline Design

## *Predicted Uncoupled Resonances*

| | Hydrodynamic Model | | |
|---|---|---|---|
| Mass [kg] | 2051541 | | |
| COG (x,y,z) | 5.09 | 0.00 | -4.74 |
| COB (x,y,z) | 5.09 | 0.00 | -3.27 |
| Radius of Gyration [m] x | 12.8 | 0.0 | 0.0 |
| Radius of Gyration [m] y | 0.0 | 14.6 | 0.0 |
| Radius of Gyration [m] z | 0.0 | 0.0 | 14.8 |

COG & COB given relative to the center of the air chamber.




Directly set by device envelope

Altered by COG/COB locations and the device envelope

ReVision

| Uncoupled Structure Resonances | ω [rad/sec] | T [sec] |
|---|---|---|
| Heave Resonance | 0.42 | 15.11 |
| Roll Resonance | 0.50 | 12.49 |
| Pitch Resonance | 0.55 | 11.38 |

| Uncoupled OWC Resonances | ω [rad/sec] | T [sec] |
|---|---|---|
| Piston Resonance | 0.53 | 11.87 |
| Slosh Resonance | 1.33 | 4.74 |

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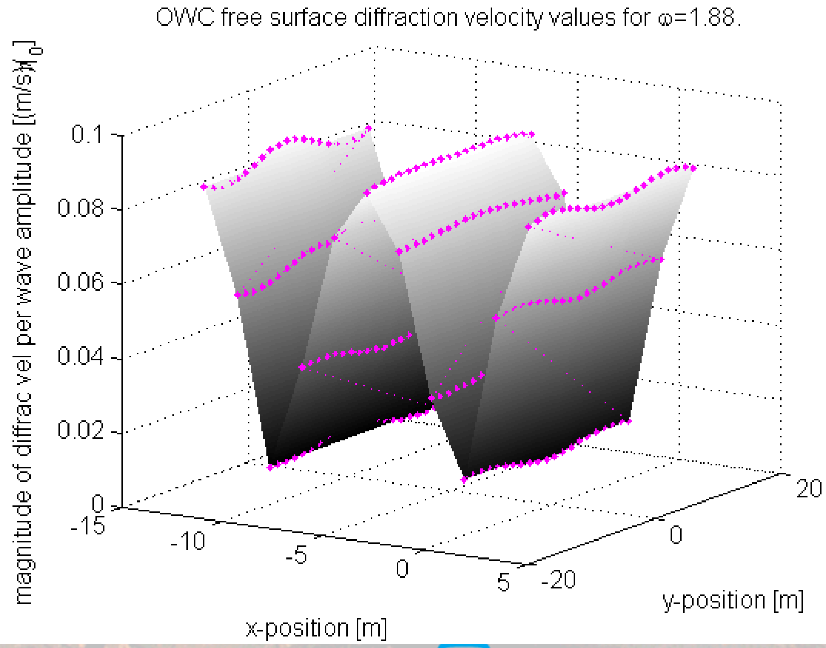
# BBDB Modeling in WAMIT.

- **Geometry:**
  - Use higher order geometry (B-spline representation)
  - Use cosine spacing to obtain higher panel density near edges.
  - Use dipole surfaces to represent body of device since it is so thin in comparison to every other dimension.
  - Define the interior of solid surfaces with panels to facilitate irregular frequency removal at the free surface interfaces.
  - Input the matrix of body inertia coefficients using alternative form 2 of the force input files.
- **Degrees of Freedom:**
  - Evaluate all degrees of freedom
- **Internal Free Surface Representation**
  - Use an array of field points (231) to discretize the free surface of the OWC to obtain position and velocity distributions for each frequency in the vertical, z, direction.
- **"Environment"**
  - Evaluate 250 equally spaced frequencies spanning 0.1 to 2.5[rad/sec]
  - Evaluate 17 distinct headings spanning 0 to π

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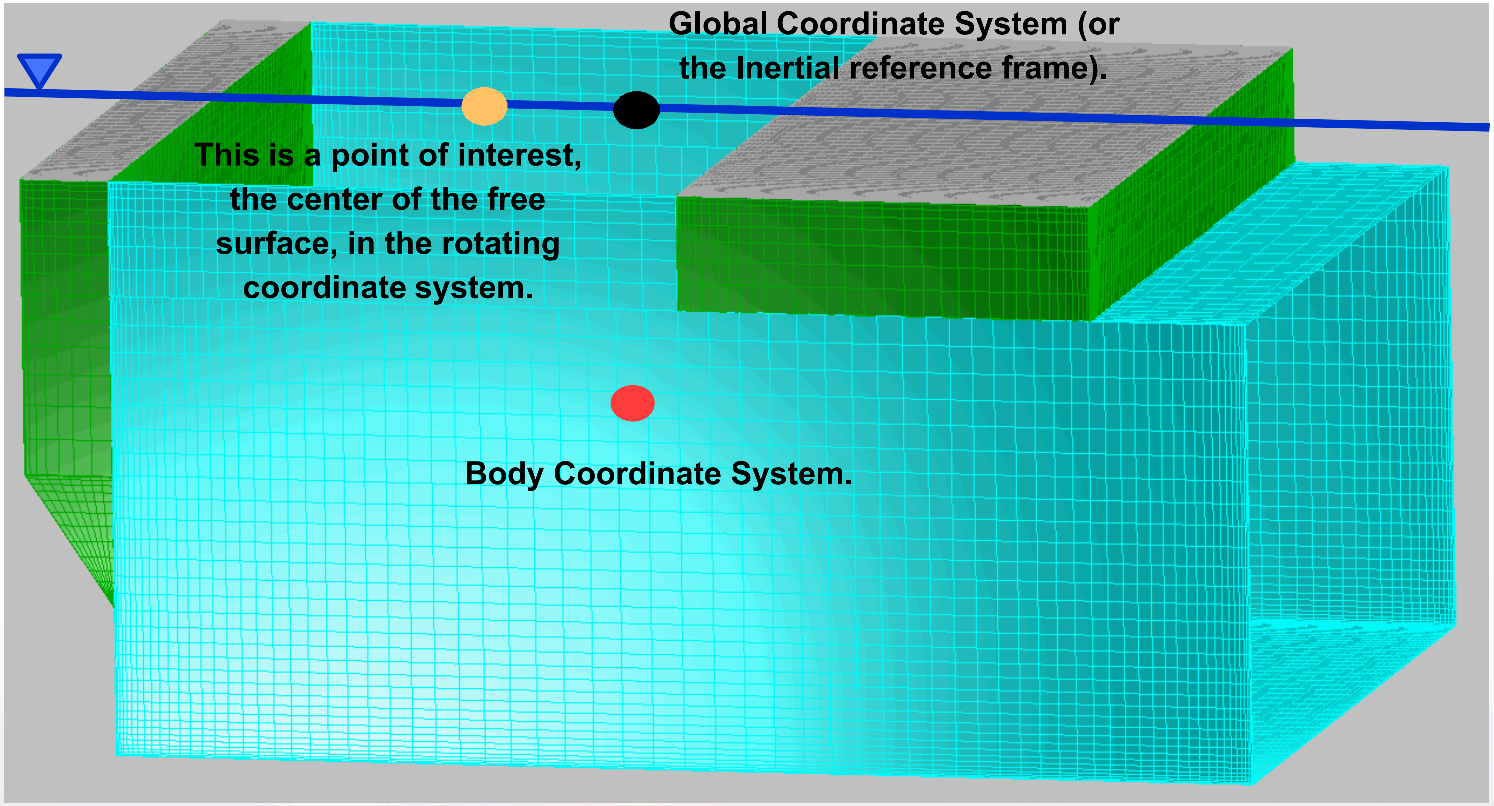
# BBDB Modeling in WAMIT.




- **Coordinate system definitions:**
  - Inertial reference frame=(0,0,0): This is the fixed global coordinate system and defines phases.
  - Body reference frame=(0,0,-$z_{cog}$): This is the system that forces and motions are defined relative to.
  - Point of interest=(-$X_{shift}$,0,0): This a point on the moving body located away from COG.
- **Transformation Vector to evaluate the Point in the inertial reference frame:**

$$u_{z,FreeSurfaceCenter} = [0 \quad 0 \quad 1 \quad 0 \quad -(-X_{shift}) \quad 0]^T$$

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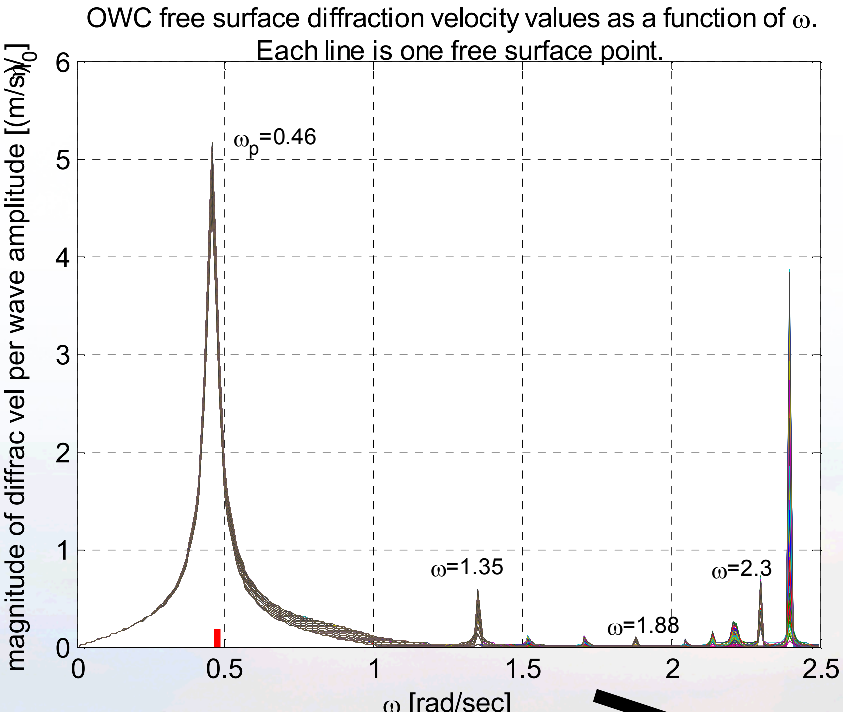
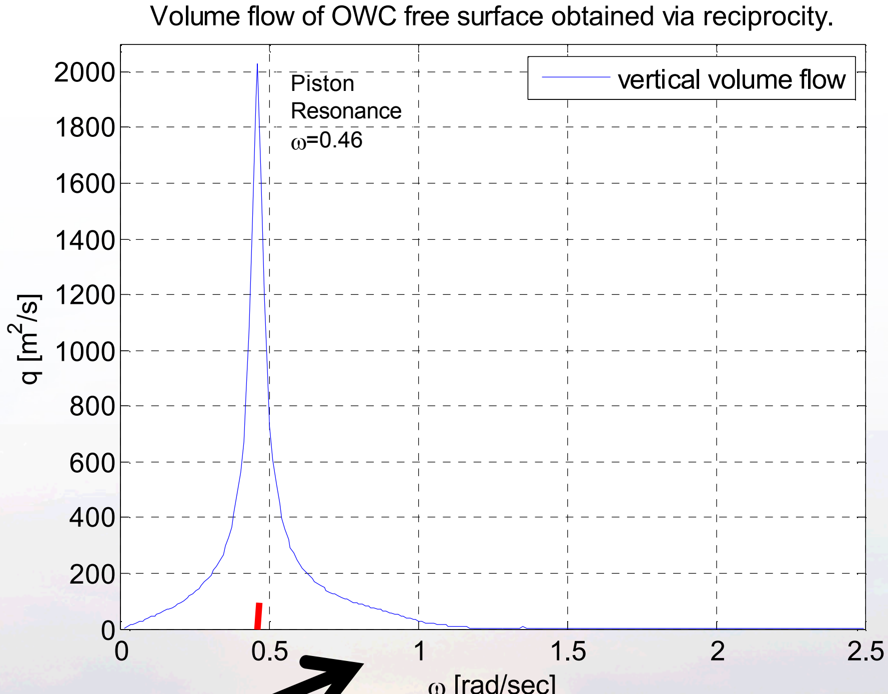
# Hydrodynamic Results
# Free Surface

## Diffraction Velocity




$$\frac{1}{A}\frac{\partial \varphi_D}{\partial z} = \frac{ig}{\omega L}(\bar{v}_{D,z_{complex}})$$

