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SAND2018-7024C

WEC Design Practices and Tools

OMAE 2018 Madrid

37th International Conference
on Ocean, Offshore and
Arctic Engineering
Madrid, Spain, June 17-22, 2018

June 16, 2018

Yi-Hsiang Yu (NREL)

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Agenda

1. Introduction
2. WEC fundamentals
3. Ocean waves
4. Numerical methods
5. Experimental methods
6. WEC control
7. Extreme response and fatigue

Introduction

Presented by Ryan Coe

Introductions

- Who are we?
  - Ryan Coe
  - Yi-Hsiang Yu
  - Kelley Ruehl

- Who are you?

- What are our goals for today?

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Sandia
National
Laboratories

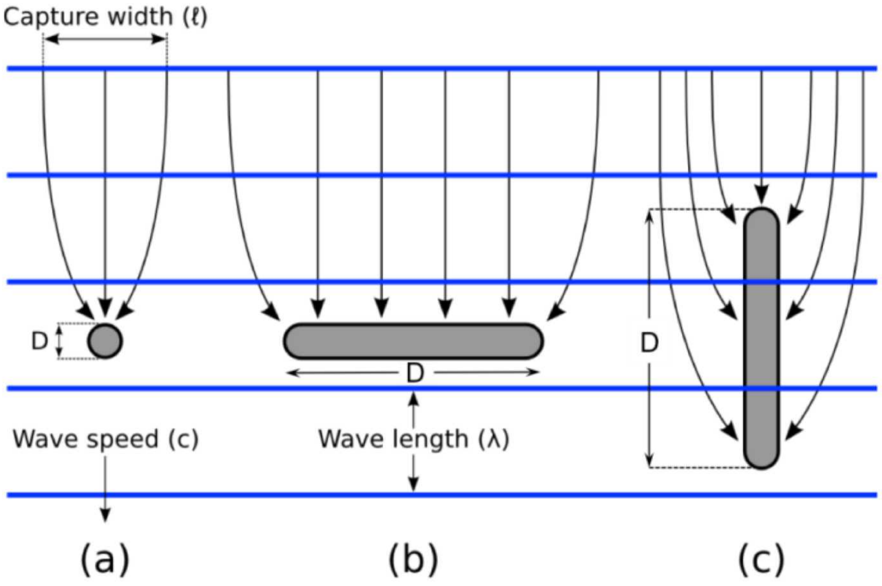
U.S. DEPARTMENT OF
ENERGY

WEC fundamentals

Presented by Yi-Hsiang Yu

Typical WEC Descriptions

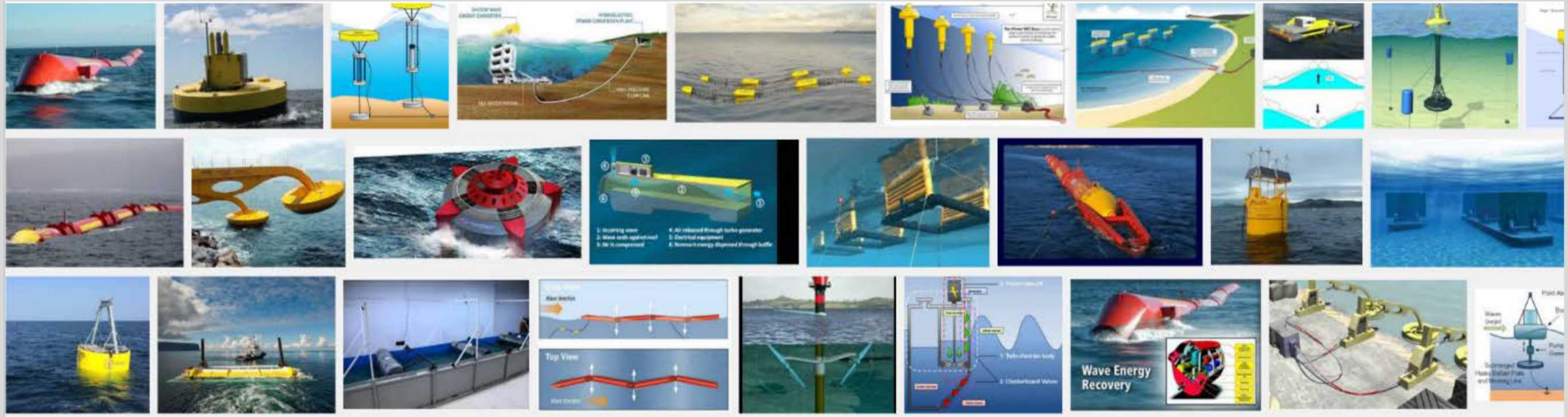
- WEC devices extract energy contained within ocean surface waves and convert it to useful electric power.
- Traditionally, these devices are typically divided into three categories



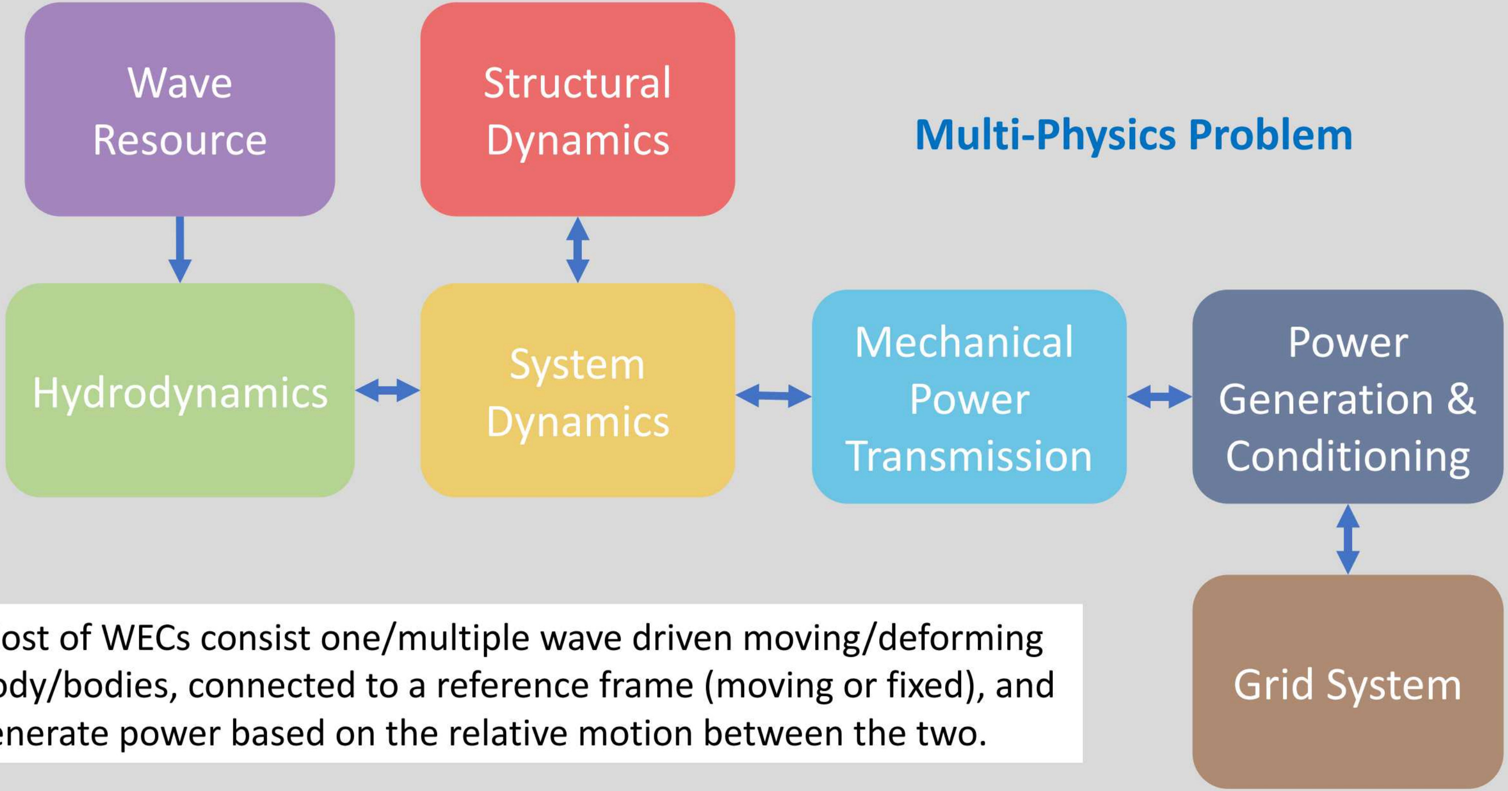
Falnes J., 2002, Ocean Waves and Oscillating Systems, Cambridge University Press.

What is a WEC?