## Excitation Volume Flow




$$q = \frac{1}{A}\iint_{S_k} \frac{\partial \varphi_d}{\partial z} dS$$

Uncoupled Resonance Predictions: piston=0.53

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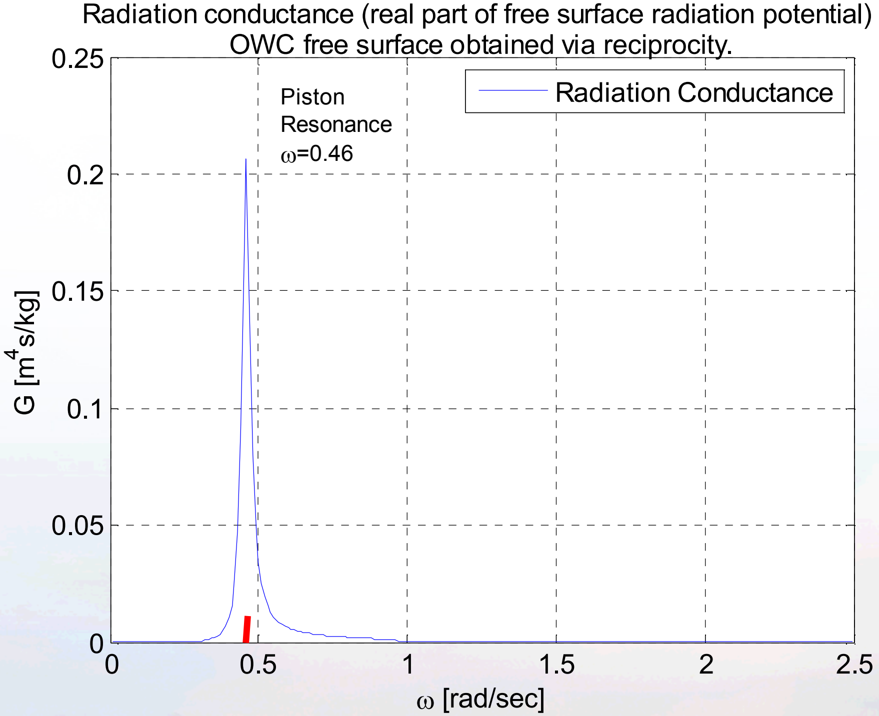
# Hydrodynamic Results
# Free Surface

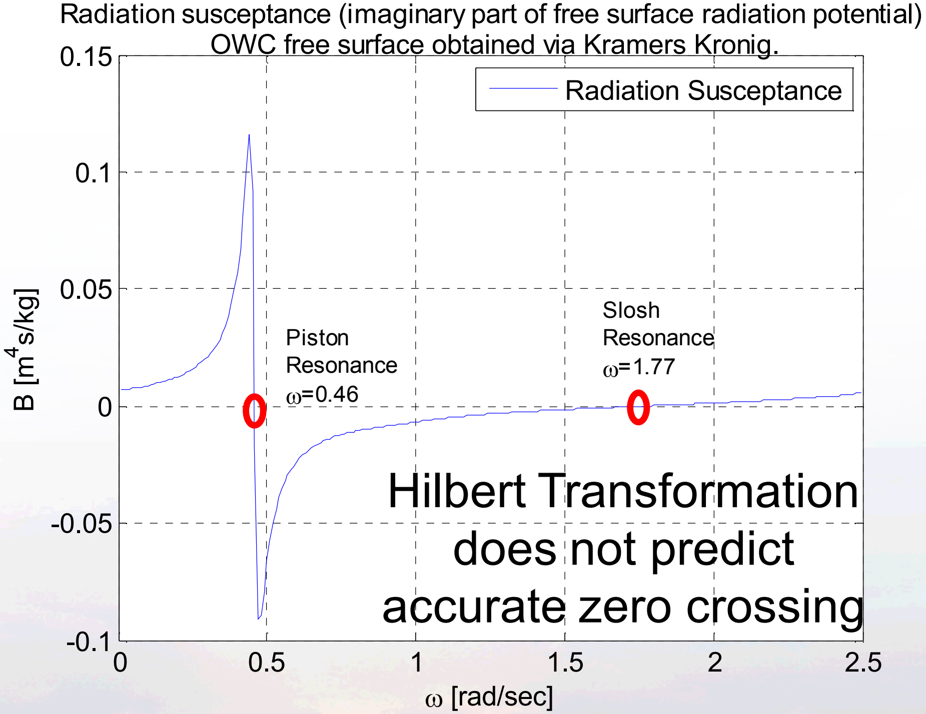
$$Y = -\iint_{S_k} \frac{\partial \varphi_k}{\partial z} dS = G + iB$$

## Radiation Conductance, $G$




$$G = \frac{2\omega}{4\pi\rho g v_g} \int_0^{\pi} |q(\beta)|^2 d\beta$$

## Radiation Susceptance, $B$

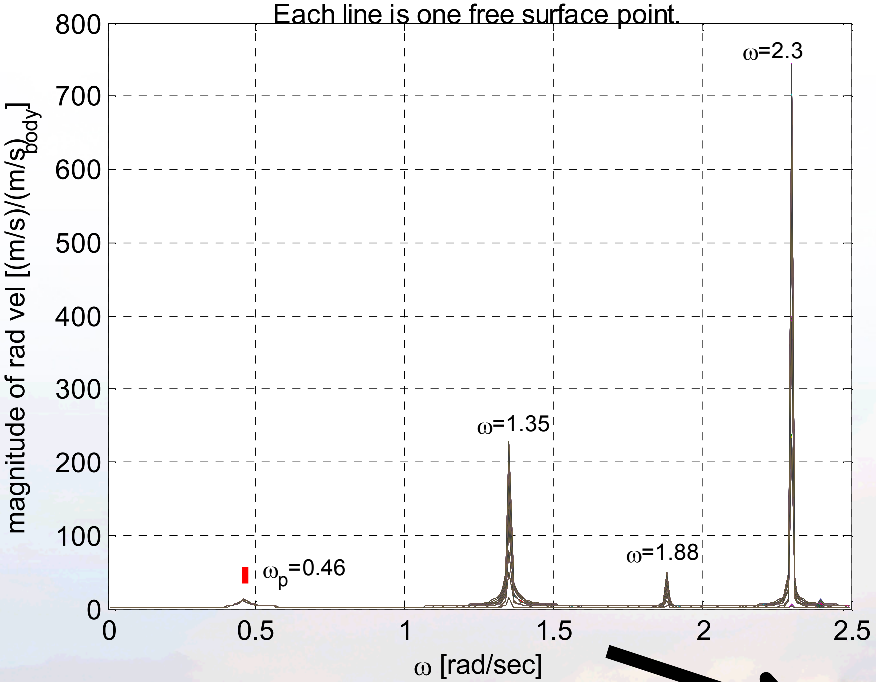



$$B(\omega) = -\frac{2\omega}{\pi} \int_0^{\infty} \frac{G(y)}{\omega^2 - y^2} dy$$

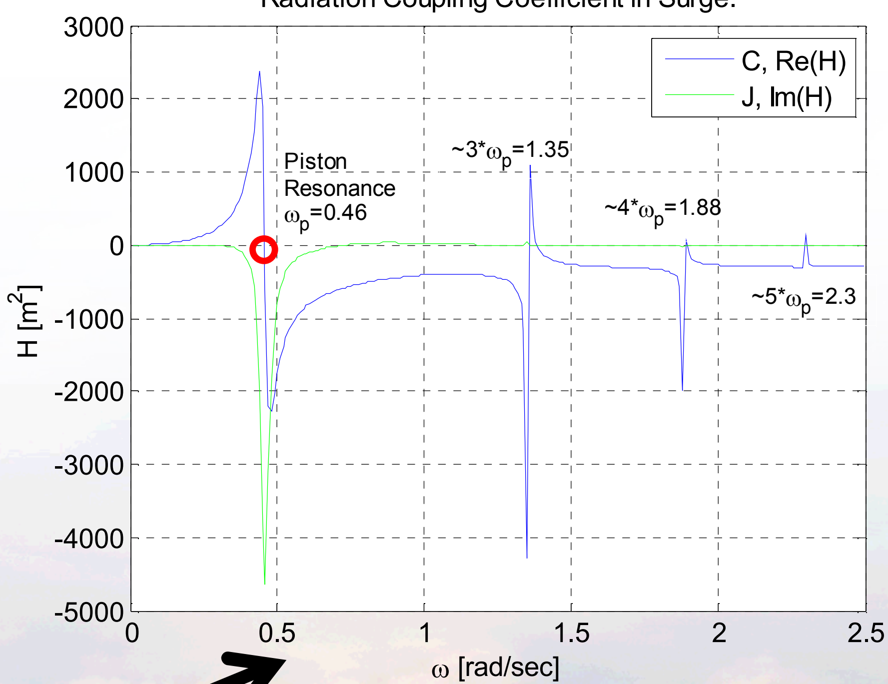
Uncoupled Resonance Predictions: piston=0.53, slosh=1.33

# Hydrodynamic Results
# Free Surface

## Radiation Velocity of Structure




## Surge Coupling Term, $H_1$




★ $$\frac{1}{v_j}\frac{\partial \varphi_j}{\partial z} = \frac{g}{\omega^2 L} L^n(\bar{v}_{R,z_{complex}})$$

$$H_j^u = -\iint_{S_k} \frac{1}{v_j}\frac{\partial \varphi_j}{\partial z} dS = C + iJ$$

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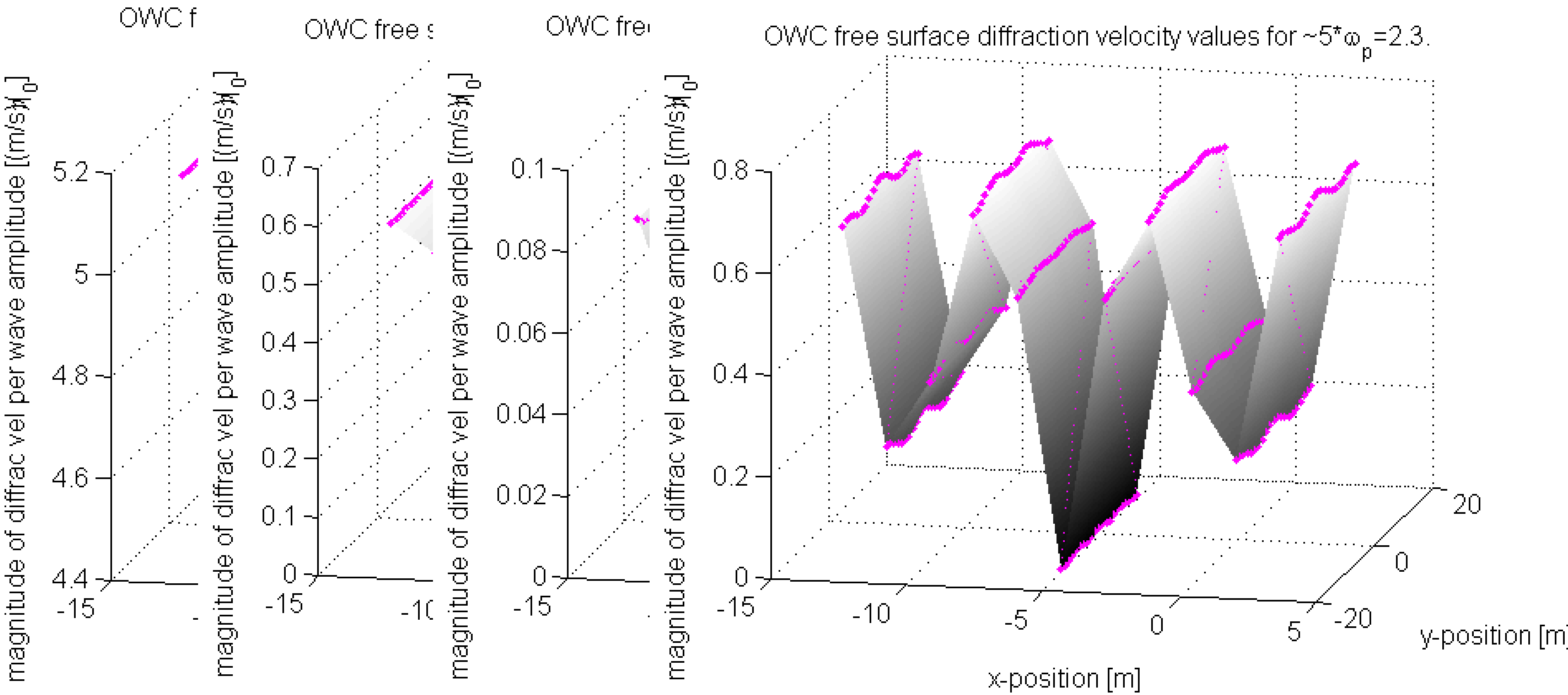
★ This is the correct dimensionalization—it was incorrect in User Manual 6 from WAMIT

# Hydrodynamic Results
# Free Surface



# Floating OWC Governing Equations

$$F_{total} = F_{hydrodynamic} + F_{hydrostatic} + F_{ViscousDamping} + F_{mooring}$$

$$i\omega m_{ij} u_j = \left(f_j A - (b_{ij} + i\omega a_{ij}) u_j - (-H_j^u) p\right) + \left(\frac{i}{\omega} C_{ij} u_j\right) - \left(b_{vis,ij} u_j\right) + \left(\frac{i}{\omega} K_{ij} u_j\right)$$

Traditional '**ma**'

Linearized viscous damping term.

$$Q_{total,compressible} = Q_{hydrodynamic} + Q_{ViscousDamping} + Q_{PTO}$$

$$\left(i \frac{\omega \forall_o}{\gamma p_{atm}}\right) p = \left(qA - (G + iB) p - H_j^u u_j\right) - \left(\frac{1}{R_{vis}}\right) p - \left(\frac{1}{R_{load}}\right) p$$

Linearized air compressibility

Linearized viscous damping term.

Linear PTO mechanism

- Formalism developed in: Ocean Waves and Oscillating Systems. J. Falnes. 2002. Cambridge University Press. Chapter 7

# Viscous Damping Factors

- Without experimental data the viscous affects must be approximated from system based parameters.
- Purpose of damping factors is to reduce the coupled RAO magnitudes to ~2 at their respective resonance locations.

## Structure

- Factor approximated as a constant across all frequencies. In addition, only diagonal elements are used.
  - One approach is to use the critical damping as the basis

$$B_{ij,crit} = 2\sqrt{M_{tot} C_{tot}} \qquad b_{vis,jj} = \%B_{jj,crit}$$

  - Could equivalently use the maximum radiation damping terms as the basis

$$b_{vis,jj} = \%b_{jj,\max}$$

## OWC

- Factor approximated as a constant across all frequencies.
- The Free Surface Elevation RAO that should be reduced to ~2 can be calculated from: $\xi_{FSE} = \frac{\mu_{FSE}}{\eta_o} = \frac{Q}{i\omega \vee_k}$
  - mimic the structural approximation and use the equivalent maximum radiation conductance term

$$\frac{1}{R_{vis}} = G_{vis} = \%G_{\max}$$

# Floating OWC Governing Equations: Matrix Form

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

- **Solve linear system of equations above to obtain the coupled structure response u and the coupled oscillating pressure response** p.

**Effective Radiation Potentials**

$$\mathbf{H}_i = H_j^u + [0 \quad 0 \quad 1 \quad 0 \quad -x_{cog} \quad 0]^T \vee_k$$

Force-velocity to pressure-flow

$$Z_i = b_{ij} + b_{vis,ij} + i\omega\left( m_{ij} + a_{ij} - \frac{(C_{ij} + K_{ij})}{\omega^2} \right)$$

The effective structural radiation term includes the damping losses and the hydrostatic restoring forces.

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

The effective free surface radiation term includes the damping losses and the linearized air compressibility

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Formalism developed in: Ocean Waves and Oscillating Systems. J. Falnes. 2002. Cambridge University Press. Chapter 7

# Power Production & Optimal Slow Tuning Parameter

- **The power produced by the turbine will be the product of the pressure in the chamber and the flow through the turbine.**

$$\mathrm{P}(t) = p(t)Q(t)$$

  - The flow through the turbine is given by: $Q = qA - Y_i p - H_j^u u_j = \frac{1}{R_{load}} p$

- **Combining and averaging for regular waves, the power becomes:**

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

- **An optimal power value can be found for each frequency by choosing the most appropriate load on the turbine according to the following relationship.**

Solve $\dfrac{\partial \langle \mathrm{P} \rangle}{\partial \, {}^{1}/_{R_{load}}} = 0$ to find $R_{load,opt}(\omega)$

- Formalism developed in: Ocean Waves and Oscillating Systems. J. Falnes. 2002. Cambridge University Press. Chapter 7

# *Optimal $R_{load}$ dependent upon phase of system*

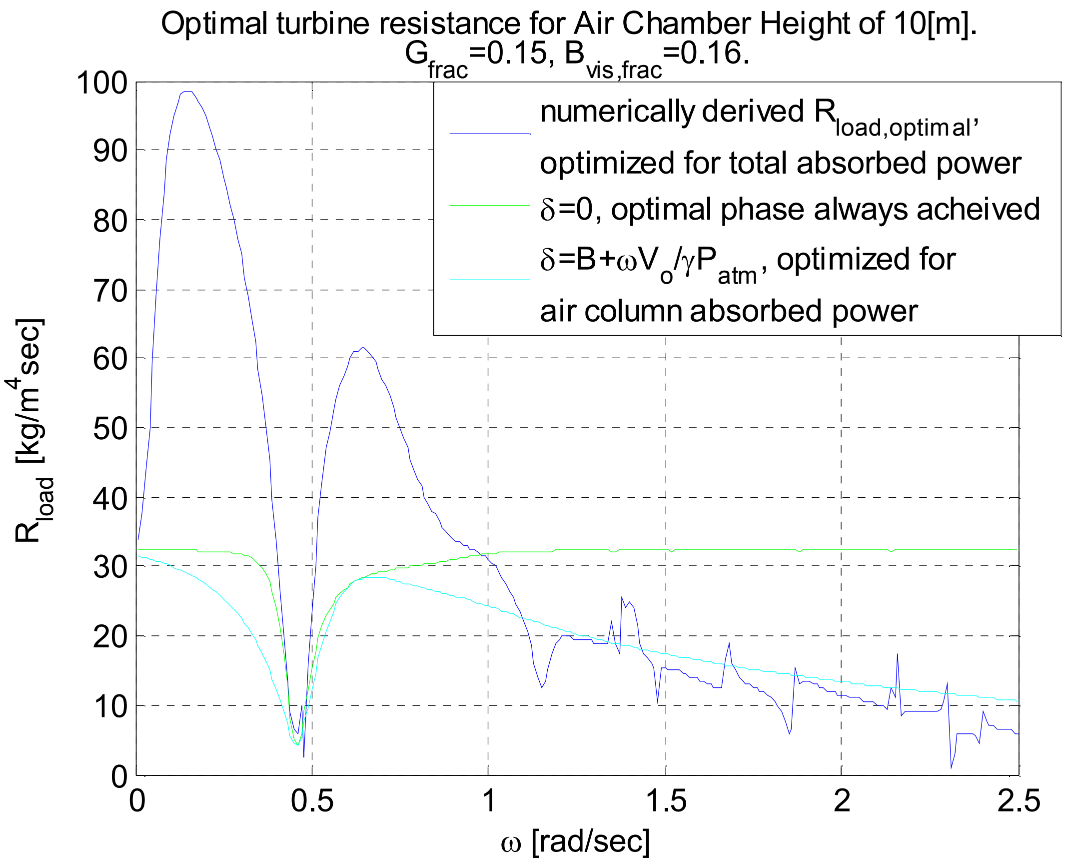
- Looking only at power absorbed from the air column, see $R_{load,opt}$ is given by:

$$R_{load,opt} = \frac{1}{\sqrt{\alpha^2 + \delta^2}} \qquad \alpha = G + G_{vis} \qquad \delta = B + \frac{\omega \forall_o}{\gamma p_{atm}}$$

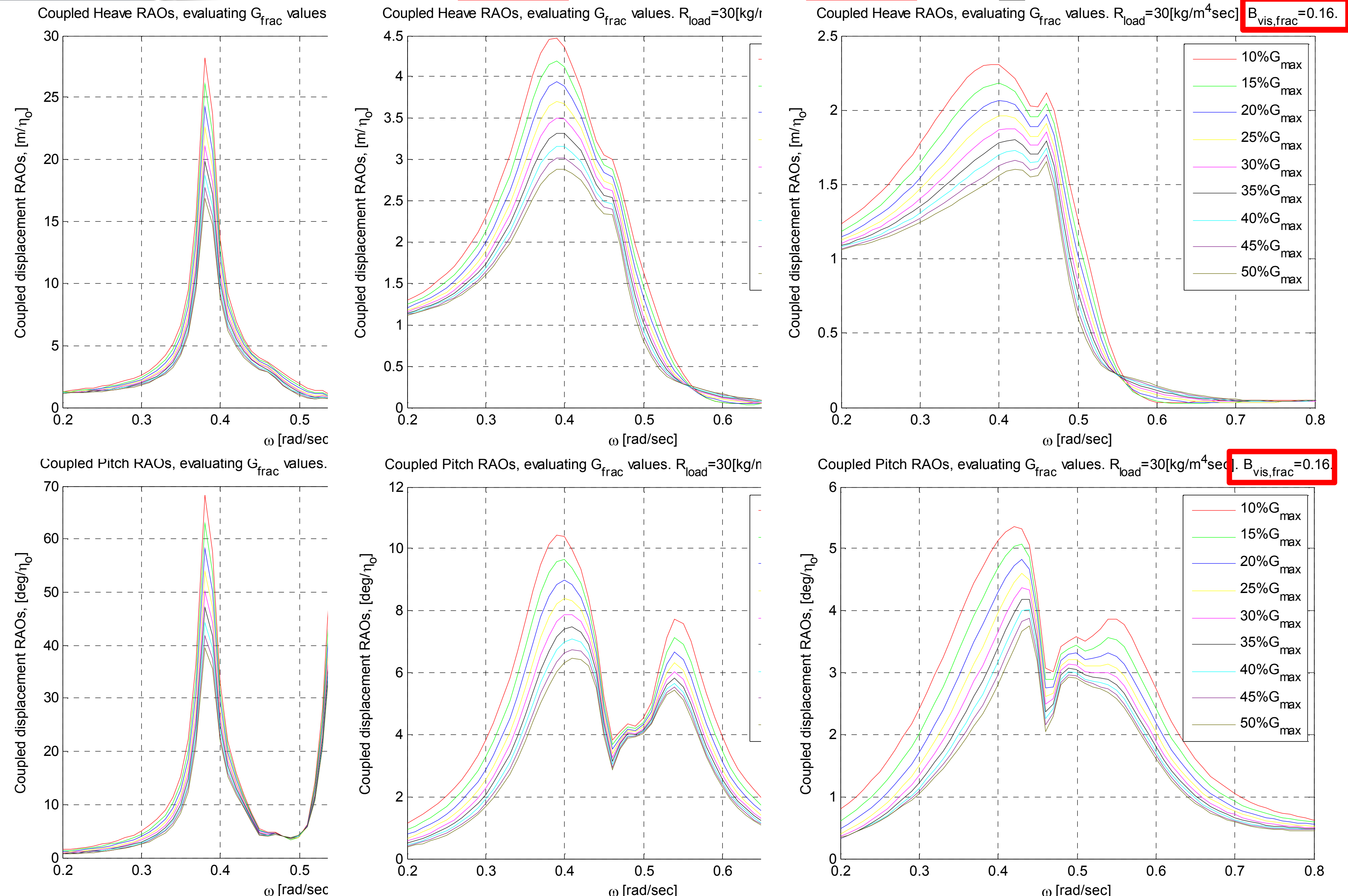
- Green curve = idealization; always have phase match
- Cyan curve= only looking at power absorbed from air column.
- Blue curve= numerically derived, looking at total absorbed power (structure & free surface)