- A wide variety of WEC design concepts



WEC Analysis



Wave Resource

Structural Dynamics

Multi-Physics Problem

Hydrodynamics

System Dynamics

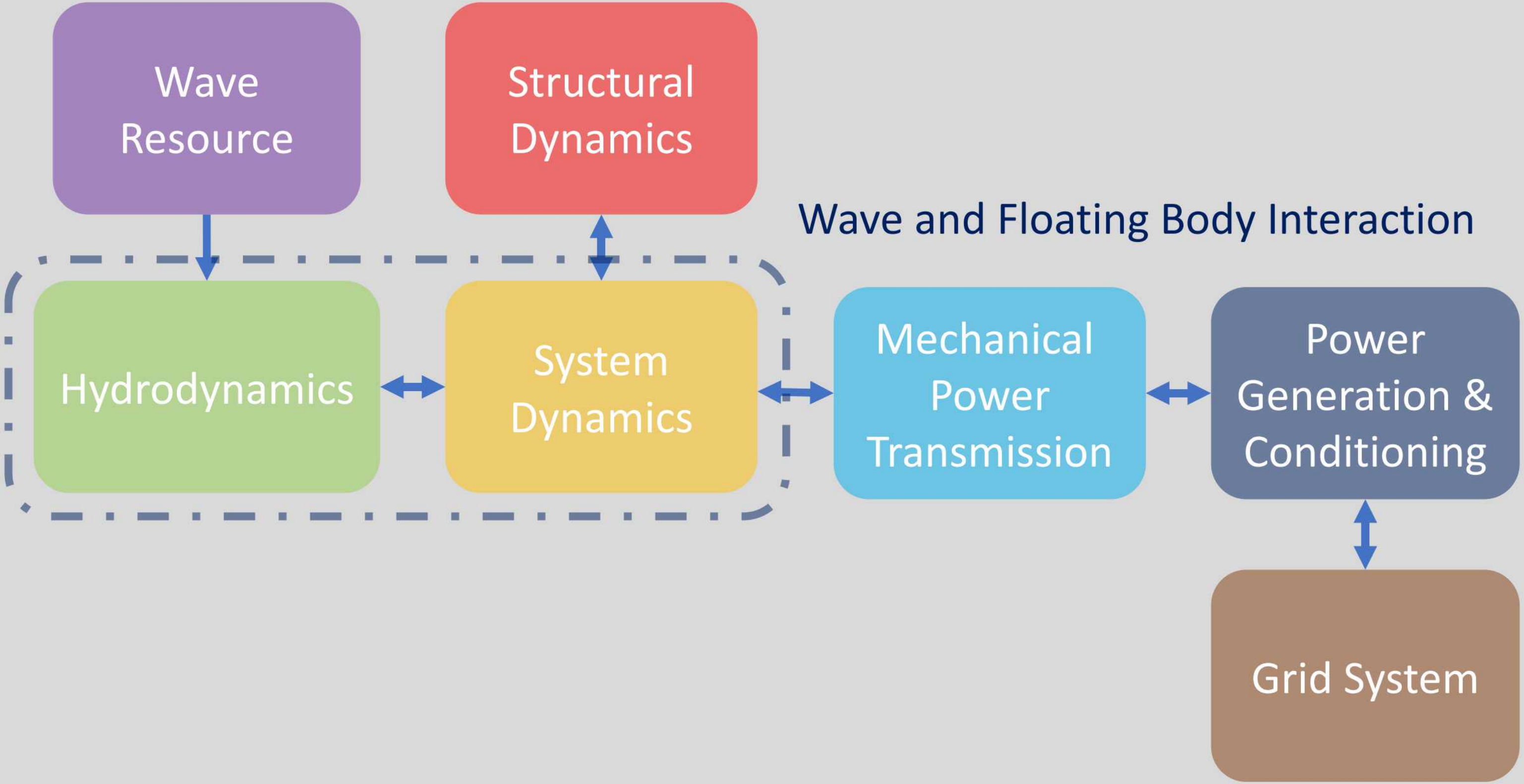
Mechanical Power Transmission

Power Generation & Conditioning

Grid System

Most of WECs consist one/multiple wave driven moving/deforming body/bodies, connected to a reference frame (moving or fixed), and generate power based on the relative motion between the two.

WEC Analysis



Wave Resource

Structural Dynamics

Wave and Floating Body Interaction

Hydrodynamics

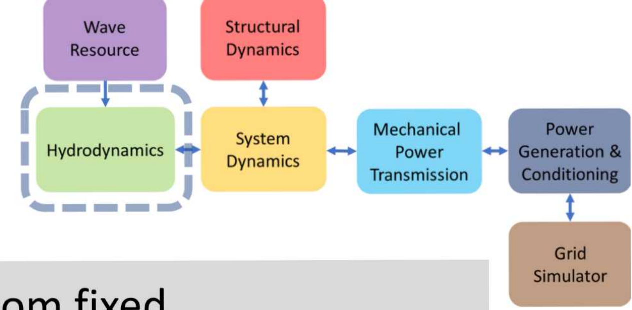
System Dynamics

Mechanical Power Transmission

Power Generation & Conditioning

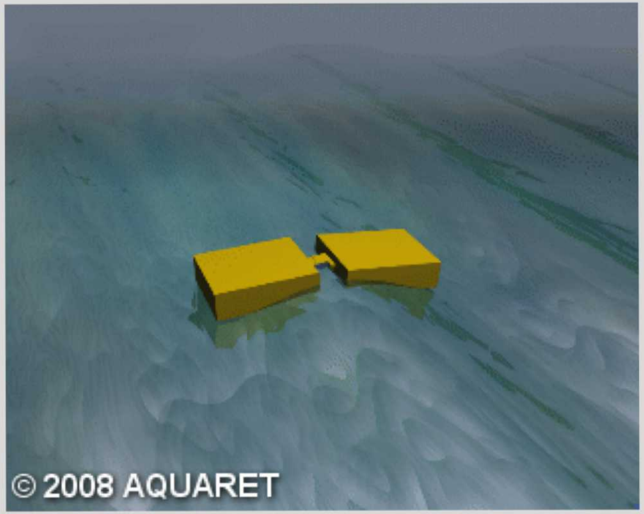
Grid System

WEC Classification

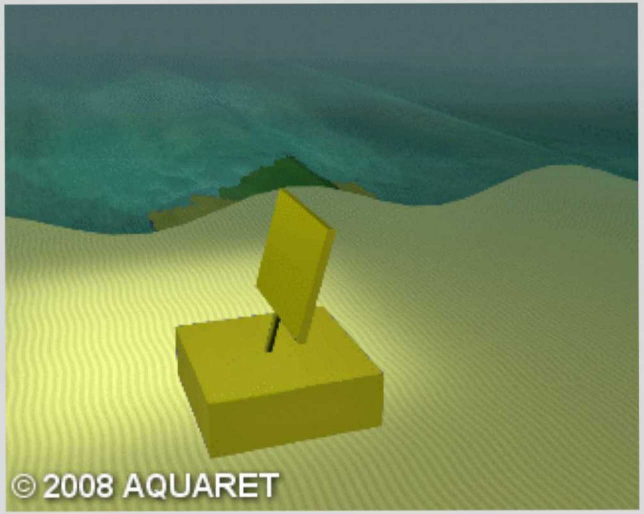


- From hydrodynamics prospective:

Floating

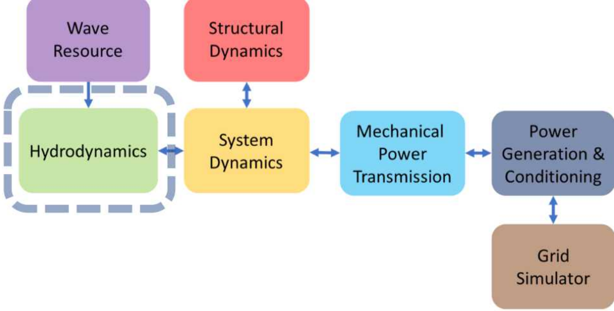


Bottom fixed



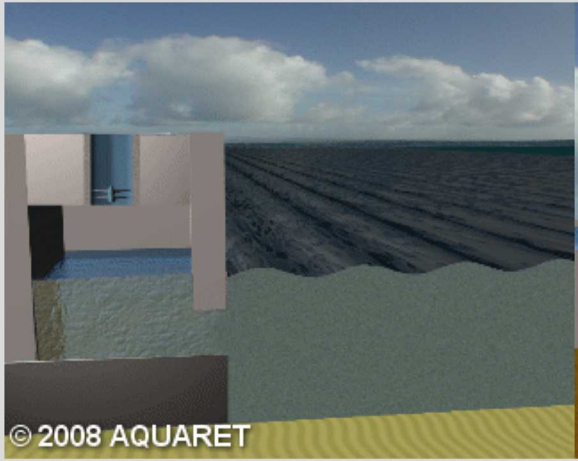
http://www.emec.org.uk/

WEC Classification

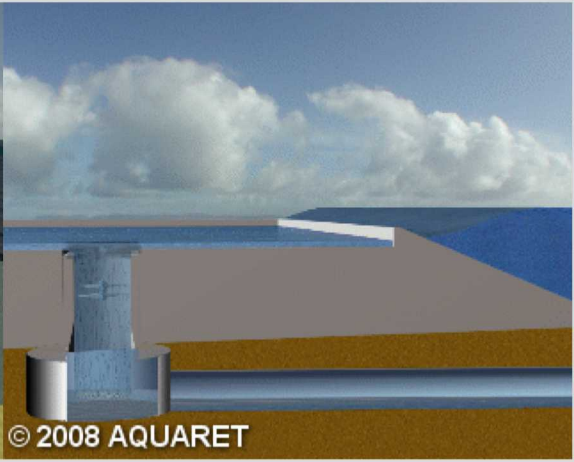

Wave Resource
Structural Dynamics
Hydrodynamics
System Dynamics
Mechanical Power Transmission
Power Generation & Conditioning
Grid Simulator

- From hydrodynamics prospective:

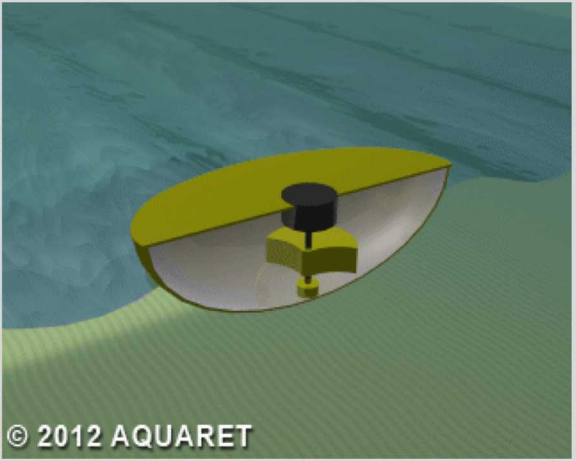
Oscillating water Column



Overtopping device

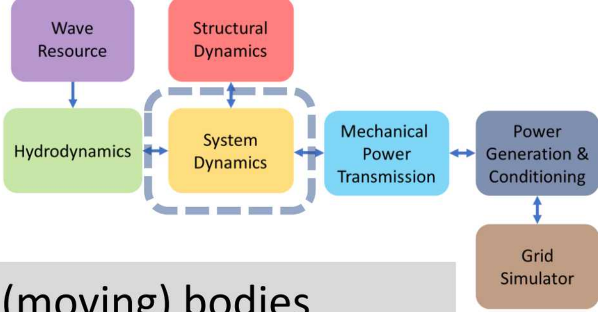


Gyroscopic device



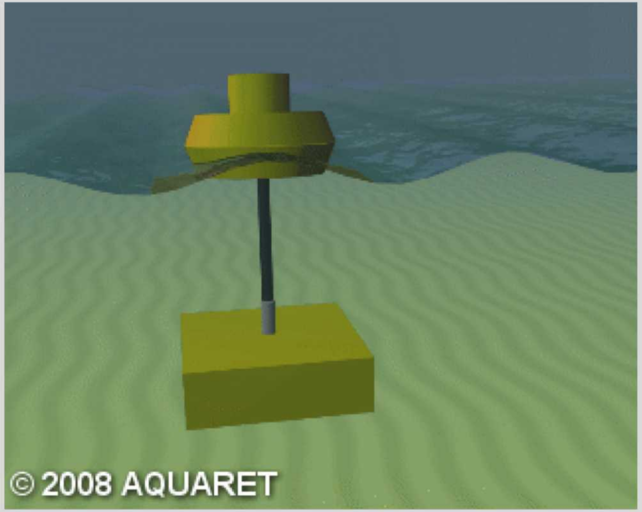
http://www.emec.org.uk/

WEC Classification

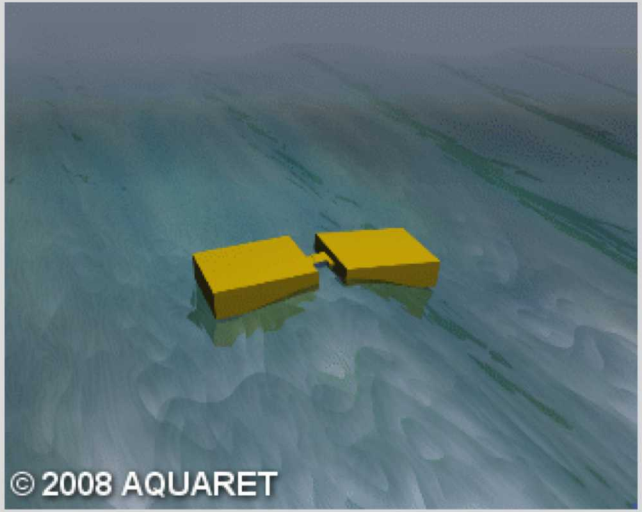


- From system dynamics:

Single (moving) body

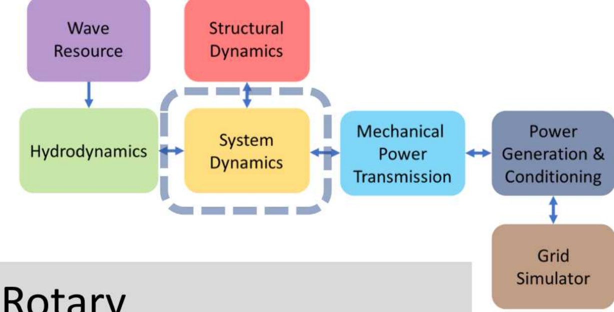


Multiple (moving) bodies



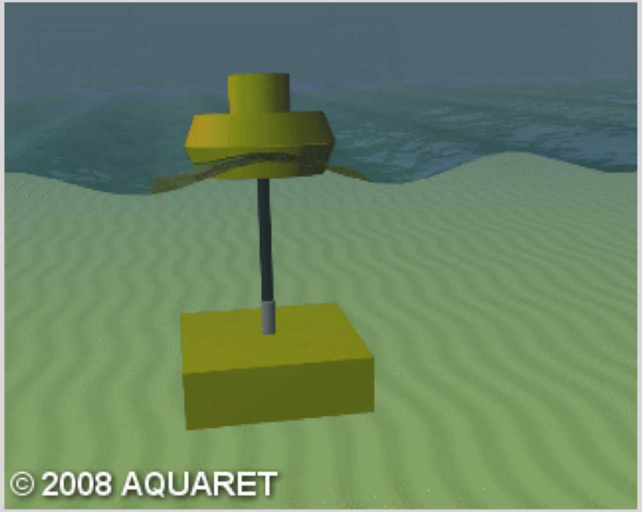
http://www.emec.org.uk/

WEC Classification

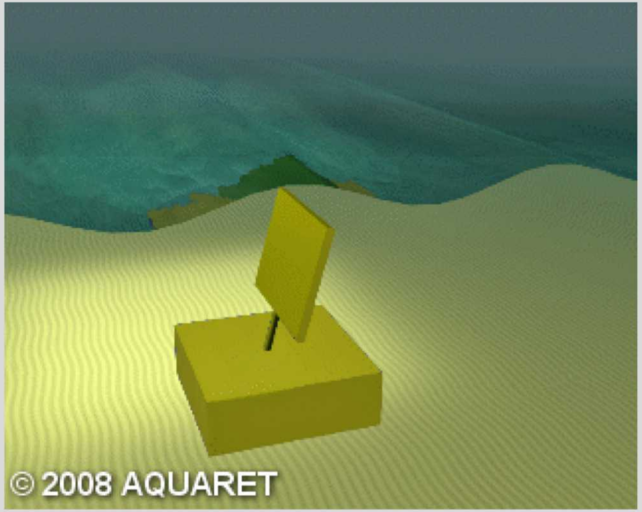


- From system dynamics:

Translational

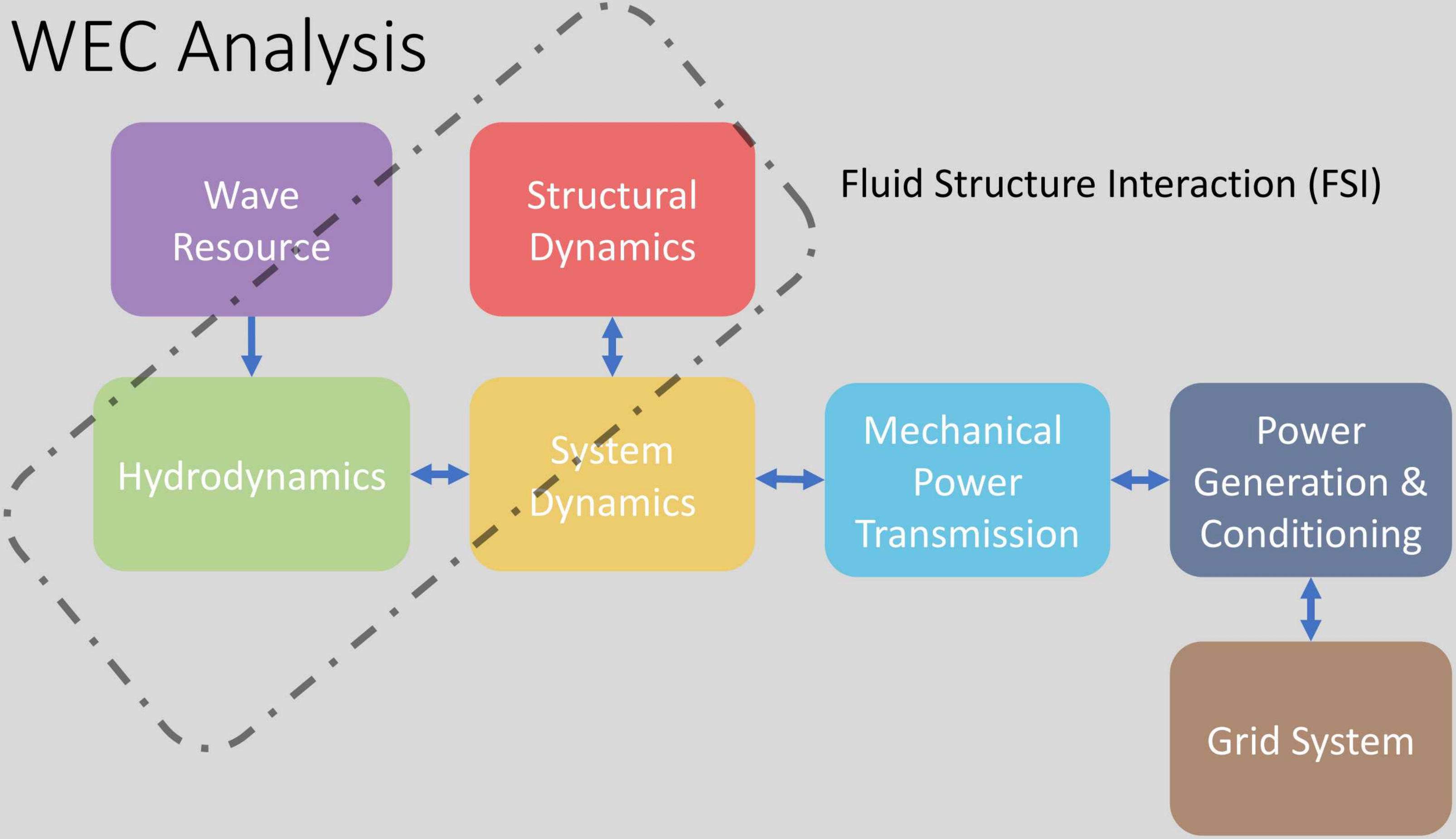


Rotary



http://www.emec.org.uk/

WEC Analysis



Fluid Structure Interaction (FSI)

Wave Resource

Structural Dynamics

Hydrodynamics

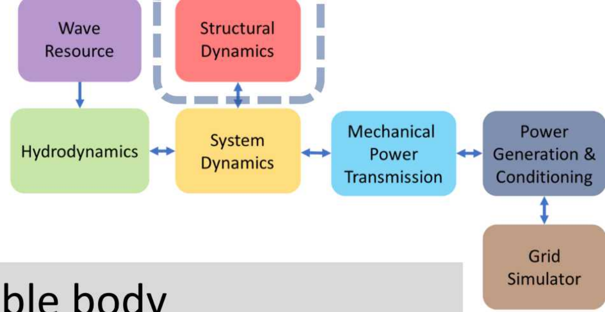
System Dynamics

Mechanical Power Transmission

Power Generation & Conditioning

Grid System

WEC Classification



Wave Resource

Structural Dynamics

Hydrodynamics

System Dynamics

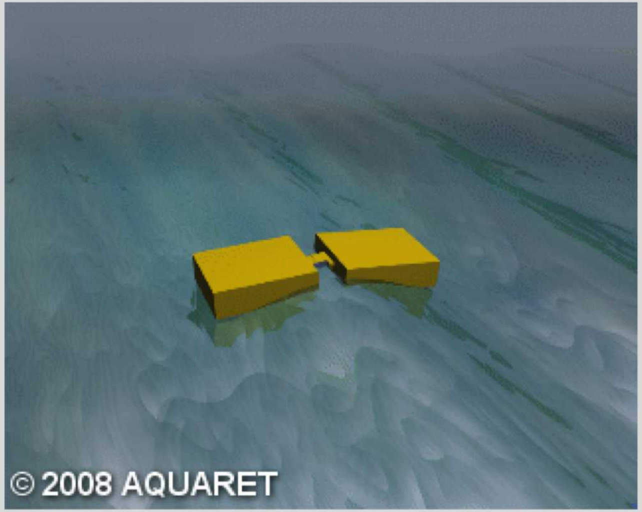
Mechanical Power Transmission

Power Generation & Conditioning

Grid Simulator

- From structural dynamics:

Rigid body



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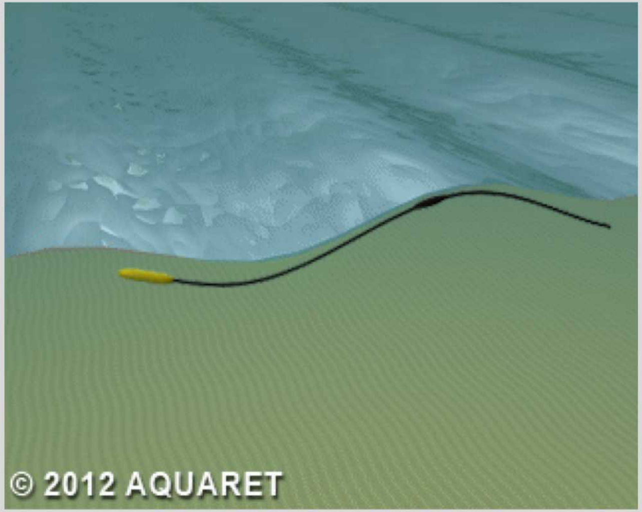
Flexible body