$R_{load}$~40 for $\omega_{33}$

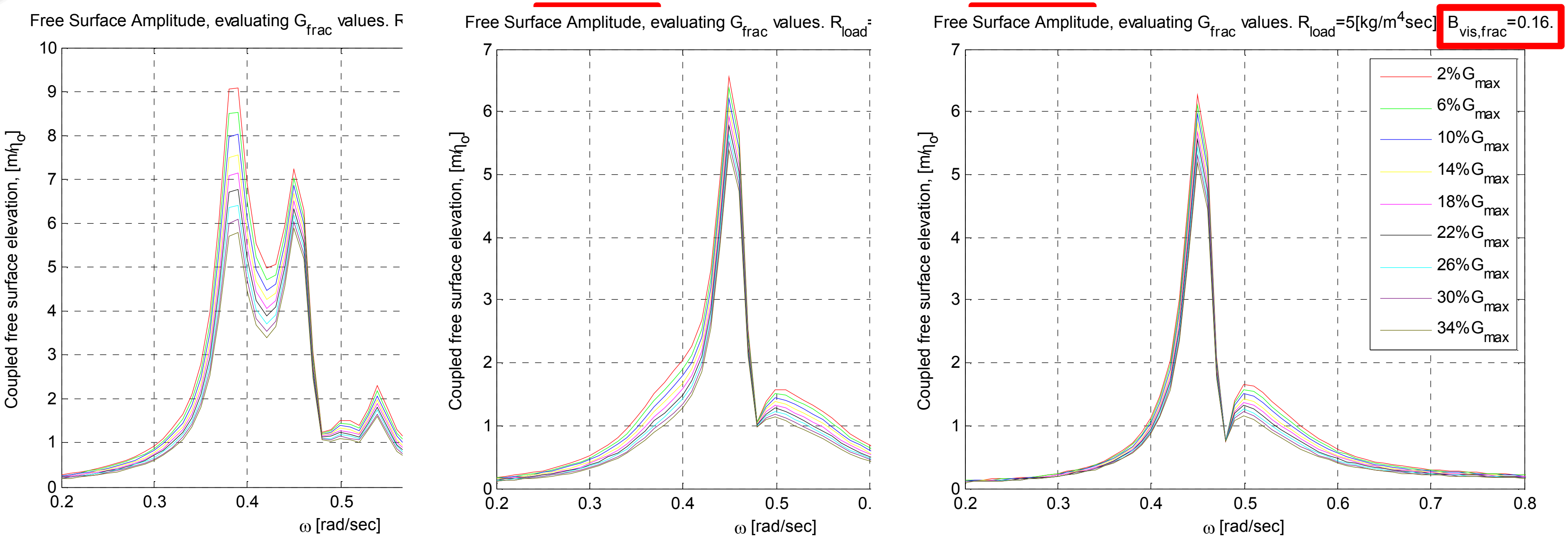
$R_{load}$~6 for $\omega_{piston}$



# BBDB Viscous Damping Selection



# OWC Viscous Damping Selection




- The largest influence on the FSE RAO is the structural viscous damping.
- Moving from 2%-34% of $G_{max}$ only changes the FSE RAO from ~6.2 to ~5.2.
- If move to ~300% of $G_{max}$, can get FSE RAO to reduce down to ~2.
- **Ideas on why this method is not working?**
  - **Is my calculation of FSE RAO correct?**
  - **Is my hesitancy to accept 300% unjustified?**

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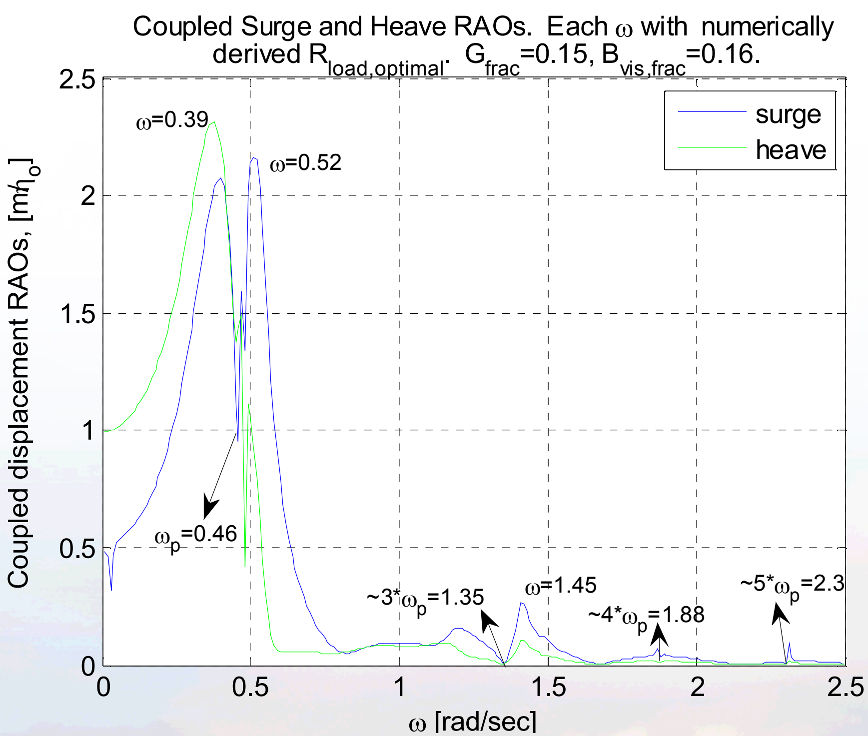
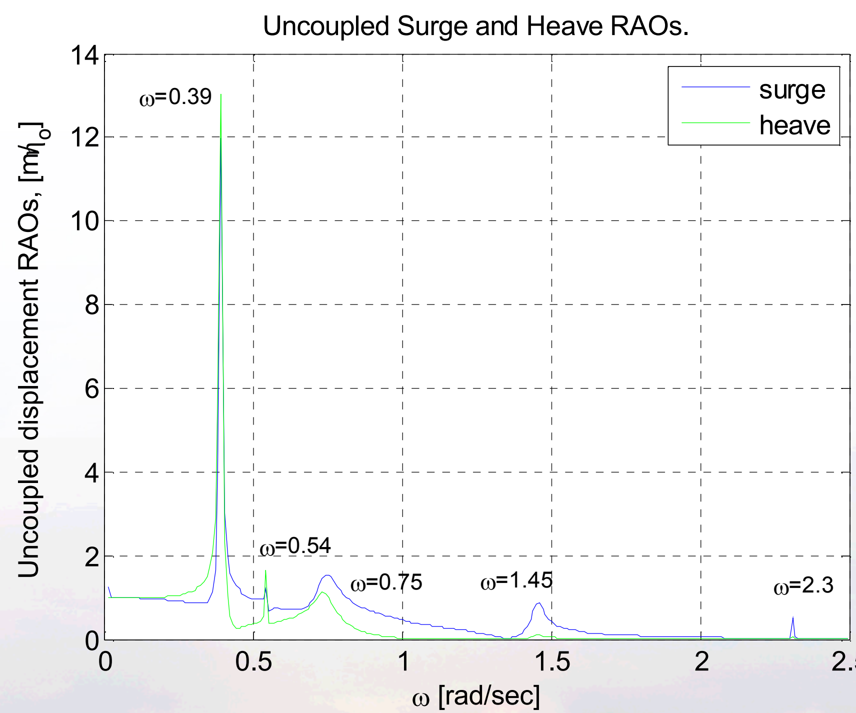
# Frequency Domain Model Results