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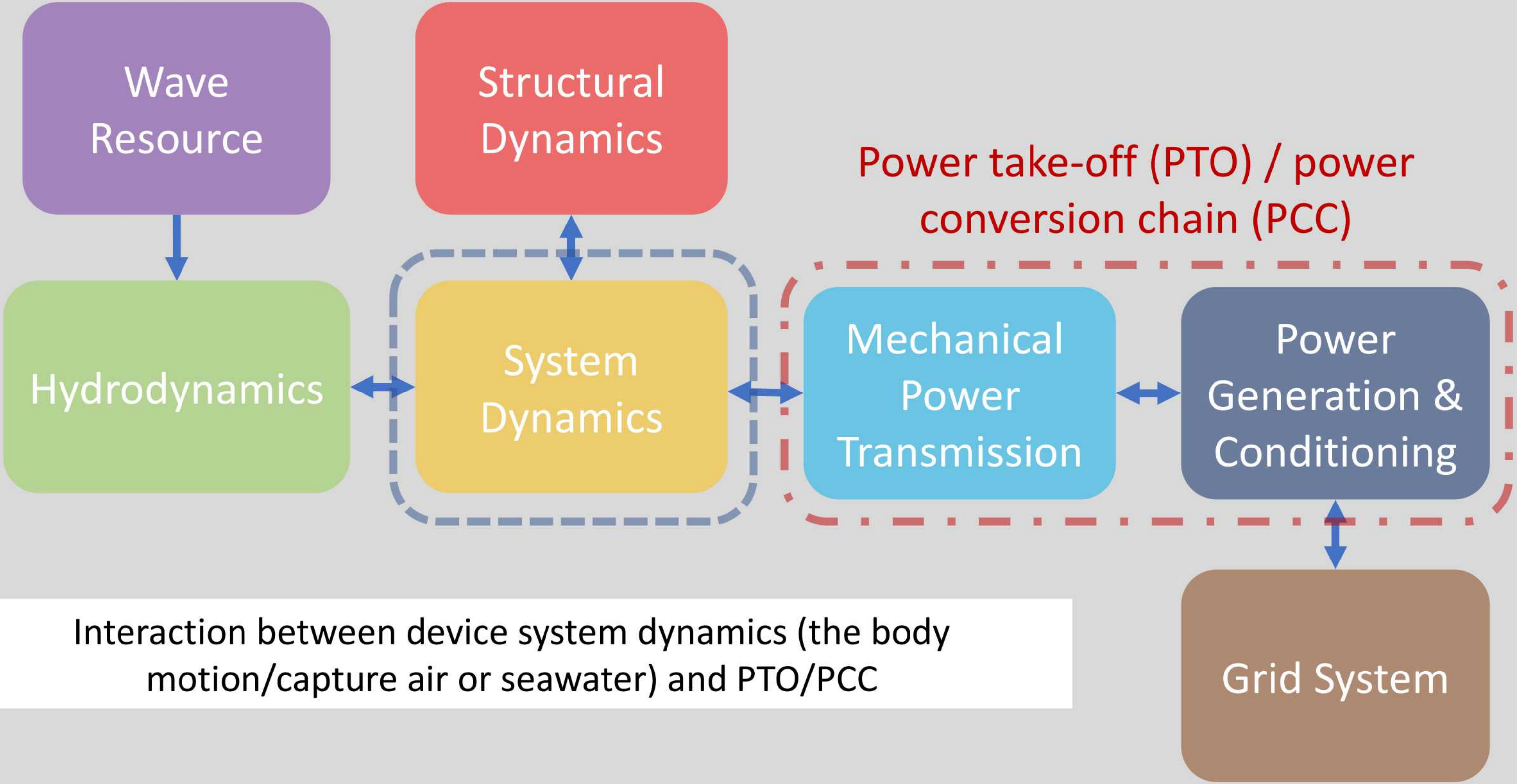
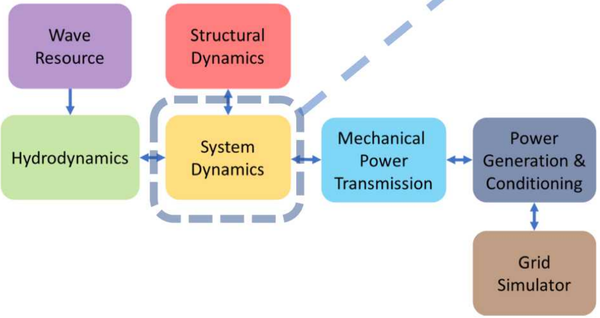
http://www.emec.org.uk/

WEC Analysis



Interaction between device system dynamics (the body motion/capture air or seawater) and PTO/PCC

Power capture mechanisms



Wave Resource

Structural Dynamics

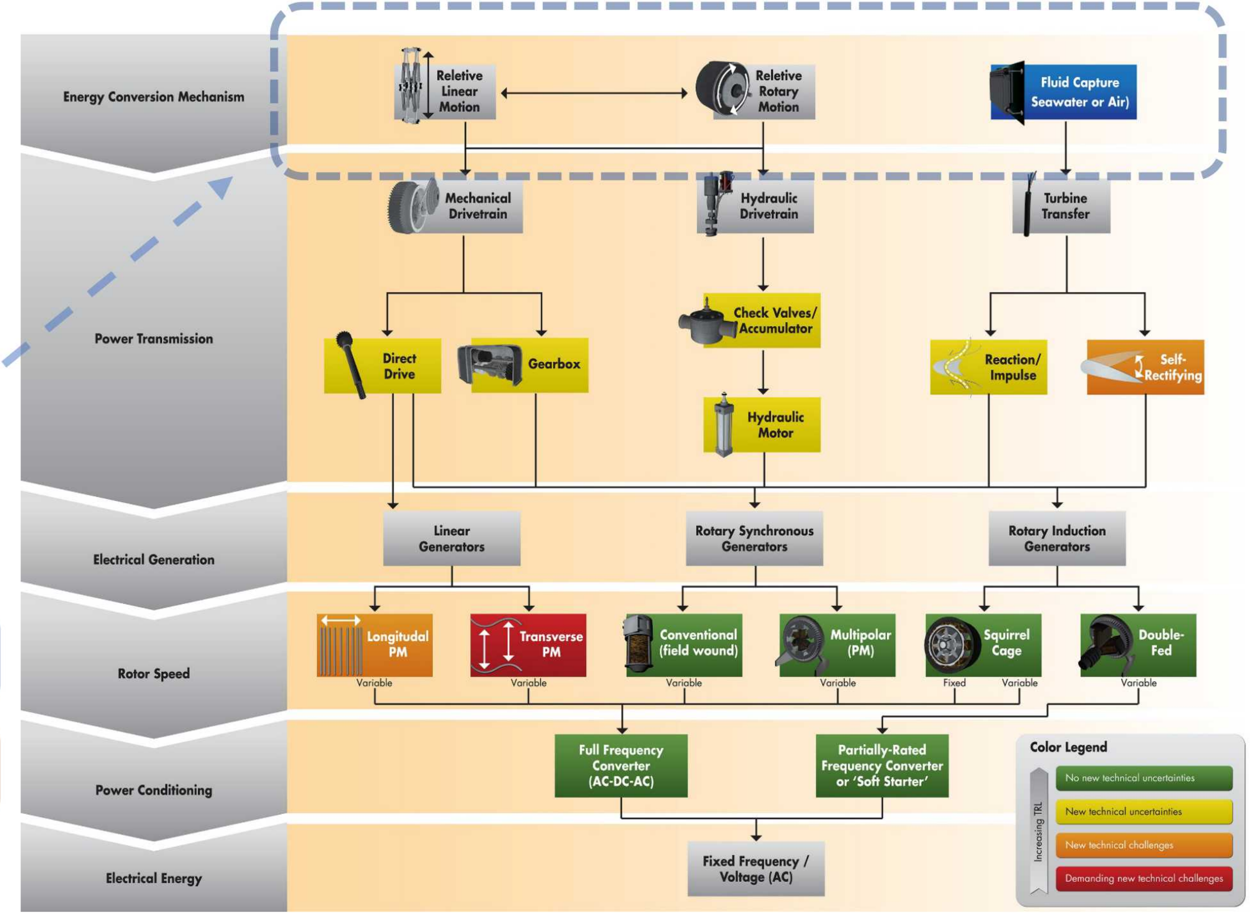
Hydrodynamics

System Dynamics

Mechanical Power Transmission

Power Generation & Conditioning

Grid Simulator



Energy Conversion Mechanism

Power Transmission

Electrical Generation

Rotor Speed

Power Conditioning

Electrical Energy

Reletive Linear Motion

Reletive Rotary Motion

Fluid Capture Seawater or Air)

Mechanical Drivetrain

Hydraulic Drivetrain

Turbine Transfer

Direct Drive

Gearbox

Check Valves/ Accumulator

Hydraulic Motor

Reaction/ Impulse

Self-Rectifying

Linear Generators

Rotary Synchronous Generators

Rotary Induction Generators

Longitudinal PM

Variable

Transverse PM

Variable

Conventional (field wound)

Variable

Multipolar (PM)

Variable

Squirrel Cage

Fixed

Variable

Double-Fed

Variable

Full Frequency Converter (AC-DC-AC)

Partially-Rated Frequency Converter or 'Soft Starter'

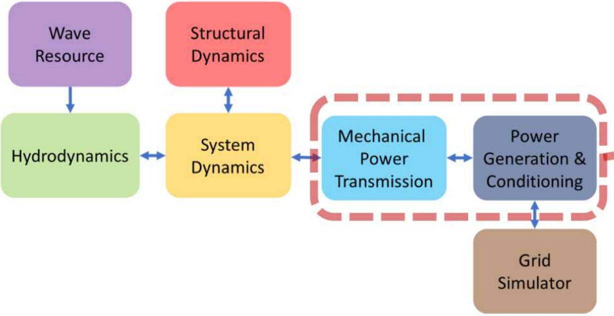
Fixed Frequency / Voltage (AC)

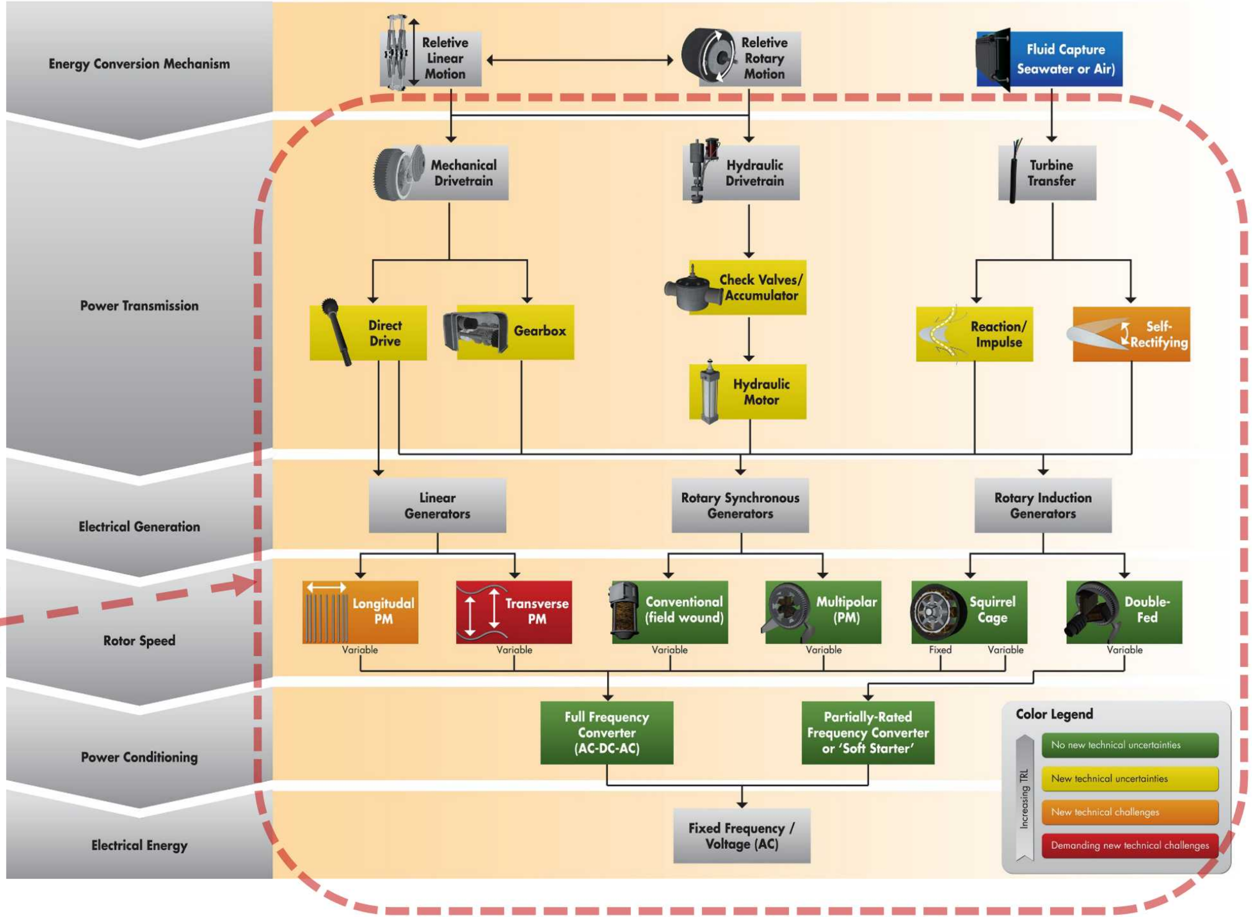
Color Legend

Increasing TRL

- 🟩 No new technical uncertainties
- 🟨 New technical uncertainties
- 🟧 New technical challenges
- 🟥 Demanding new technical challenges

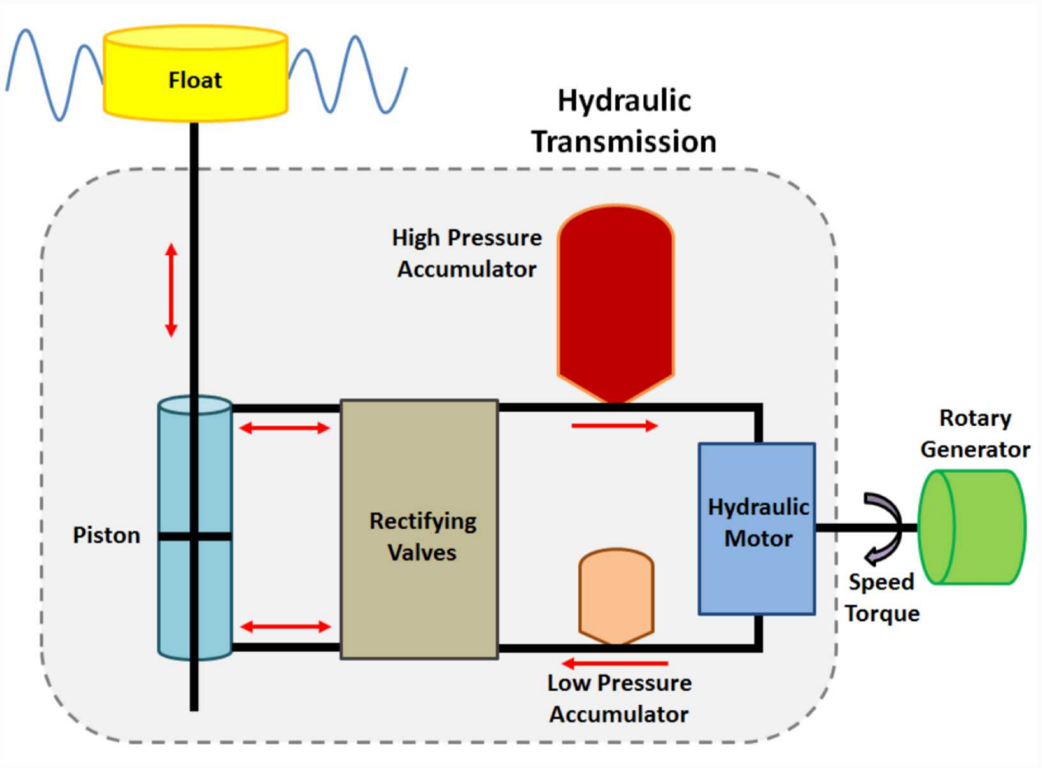
Power capture mechanisms



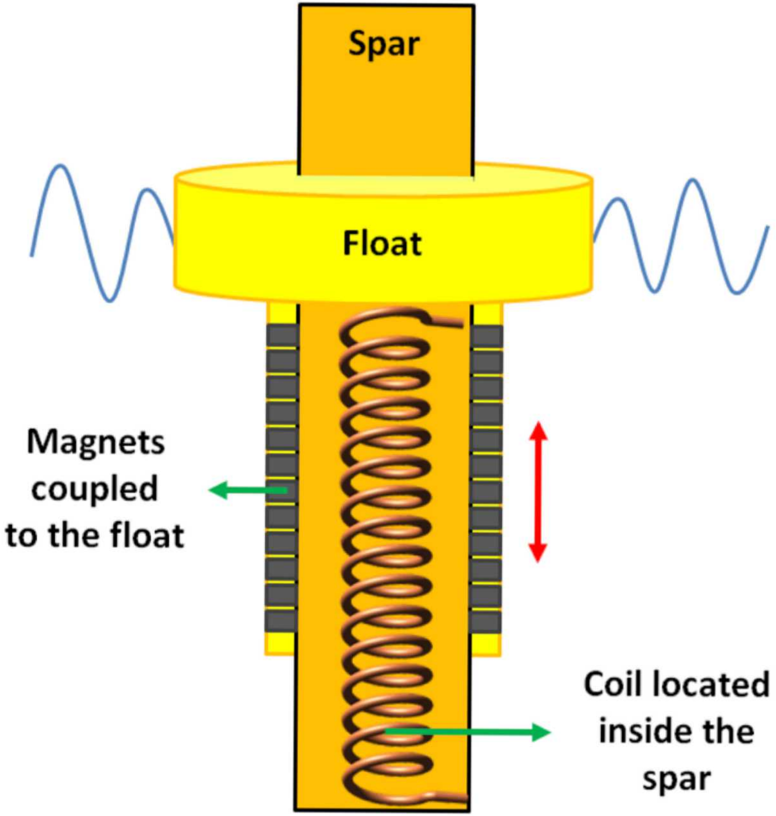


Power capture mechanisms: Hydraulic System

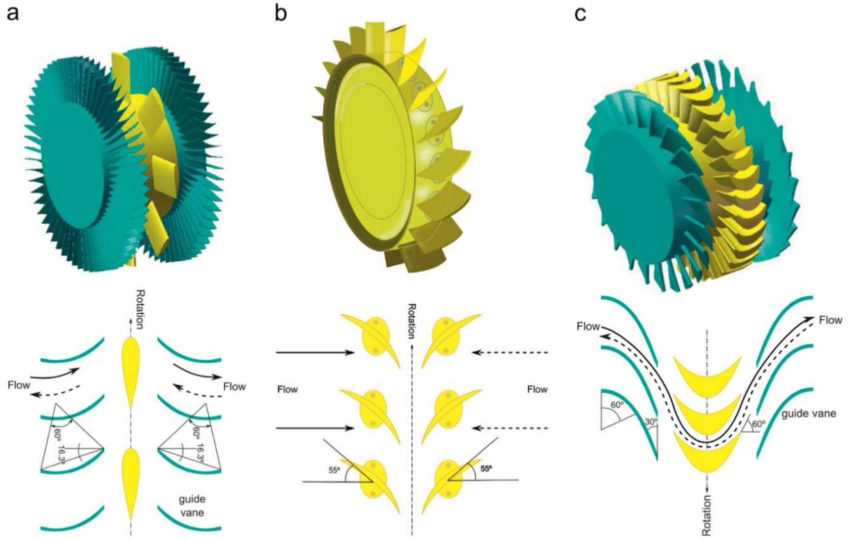
Hydraulic PTO



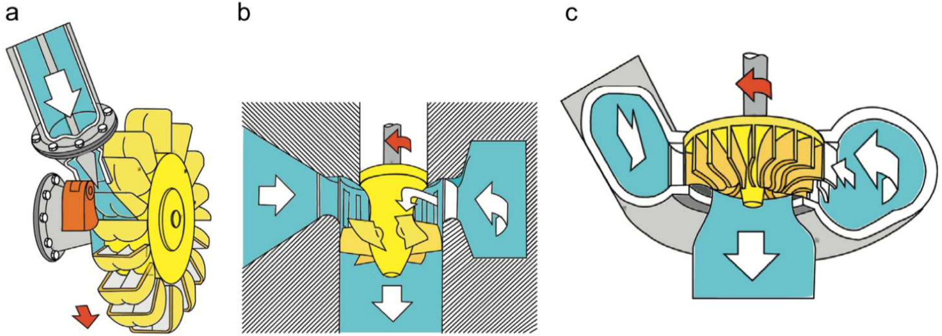
Power capture mechanisms: Mechanical System



Power capture mechanisms: Air and Hydraulic Turbines



Air turbines for WECs. (a) Wells turbine, (b) Denniss–Auld turbine and (c) impulse turbine.