## Coupled Heave & Surge RAOs

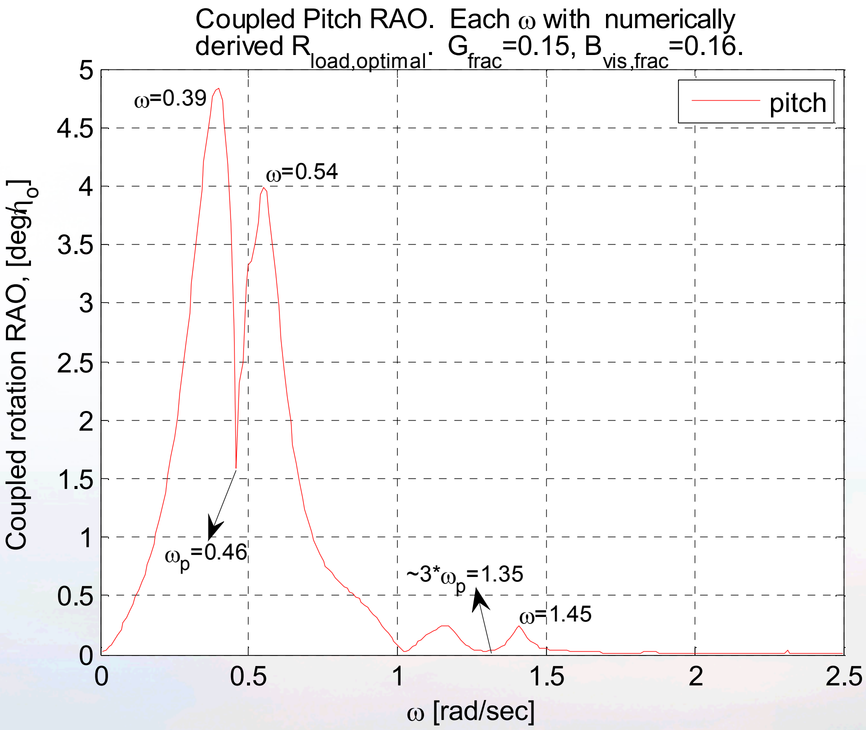



## Uncoupled Heave & Surge RAO

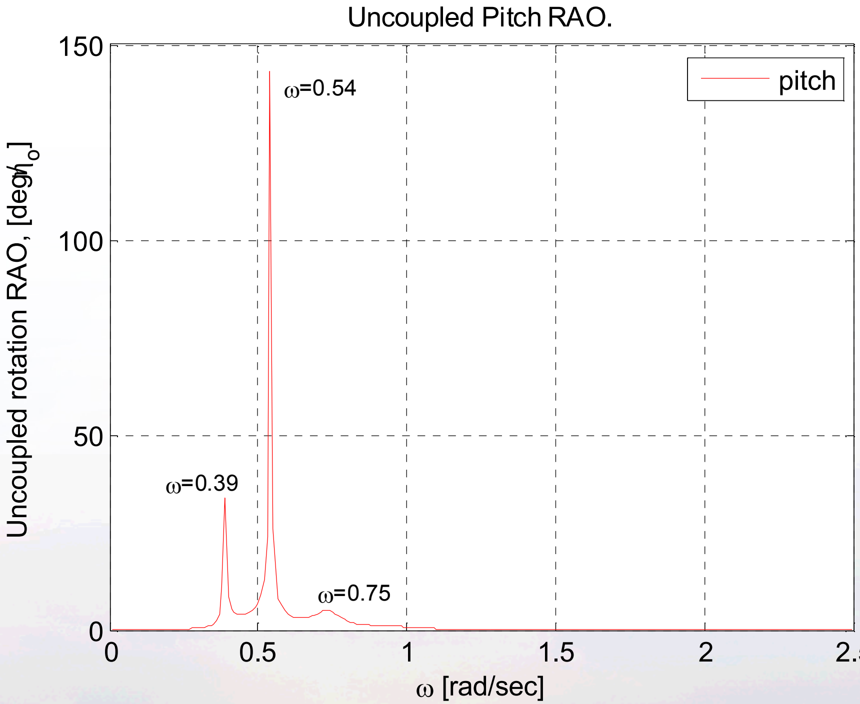


# Frequency Domain Model Results

## Coupled Pitch RAOs

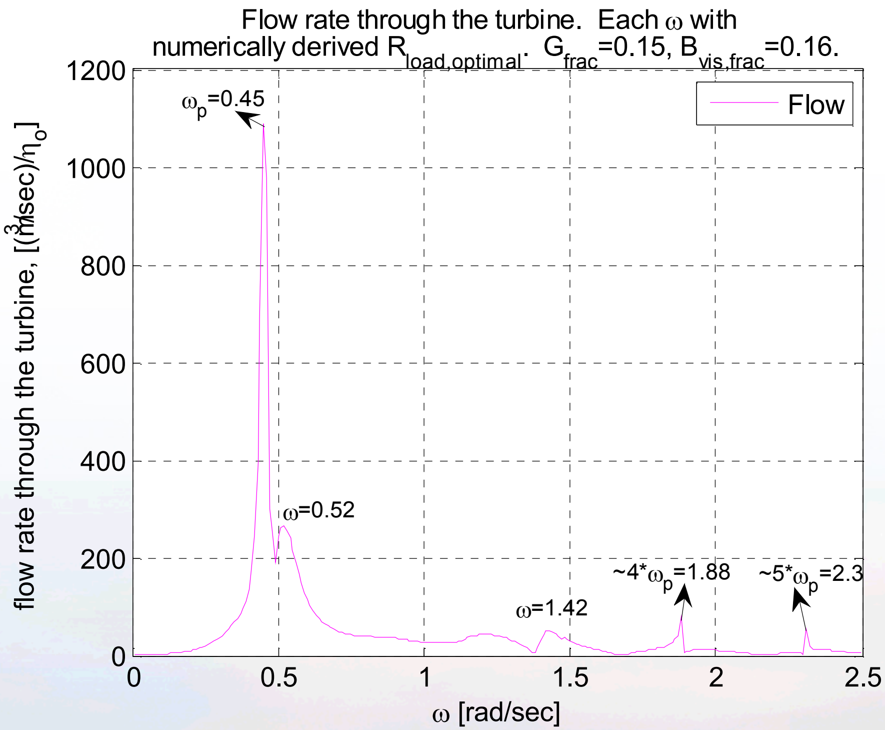



## Uncoupled Pitch RAO

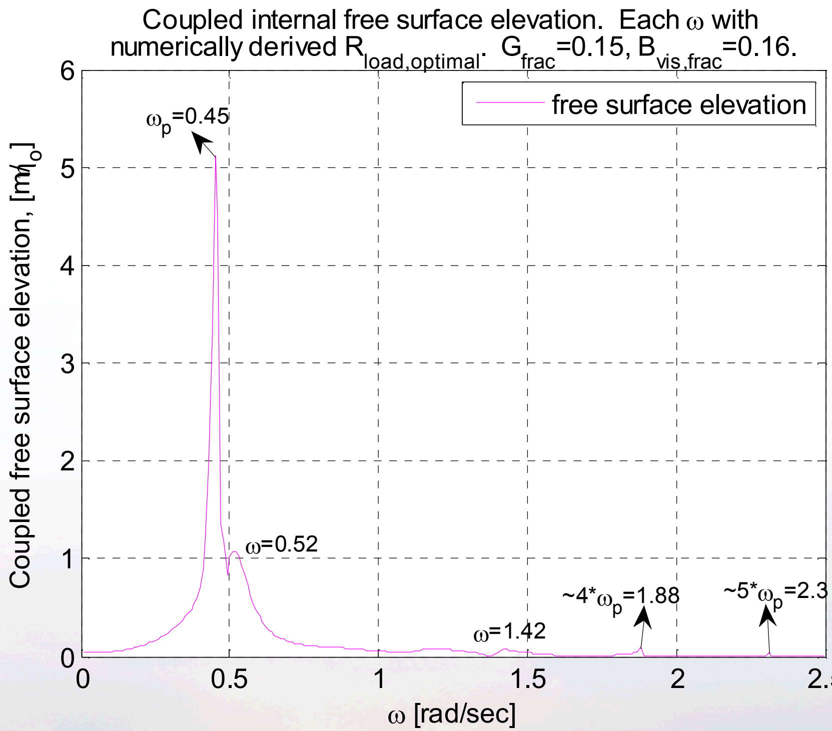


# Frequency Domain Model Results

## Coupled Flow Rate in the Chamber




## Coupled Free Surface Elevation RAO

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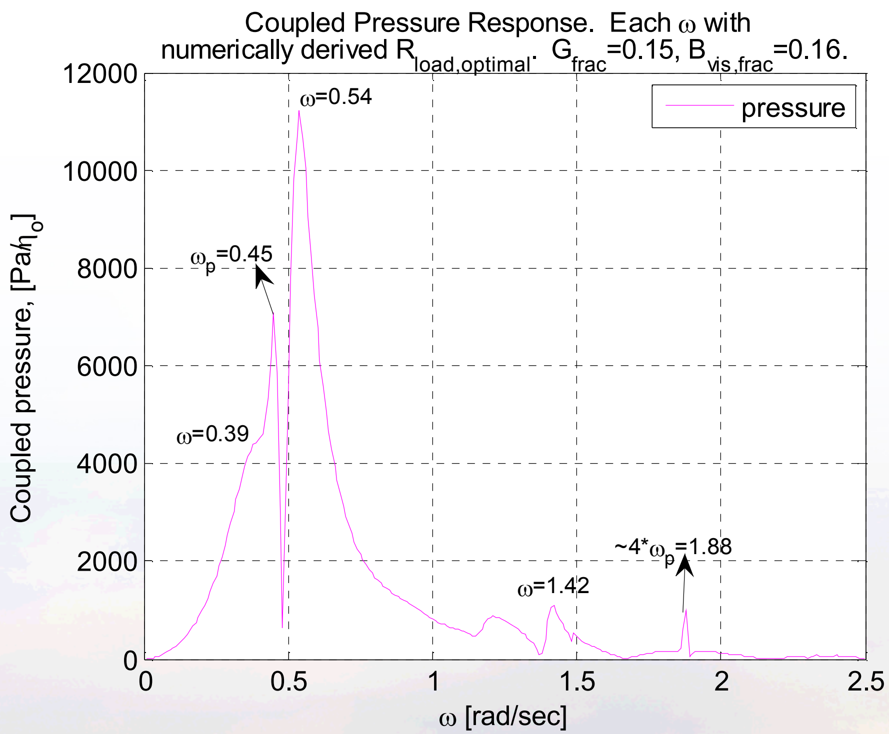
# Frequency Domain Model Results

## Coupled Pressure in the Chamber



# Create Performance Model Frequency Domain

**Determine average power for each spectrum in the JPD**

$$\langle \mathrm{P} \rangle = \frac{1}{R_{loadOpt@T_p}} \int_0^{\infty} |p|^2 S(\omega) d\omega$$

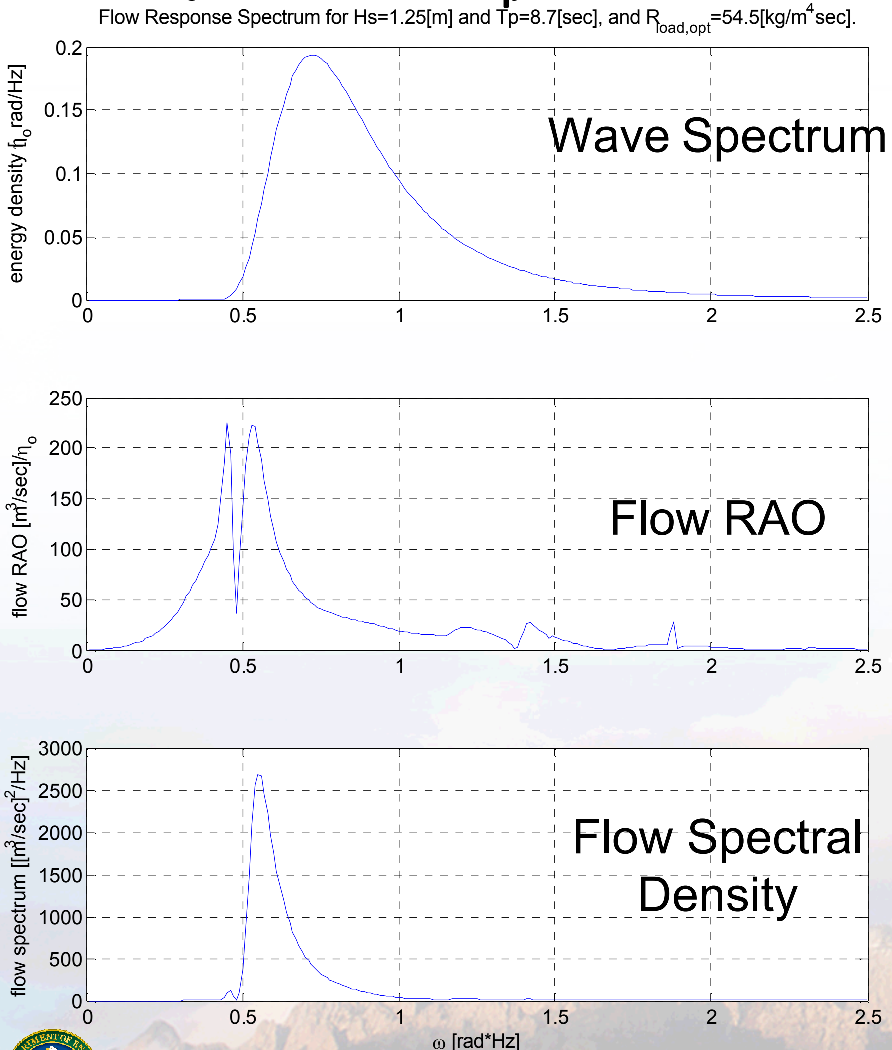
**Determine RMS pressure and flow rates to size the PTO for each spectrum in the JPD**

$$p_{RMS} = \sqrt{\int_0^{\infty} |p|^2 S(\omega) d\omega} \qquad Q_{RMS} = \sqrt{\int_0^{\infty} |Q|^2 S(\omega) d\omega}$$

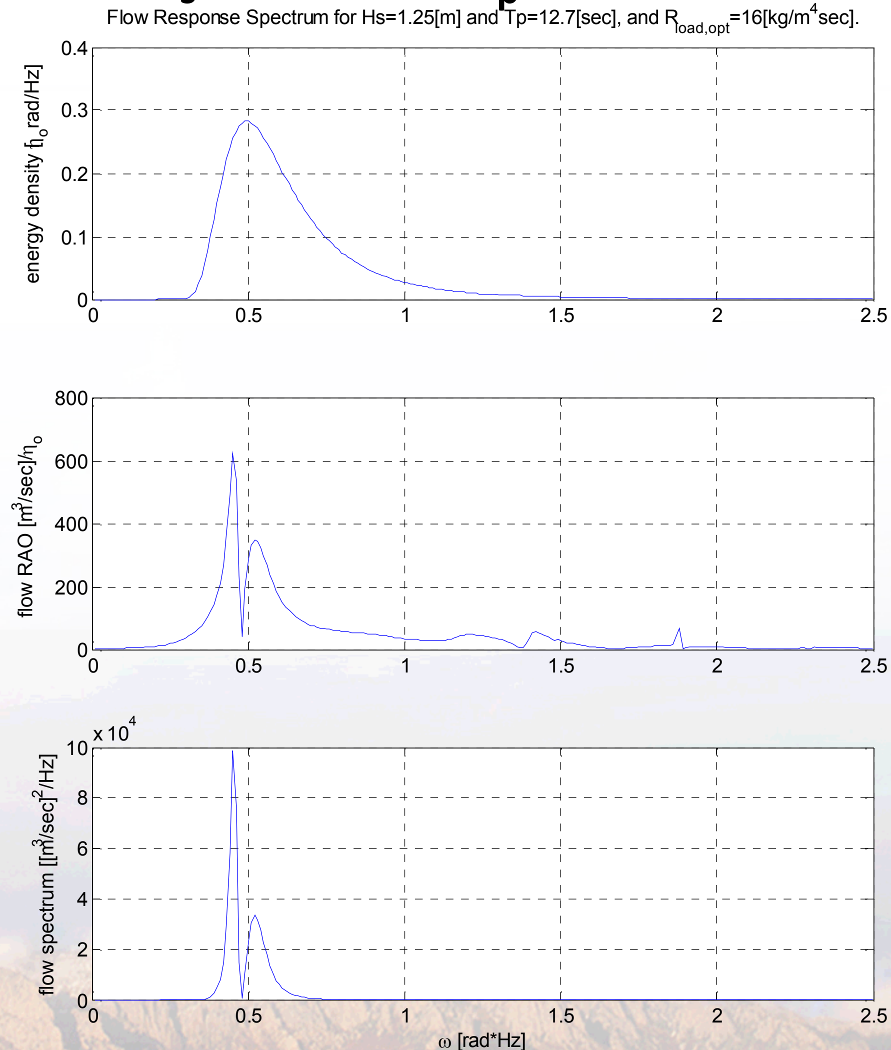
Developed from Subrata Chakrabarti's 'Hydrodynamics of Offshore Structures.' Chapter 9. 2001.

# Spectral Performance Model

## $H_s$=1.25[m] $T_p$=8.7[sec]




## $H_s$=1.25[m] $T_p$=12.7[sec]




Developed from Subrata Chakrabarti's 'Hydrodynamics of Offshore Structures.' Chapter 9. 2001.