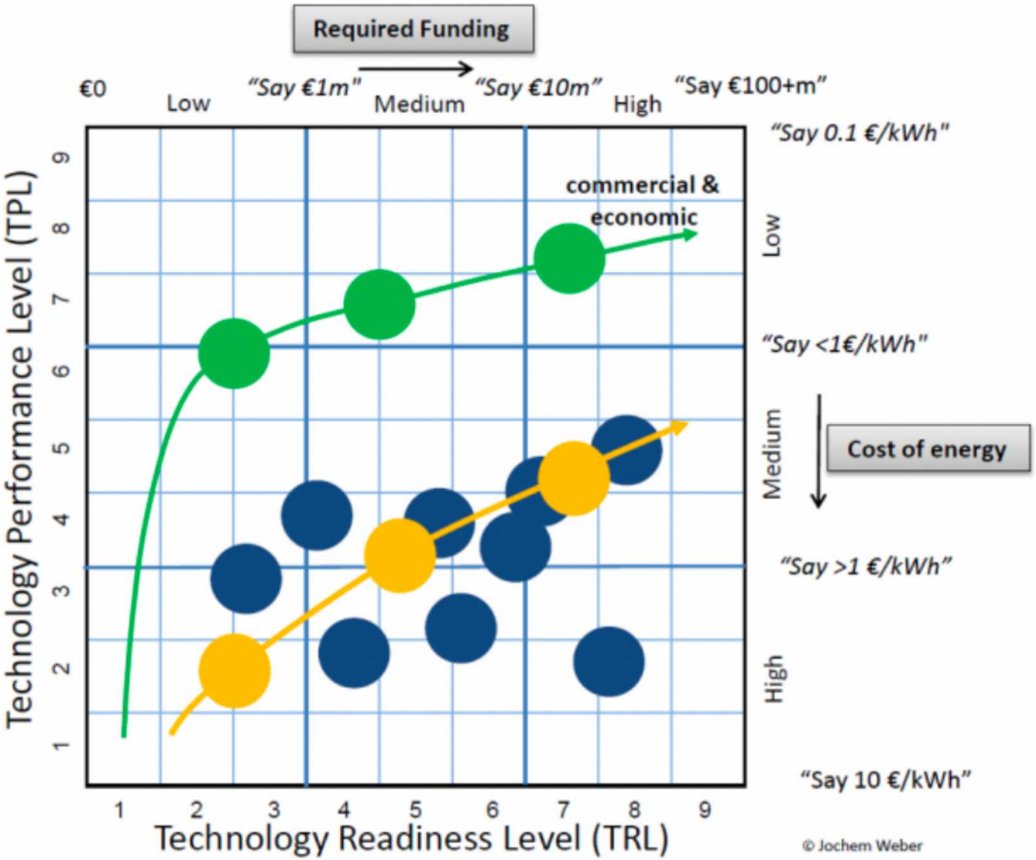


Hydro turbines for WECs. (a) Pelton turbine, (b) Kaplan turbine and (c) Francis turbine.

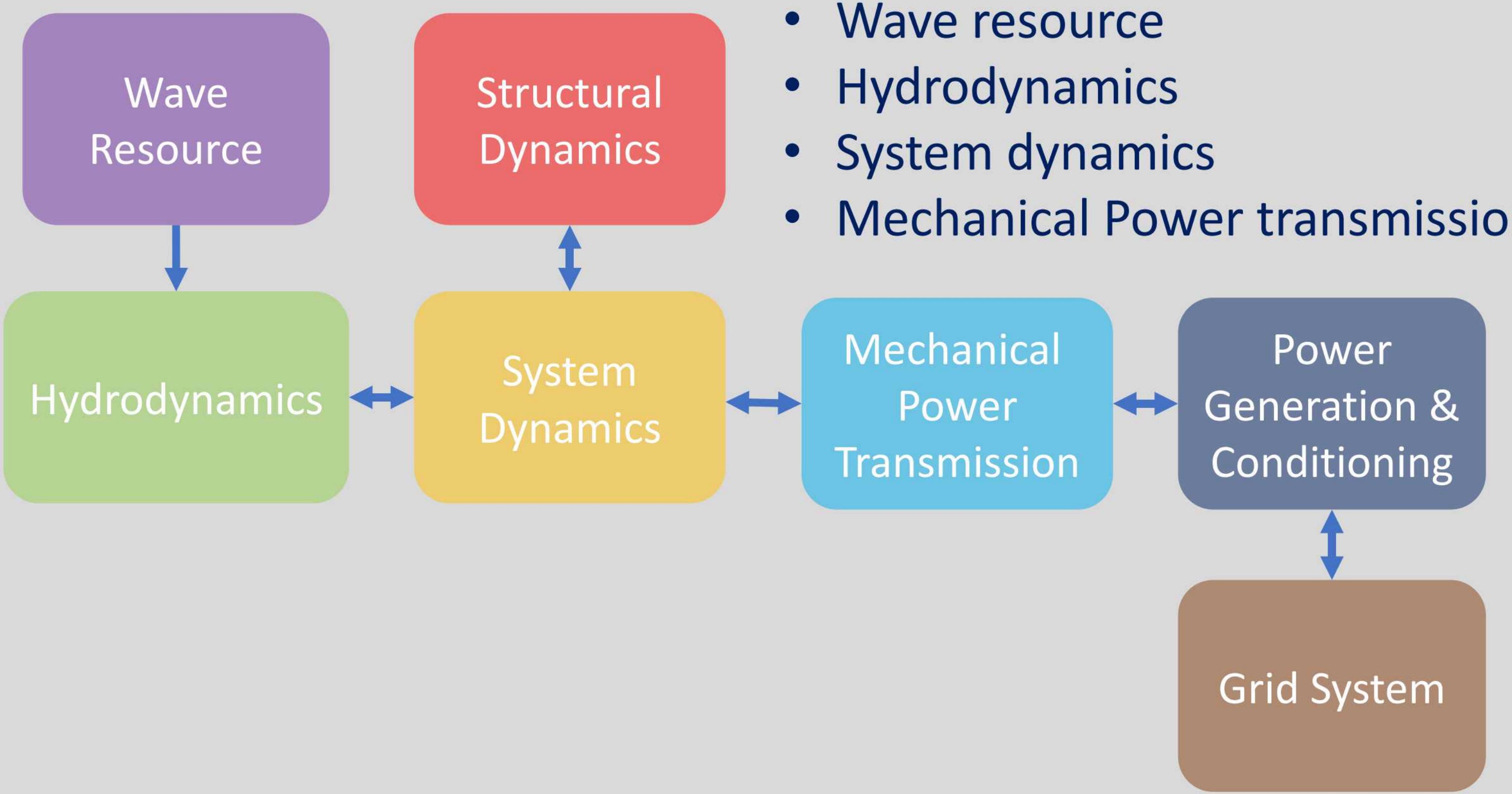
López I., Andreu J., Ceballos S., Martínez de Alegría I., and Kortabarria I., 2013, “Review of wave energy technologies and the necessary power-equipment,” Renew. Sustain. Energy Rev., **27**, pp. 413–434.

Cost Effective WEC

TRL vs TRL



WEC Analysis



Focus of this OMAE Short Course

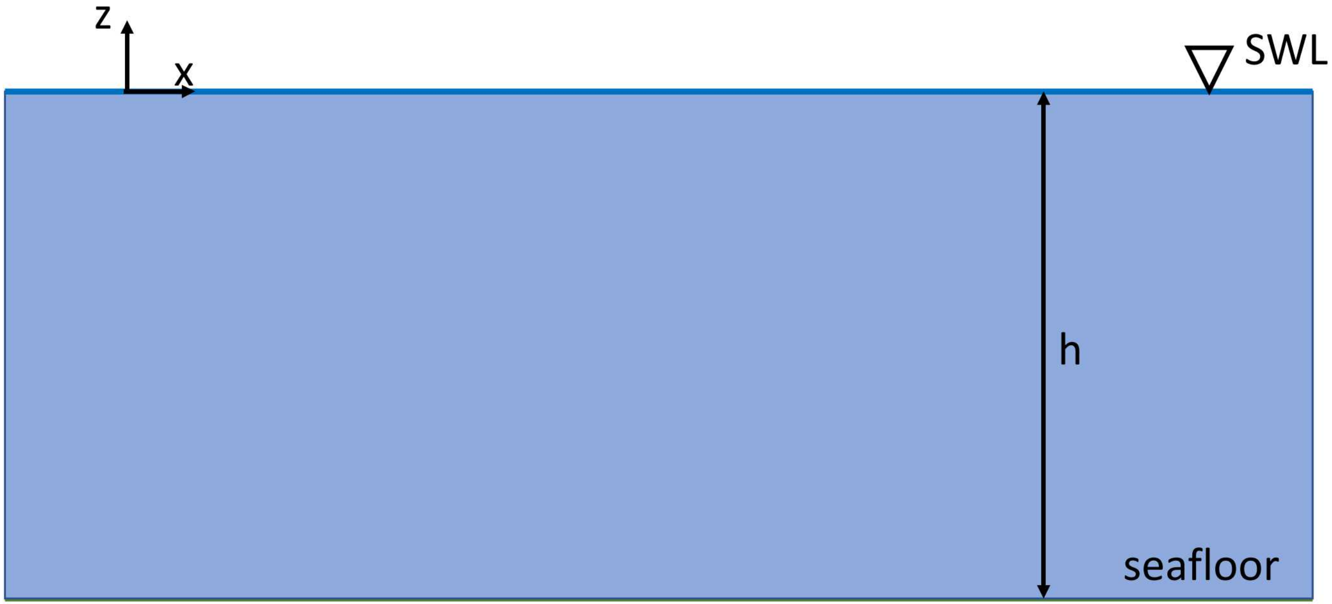
- Wave resource
- Hydrodynamics
- System dynamics
- Mechanical Power transmission

Ocean Waves

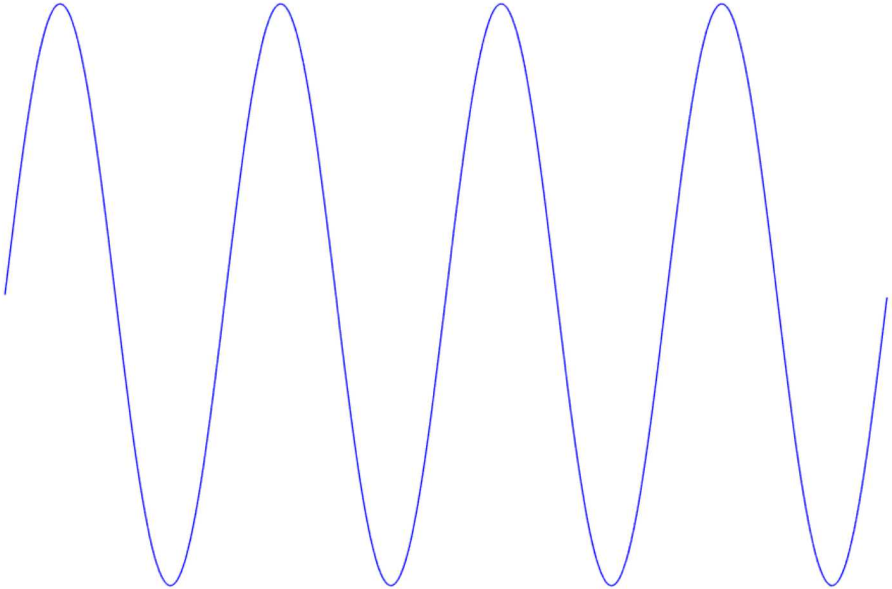
Presented by Kelley Ruehl

Free Surface

- Still Water Line (SWL) refers to the undisturbed free surface, denoted by ∇
- Origin defined at SWL with +z up and +x to the right
- Water depth, h (seafloor at z = -h)



Harmonic Waves



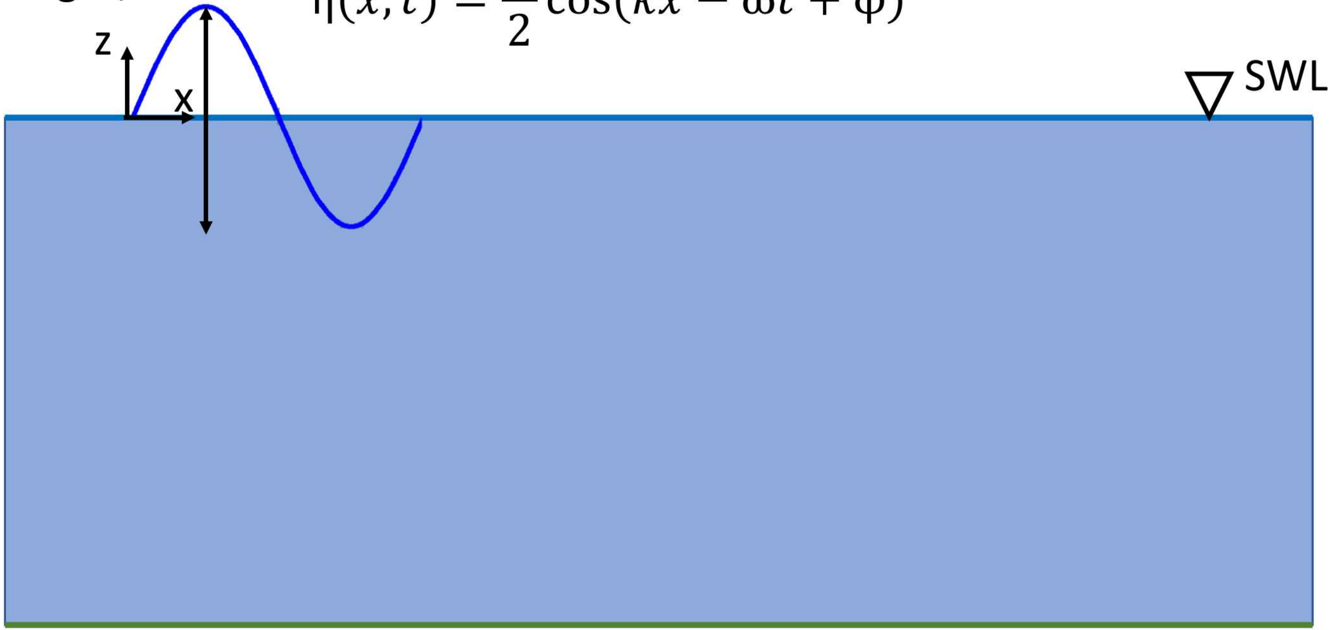
Harmonic Waves (fixed in time)

Wave amplitude, $A = \frac{H}{2}$

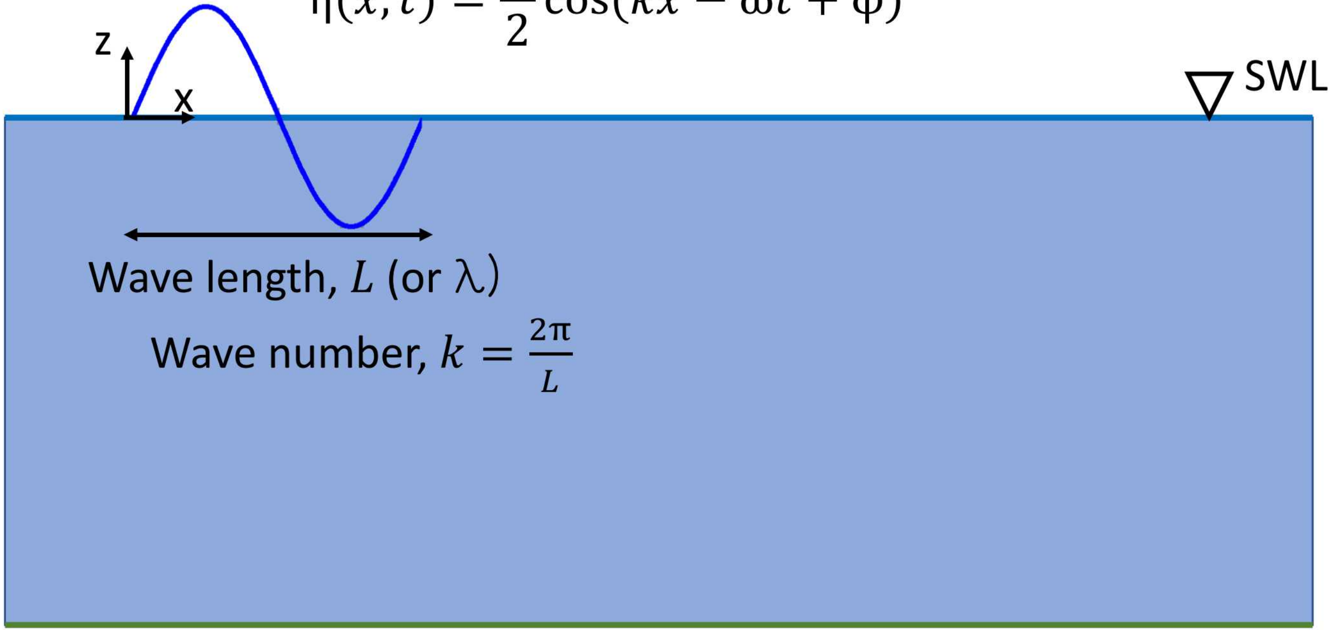
Wave surface elevation, η

Wave height, H

$$\eta(x, t) = \frac{H}{2}\cos(kx - \omega t + \varphi)$$



Harmonic Waves (fixed in time)



Wave surface elevation, η

$$\eta(x,t) = \frac{H}{2}\cos(kx - \omega t + \varphi)$$

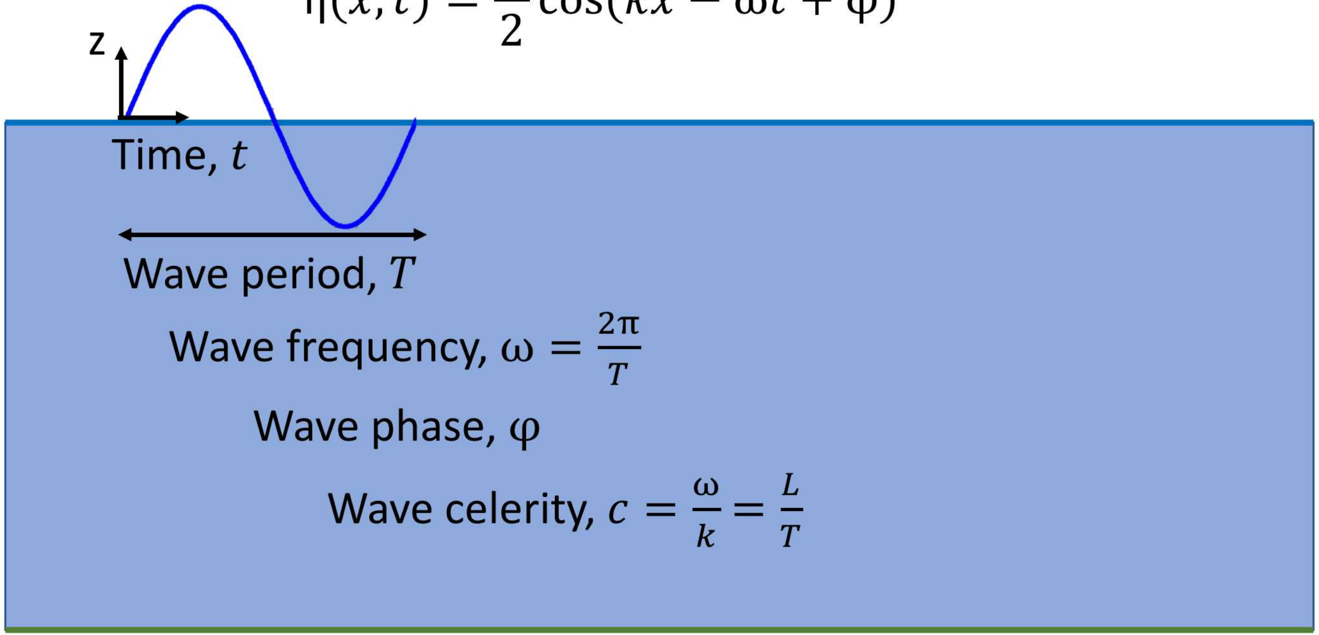
Wave length, L (or λ)

Wave number, $k = \frac{2\pi}{L}$

Harmonic Waves (fixed in space)

Wave surface elevation, η

$$\eta(x,t) = \frac{H}{2}\cos(kx - \omega t + \varphi)$$



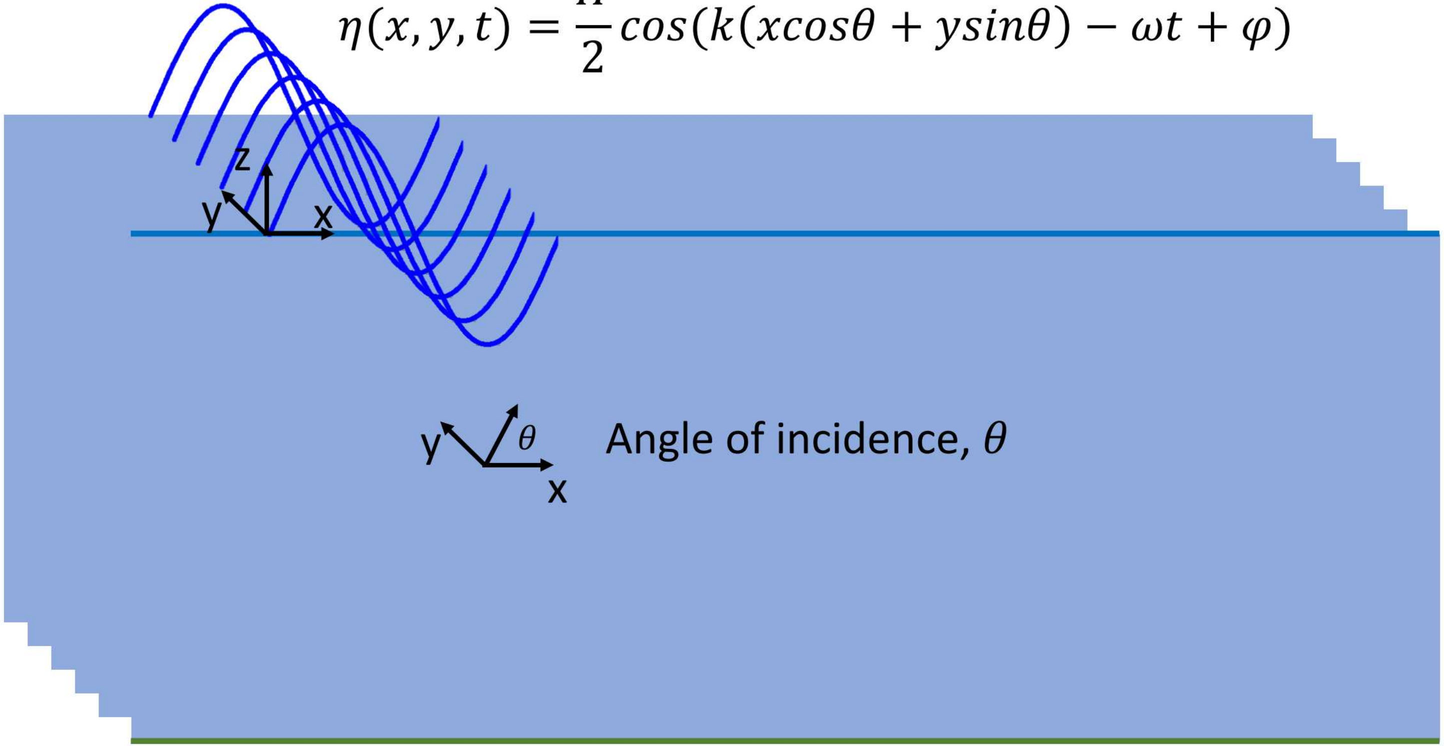
Wave frequency, $\omega = \frac{2\pi}{T}$