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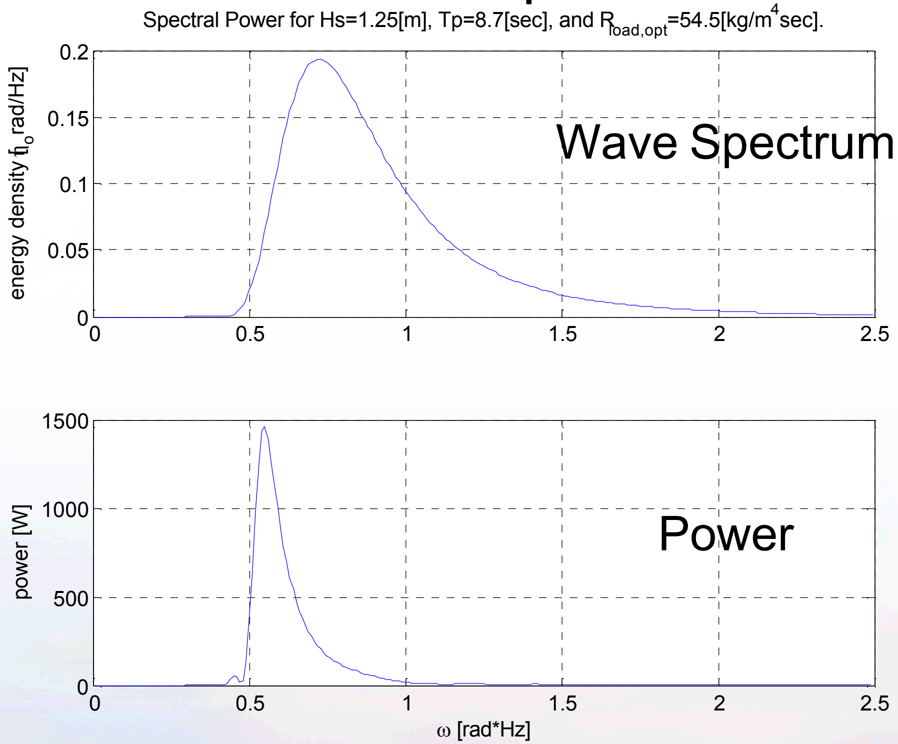
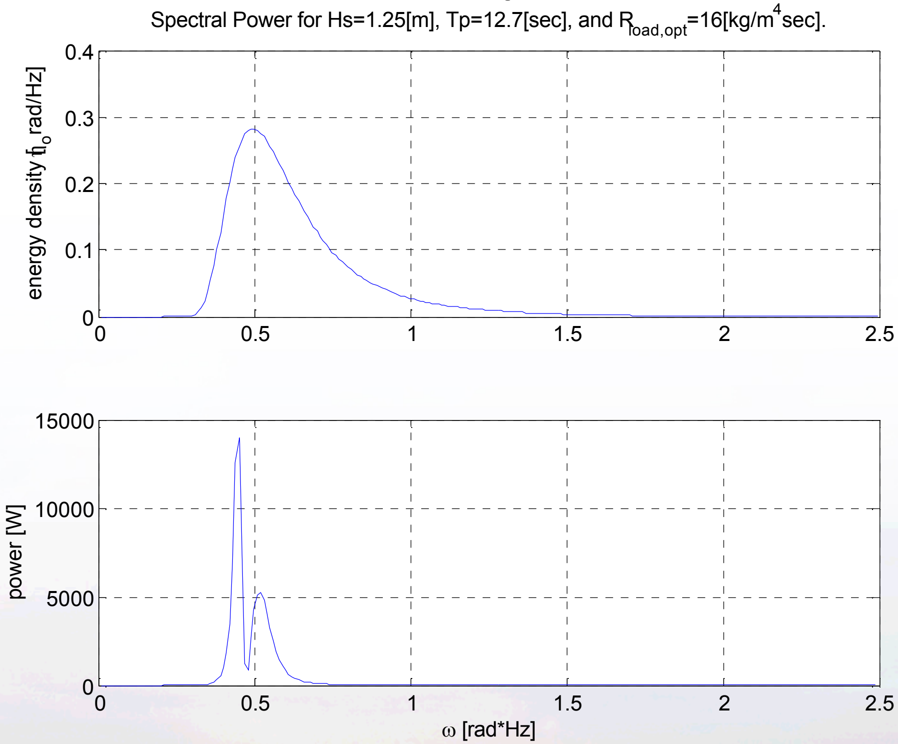
# Spectral Performance Model

## $H_s$=1.25[m]  $T_p$=8.7[sec]




## $H_s$=1.25[m]  $T_p$=12.7[sec]




Developed from Subrata Chakrabarti's 'Hydrodynamics of Offshore Structures.' Chapter 9. 2001.

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# *Spectral Model Power Results.*

- **Deployment climate is in northern California (Humboldt—NDBC 46212).**
  - Do not consider directionality and assume a Bretschneider Spectrum
  - Incident Power: 32[kW/m]

$\langle P \rangle_{Mechanical}$ Available to PTO, [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** | 0.0 | 0.1 | 0.1 | 0.3 | 0.8 | 1.5 | 2.4 | 3.1 | 3.7 | 3.2 | 4.0 | 3.7 | 3.2 | 2.6 | 2.3 |
| **0.75** | 0.4 | 0.6 | 1.1 | 2.8 | 7.2 | 13.9 | 21.2 | 28.1 | 33.0 | 28.6 | 35.8 | 33.7 | 28.8 | 23.8 | 20.8 |
| **1.25** | 1.1 | 1.8 | 3.2 | 7.7 | **20.1** | 38.6 | 58.8 | 77.9 | 91.7 | 79.6 | 99.4 | 93.5 | 79.9 | 66.2 | 57.7 |
| **1.75** | 2.2 | 3.5 | 6.2 | 15.1 | 39.3 | 75.7 | 115.3 | 152.7 | 179.7 | 155.9 | 194.8 | 183.3 | 156.6 | 129.7 | 113.0 |
| **2.25** | 3.7 | 5.8 | 10.2 | 24.9 | 65.0 | 125.2 | 190.6 | 252.5 | 297.1 | 257.7 | 322.0 | 302.9 | 258.9 | 214.4 | 186.9 |
| **2.75** | 5.5 | 8.7 | 15.3 | 37.2 | 97.1 | 187.0 | 284.7 | 377.2 | 443.8 | 385.0 | 481.0 | 452.5 | 386.7 | 320.2 | 279.2 |
| **3.25** | 7.7 | 12.2 | 21.4 | 51.9 | 135.7 | 261.2 | 397.6 | 526.8 | 619.9 | 537.8 | 671.8 | 632.1 | 540.1 | 447.2 | 389.9 |
| **3.75** | 10.2 | 16.2 | 28.4 | 69.1 | 180.6 | 347.8 | 529.4 | 701.4 | 825.3 | 716.0 | 894.5 | 841.5 | 719.1 | 595.4 | 519.1 |
| **4.25** | 13.1 | 20.9 | 36.5 | 88.8 | 232.0 | 446.7 | 680.0 | 900.9 | 1060.0 | 919.6 | 1148.9 | 1080.9 | 923.7 | 764.8 | 666.7 |
| **4.75** | 16.4 | 26.1 | 45.6 | 110.9 | 289.8 | 558.0 | 849.4 | 1125.3 | 1324.1 | 1148.7 | 1435.1 | 1350.1 | 1153.8 | 955.3 | 832.8 |
| **5.25** | 20.0 | 31.8 | 55.8 | 135.5 | 354.0 | 681.7 | 1037.6 | 1374.7 | 1617.5 | 1403.3 | 1753.1 | 1649.3 | 1409.5 | 1167.1 | 1017.4 |
| **5.75** | 24.0 | 38.2 | 66.9 | 162.5 | 424.6 | 817.7 | 1244.6 | 1649.0 | 1940.3 | 1683.3 | 2103.0 | 1978.5 | 1690.7 | 1399.9 | 1220.4 |
| | **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] $2\pi(m_{-1}/m_0)$**

- **The average annual "mechanical" power produced = 225[kW]**
- **For a device of this size in this climate does this power number seem reasonable?**

# Effect of Viscous Damping Values on Spectral Performance

- Deployment location: 31[kW/m]

**Constant Structural Damping**

| Structural Bvis | Air Column Gvis | Average Annual Values <Power> | RMS Flow | RMS Pressure | Capture Length | Energy |
|---|---|---|---|---|---|---|
| % | % | [kW] | [$m^3$/sec] | [Pa] | [m] | [MW-hr] |
| 16 | 20 | 177.7 | 74.8 | 1761 | 4.37 | 1557 |
| 16 | 15 | 225 | 77.9 | 2265 | 5.7 | 1971 |
| 16 | 10 | 315.7 | 83.2 | 3213 | 8.47 | 2766 |
| 16 | 0 | 2216 | 148.4 | 13518 | 86.5 | 19413 |

1000% increase

80% increase

**Constant OWC Damping**

| Structural Bvis | Air Column Gvis | Average Annual Values <Power> | RMS Flow | RMS Pressure | Capture Length | Energy |
|---|---|---|---|---|---|---|
| % | % | [kW] | [$m^3$/sec] | [Pa] | [m] | [MW-hr] |
| 32 | 20 | 186.8 | 81.5 | 1617 | 4.41 | 1636 |
| 16 | 20 | 177.7 | 74.8 | 1761 | 4.37 | 1557 |
| 7 | 20 | 239.8 | 86.4 | 1998 | 5.59 | 2101 |
| 3 | 20 | 470.9 | 115.4 | 2567 | 9.78 | 4125 |

200% increase

35% increase

Decrease by a factor of ~2

- The viscous damping on the air column influences average annual power more than the viscous damping on the structure.

# Effect of Viscous Damping Values on Spectral Performance

- **This large of an influence on power is in contradiction to publication:** 'Modelling and Simulation of a Floating Oscillating Water Column' by Kurniawan, A., Hals, J., and Moan, T.
  - Bounded their viscous studies by going from zero to twice their unreported nominal values and only found a ±25% change in average annual power values.

- **This large of an influence on power by the OWC viscous damping value is surprising because of the small affect these damping values had on the free surface amplitude RAO.**

- **When developing your models have you seen this large of an influence on power by the viscous damping values or have you seen something more similar to the Kurniawan paper?**

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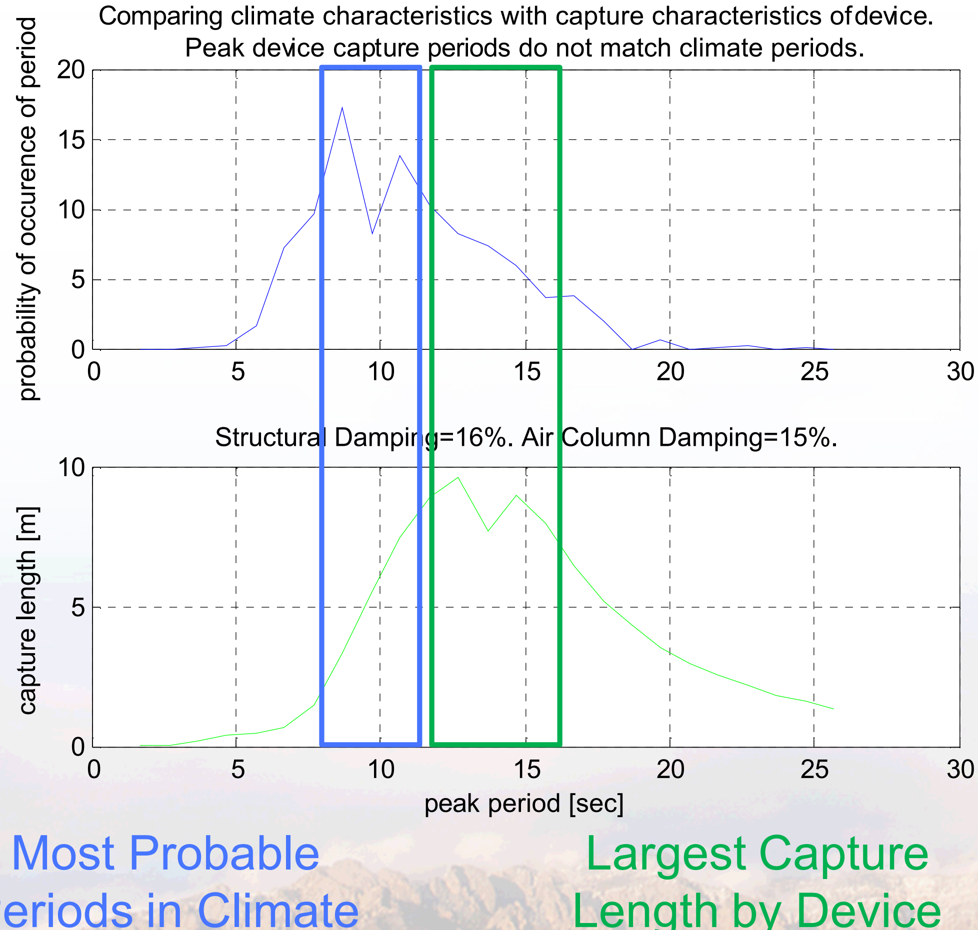
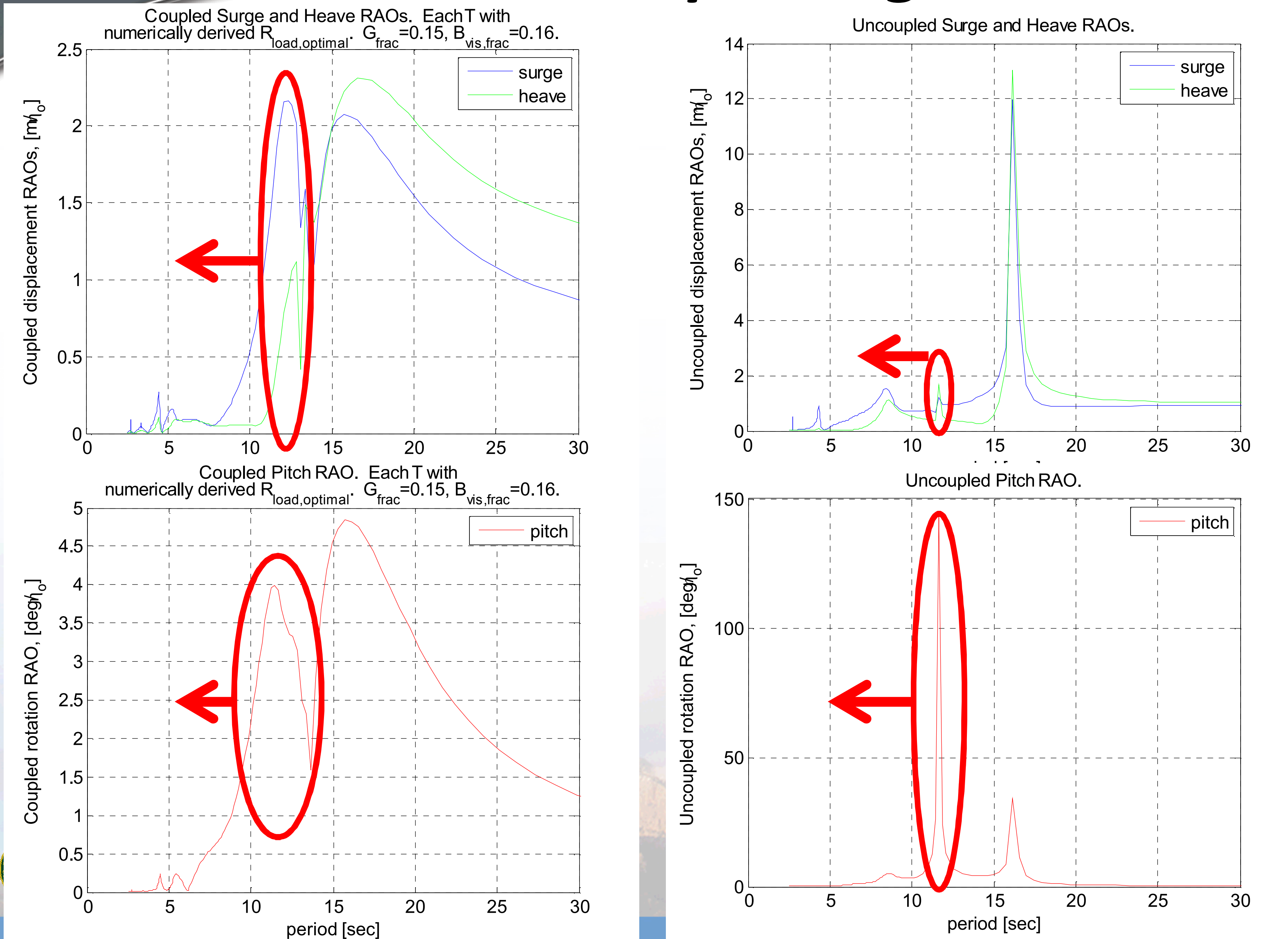
# Performance Model Outcome: Capture Length vs. Climate




- Device performance is not matched to the deployment climate.
- Power production will be less than optimal.

Capture Length is the mechanical power produced divided by the incident wave power flux: $\Lambda = \frac{< P >}{J}$

# Capturing Wind Waves



# Capturing Wind Waves

- **Design is meant to capitalize on relative motion between the OWC and the Structure.**

- **Capture length and coupled RAO's clearly show the influence of the structure on power conversion.**

- **Believe I can alter the capture length by controlling the pitch natural frequency.**

$$\omega_{pitch} \cong \sqrt{\frac{C_{55}}{k_y^2 m + A_{55}}} = \sqrt{\frac{\rho g G M_L}{I_{yy} + I_{Mass_{added\,pitch}}}}$$

- **Believe there are three parameters that I can change**
  - The distance between COG/COB: this will alter the longitudinal metacenter.
  - Length of the device: this will alter the added moment of inertia as well as the moment of inertia.
  - Location of COG/COB: this will alter the symmetry of the response relative to the resonance value.

- **Do you agree that changing the pitch natural period can increase my capture length?**
  - **Are there any other techniques to shift the capture length?**

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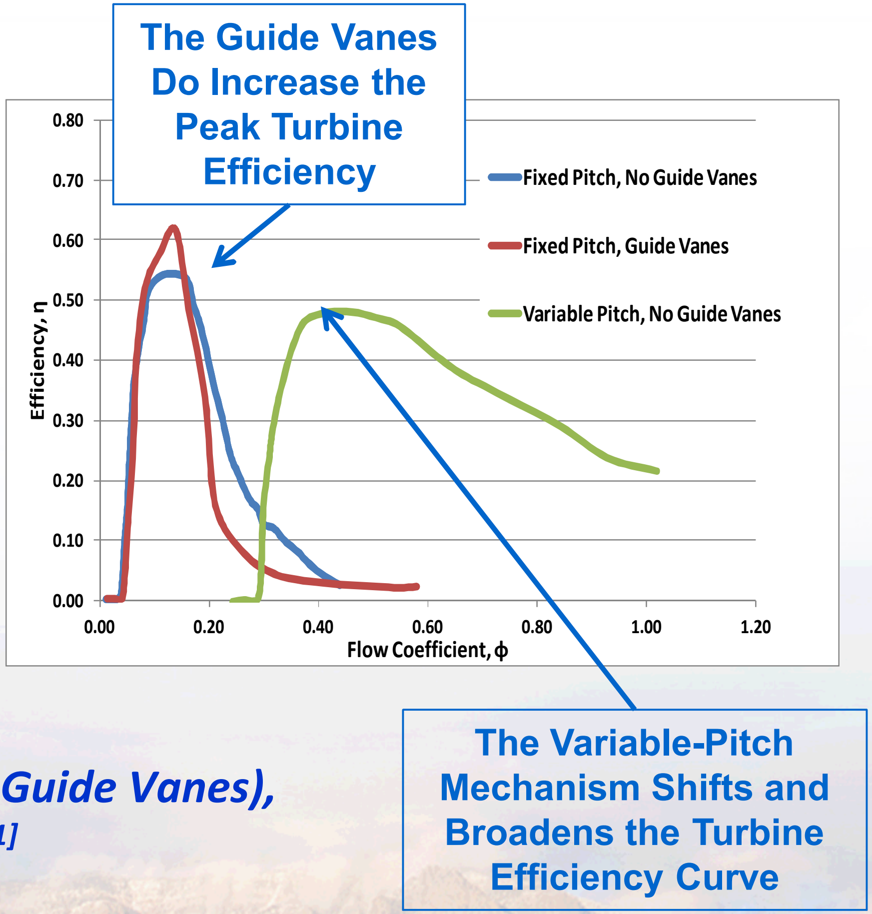
# Integrating a Prime Mover: Wells Turbine

- Fixed pitch vs. variable pitch Wells turbine.
    - *There is a finite "flow range" over which the turbine will operate efficiently*
- One turbine vs. multiple turbines.
- Steady state data and analysis vs. unsteady and pulsatile flow
- Large variability's: across the climate and within a particular climate (average vs. peak values).




***Fixed-Pitch (No Guide Vanes), Fixed-Pitch (With Guide Vanes), and Variable-Pitch Wells turbines were tested [1]***

[1]A. Brito-Melo, F. Neumann, A.J.N.A. Sarmento, Full-scale Data Assessment in OWC Pico Plant, Proceedings of The Seventeenth (2007) International OFFSHORE AND POLAR ENGINEERING CONFERENCE. Lisbon, Portugal, July 2007

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# Wells Turbine Modeling

- **Used efficiency data from Small-scale Wells turbine testing in Portugal (OWC power plant on Pico Island (Azores, Portugal))[1]**
  - ***Obtained for: steady-state flow conditions, a constant hub-to-tip ratio and a tip radius of ~0.3[m]***

- **Using the experimental data from above, generate a empirical curve fits of $\eta(\phi)$, the efficiency as a function of flow coefficient, for each turbine size investigated**

$$\eta = \frac{Mechanical\,Power}{Available\,Power} = \frac{\omega T}{V_{axial}(\Delta p A)} \qquad \phi = \frac{V_{axial}}{\omega r_{tip}} = \frac{Q}{\pi^2(1-\nu^2) r_{tip}^3 \, N/30}$$

- **Use root-mean-squared (rms) values, $Q_{rms}$ and $p_{1_{rms}}$ obtained from the spectral densities as average input values to calculate the efficiency for each sea state**
- **Comparison of small scale experimental data to large scale actual performance?**

[1]A. Brito-Melo, F. Neumann, A.J.N.A. Sarmento, Full-scale Data Assessment in OWC Pico Plant, Proceedings of The Seventeenth (2007) International OFFSHORE AND POLAR ENGINEERING CONFERENCE. Lisbon, Portugal, July 2007

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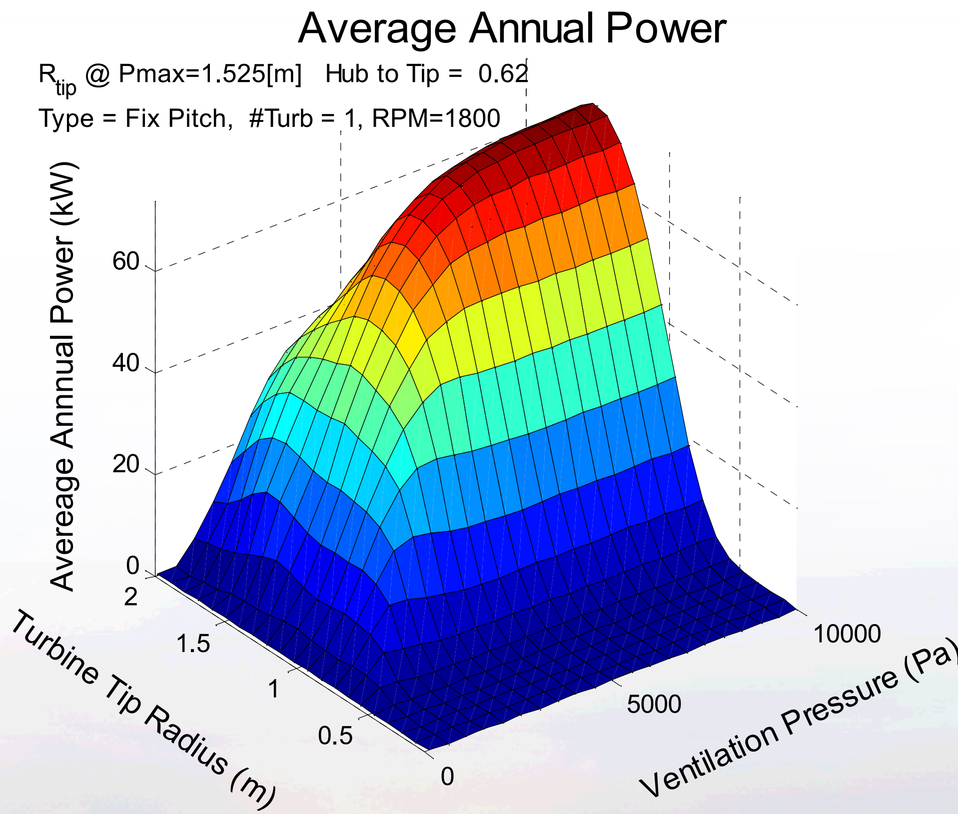
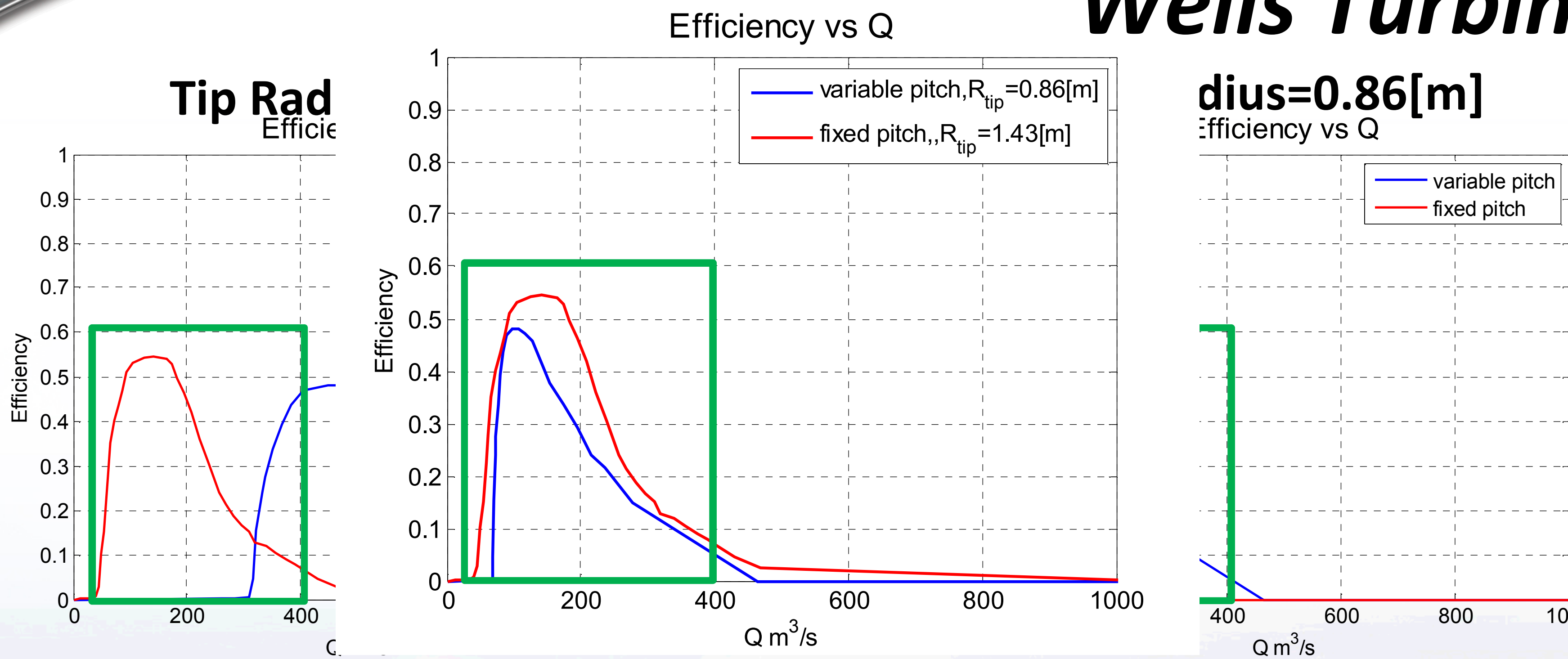
# System Optimization Code

- **Develop an optimization code to optimize average annual electrical power as a function of:**
  - Turbine type: fixed pitch, variable pitch, and fixed pitch with guide vanes.
  - Turbine Diameter
  - Vent Pressure
  - Number of turbines
  - Optimal RPM
- **System inputs are:**
  - Spectral Flow Rate & Pressure values
  - Turbine RPM (if not trying to optimize)
  - Turbine Hub-to-Tip (have 2 Hub-to-Tips that we are working with)
  - Cut-on efficiency (multiple turbines)



# Fixed vs. Variable Pitch Wells Turbines

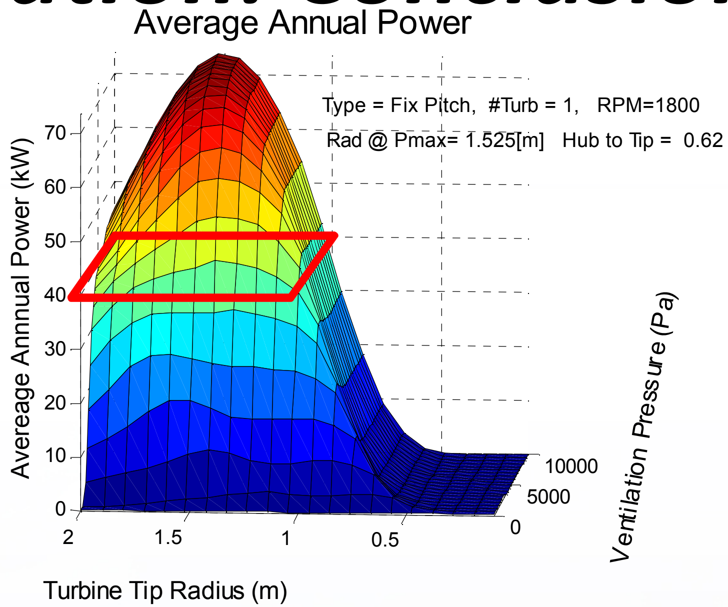


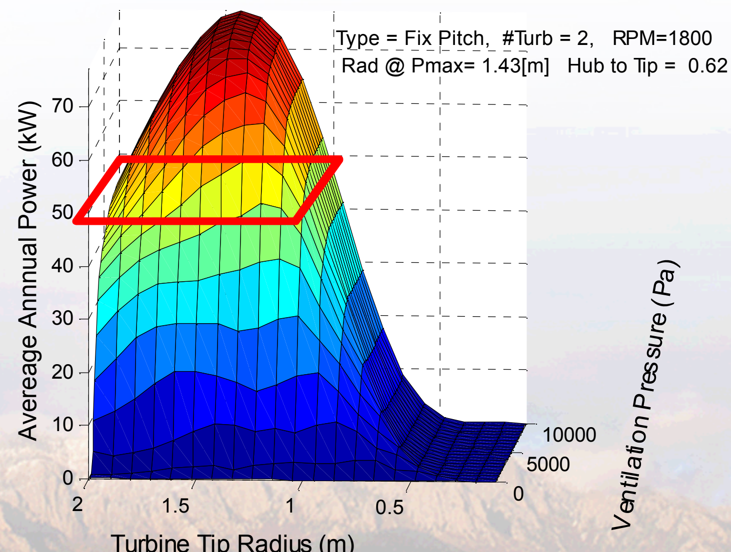

- **For the same flow range, clear that the fixed pitch Wells Turbine can perform better by just selecting a larger size.**
- **Why even pursue the Variable Pitch Wells Turbine, why not just use large fixed pitch turbines?**
  - **Is the Variable Pitch a realistic choice? What has been your experience with this design?**
  - **Is it possible for the fixed pitch efficiency curve to be broader than the variable pitch?**
  - **Is there a size limit for Wells Turbine?**

# System Optimization: Conclusions

- **With no constraints on the system, one fixed pitch turbine will deliver the most power with the least complexity for the system.**
  - ***Optimization requires a large diameter and higher ventilation pressures***

- **Multiple turbines can broaden the range over which maximum power can be delivered when including ventilation pressure.**
  - ***For multiple turbine analysis assuming that there is a mechanism to open and close vents.***

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# Mechanical Power vs. PTO Power

## Average Annual Mechanical Power = 225[kW]

$<P>_{Mechanical}$ Available to PTO, [kW]

| Significant Wave Height, Hs [m] \ Tp [sec] | 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 | 0.1 | 0.1 | 0.3 | 0.8 | 1.5 | 2.4 | 3.1 | 3.7 | 3.2 | 4.0 | 3.7 | 3.2 | 2.6 | 2.3 |
| 0.75 | 0.4 | 0.6 | 1.1 | 2.8 | 7.2 | 13.9 | 21.2 | 28.1 | 33.0 | 28.6 | 35.8 | 33.7 | 28.8 | 23.8 | 20.8 |
| 1.25 | 1.1 | 1.8 | 3.2 | 7.7 | **20.1** | 38.6 | 58.8 | 77.9 | 91.7 | 79.6 | 99.4 | 93.5 | 79.9 | 66.2 | 57.7 |
| 1.75 | 2.2 | 3.5 | 6.2 | 15.1 | 39.3 | 75.7 | 115.3 | 152.7 | 179.7 | 155.9 | 194.8 | 183.3 | 156.6 | 129.7 | 113.0 |
| 2.25 | 3.7 | 5.8 | 10.2 | 24.9 | 65.0 | 125.2 | 190.6 | 252.5 | 297.1 | 257.7 | 322.0 | 302.9 | 258.9 | 214.4 | 186.9 |
| 2.75 | 5.5 | 8.7 | 15.3 | 37.2 | 97.1 | 187.0 | 284.7 | 377.2 | 443.8 | 385.0 | 481.0 | 452.5 | 386.7 | 320.2 | 279.2 |
| 3.25 | 7.7 | 12.2 | 21.4 | 51.9 | 135.7 | 261.2 | 397.6 | 526.8 | 619.9 | 537.8 | 671.8 | 632.1 | 540.1 | 447.2 | 389.9 |
| 3.75 | 10.2 | 16.2 | 28.4 | 69.1 | 180.6 | 347.8 | 529.4 | 701.4 | 825.3 | 716.0 | 894.5 | 841.5 | 719.1 | 595.4 | 519.1 |
| 4.25 | 13.1 | 20.9 | 36.5 | 88.8 | 232.0 | 446.7 | 680.0 | 900.9 | 1060.0 | 919.6 | 1148.9 | 1080.9 | 923.7 | 764.8 | 666.7 |
| 4.75 | 16.4 | 26.1 | 45.6 | 110.9 | 289.8 | 558.0 | 849.4 | 1125.3 | 1324.1 | 1148.7 | 1435.1 | 1350.1 | 1153.8 | 955.3 | 832.8 |
| 5.25 | 20.0 | 31.8 | 55.8 | 135.5 | 354.0 | 681.7 | 1037.6 | 1374.7 | 1617.5 | 1403.3 | 1753.1 | 1649.3 | 1409.5 | 1167.1 | 1017.4 |
| 5.75 | 24.0 | 38.2 | 66.9 | 162.5 | 424.6 | 817.7 | 1244.6 | 1649.0 | 1940.3 | 1683.3 | 2103.0 | 1978.5 | 1690.7 | 1399.9 | 1220.4 |
| 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 |

## Average Annual Electrical Power =73.8[kW]

$<P>_{Electrical}$ Deliverec to Grid, [kW]

| Significant Wave Height, Hs [m] \ d, Tp [sec] | 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 | 0.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 5.5 | 0.6 | 0.1 | 0.1 | 0.0 | 0.0 |
| 1.25 | 0.0 | 0.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 36.1 | 2.1 | 0.2 | 0.1 | 0.1 |
| 1.75 | 0.0 | 0.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 96.2 | 47.4 | 13.1 | 0.8 | 0.4 |
| 2.25 | 0.0 | 0.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 166.0 | 123.1 | 71.5 | 21.8 | 7.3 |
| 2.75 | 0.0 | 0.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 247.7 | 221.3 | 152.5 | 82.8 | 44.4 |
| 3.25 | 0.0 | 0.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 314.1 | 321.6 | 250.5 | 166.7 | 123.8 |
| 3.75 | 0.0 | 0.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 340.8 | 434.2 | 360.5 | 254.3 | 202.4 |
| 4.25 | 0.0 | 0.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 326.2 | 558.0 | 472.2 | 372.1 | 290.3 |
| 4.75 | 0.0 | 0.0 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 292.8 | 690.3 | 595.4 | 481.6 | 406.4 |
| 5.25 | 0.0 | 0.1 | 0.1 | 10.6 | 118.6 | 301.5 | 526.4 | 710.8 | 350.1 | 92.9 | 271.8 | 775.1 | 728.4 | 596.0 | 512.6 |
| 5.75 | 0.0 | 0.1 | 0.3 | 20.7 | 160.2 | 398.9 | 639.1 | 849.5 | 329.0 | 67.3 | 250.7 | 835.5 | 869.6 | 721.9 | 622.3 |
| 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 |

**Is this overall efficiency (~ 33%) expected for the Wells Turbine? What is a typical overall efficiency?**

# Integrating a PTO Train: Considering reality

- How is resistance, $R_{load}$, in the Wells Turbine actually created?
  - Brake on the shaft?  Butterfly valves?
  - Using electricity for damping—is there a limit?
- Large inertia of the turbine—how is this dealt with?
  - Will the turbine be motored to get it going?
- How are Wells Turbine PTOs Rated?
  - Do the power electronics downstream actually rate the system?
- Venting large pressures—how is the value chosen?
  - Do the power electronics downstream dictate the required ventilation pressure?
  - How is venting actually implemented and how often does it occur?
- Power Electronics—do they need their own optimization routine?
  - The interplay between average and peak values will strongly dictate final power.
  - Is there any experience in approaching this aspect?
- Does industry follow a similar procedure/analysis to size the PTO?
  - Have we missed a key aspect or are we going into too much detail?

*THANK YOU.*

*QUESTIONS? RESPONSES.*