Wave phase, φ

Wave celerity, $c = \frac{\omega}{k} = \frac{L}{T}$

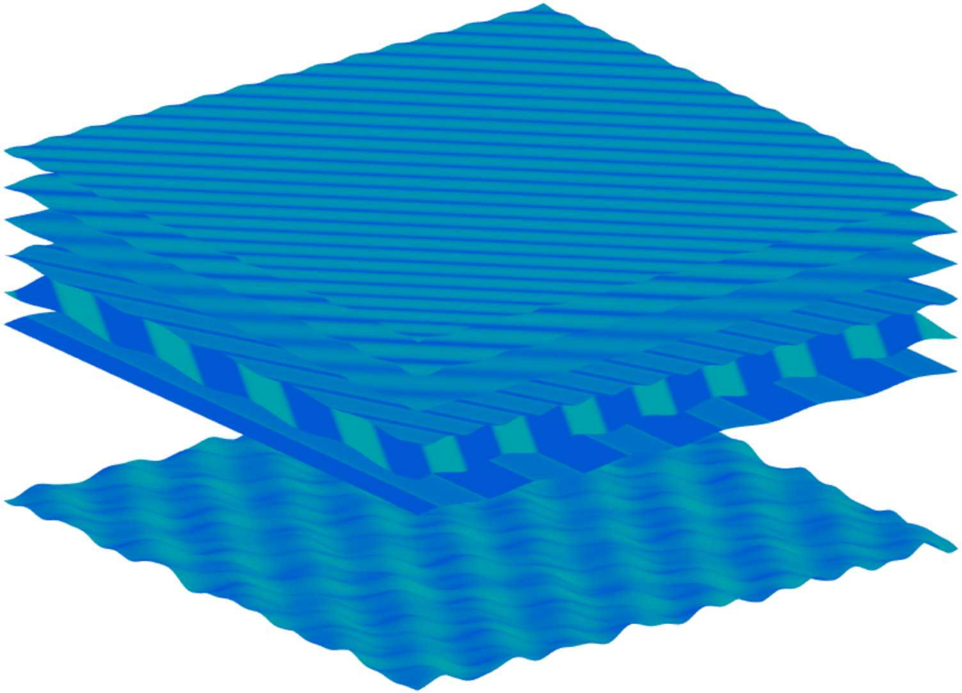
Planar Harmonic Waves (fixed in time)

$$\eta(x, y, t) = \frac{H}{2} cos(k(xcos\theta + ysin\theta) - \omega t + \varphi)$$



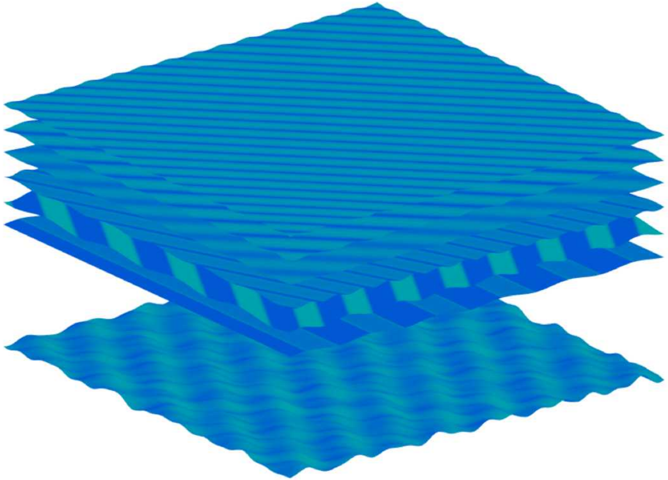
Angle of incidence, θ

Ocean Waves



Real Ocean Waves

$$\eta(x,y,t) = \sum_{i} \frac{H_i}{2} cos(k_i\ (xcos\theta_i + ysin\theta_i) - \omega_i t + \varphi_i)$$



Real ocean waves are modeled as the **linear superposition** of a large number of **harmonic waves** at **different frequencies** and **angles of incidence**

Linear superposition is the basis of linear wave theory, which assumes

- **Small amplitude motion**
- **Inviscid fluid**
- **Irrotational flow**

More on that later…

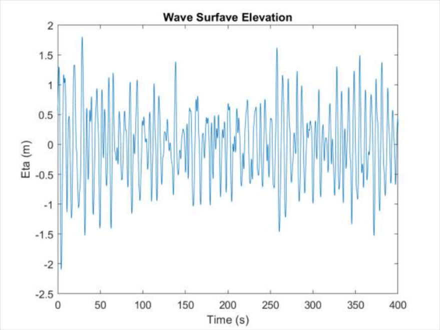
Wave Spectra

Time-domain

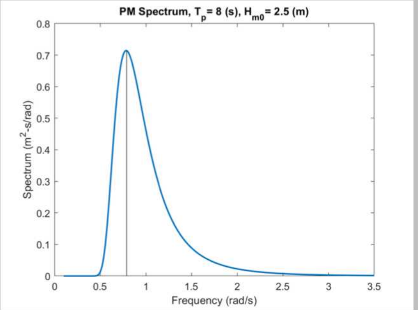
- Waves are defined as wave surface elevation as a function of time and space

Frequency-domain

- Waves are defined by energy content as a function of wave frequency
- **Spectra proportional H^2**



$$\eta(x,y,t) = \sum_i \frac{H_i}{2} cos(k_i\ (xcos\theta_i + ysin\theta_i) - \omega_i t + \varphi_i)$$



$$\overline{\eta^2\ (x,y,t)} = \int_0^\infty S(f)df$$

Wave Spectra

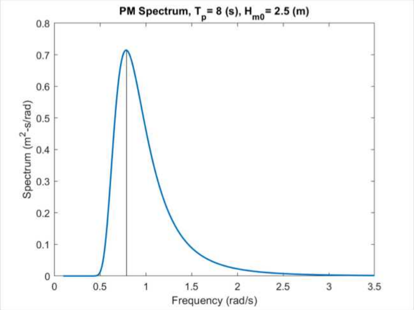
Frequency Spectra

$$m_k = \int_0^\infty f^k S(f) df \qquad H_{m0} = 4\sqrt{m_0}$$

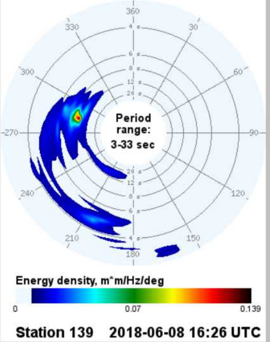
- H_{m0} = significant wave height
- Tp = peak period

Directional Spectra

- Real Ocean waves are often represented by wave spectra
- Used to determine **peak period**, **significant wave height** and **dominant wave direction**
- Θ = incident wave direction



$$\overline{\eta^2\,(x,y,t)} = \int_0^\infty S(f) df$$



$$S(f) = \int_{-\pi}^{\pi} S(f,\theta) d\,\theta$$

Wave Spectra Formulations

Pierson–Moskowitz

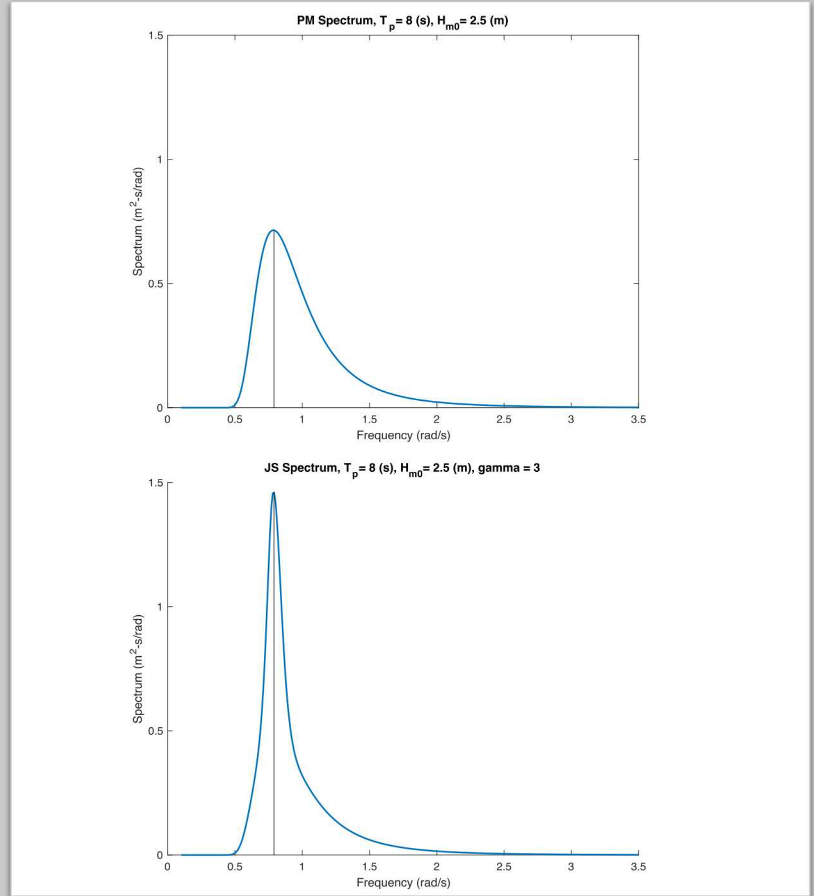
- Assumes wind blows steadily for a long time over a large area
- Fully developed seas

JONSWAP

- Joint North Sea Wave Project
- JONSWAP is a Pierson-Moskowitz spectrum multiplied by an extra peak enhancement factor ɣ

Bretschneider

- 2 parameter spectrum based on peak period and significant wave height



Wave Data Buoys

- National Data Buoy Center (NDBC) http://www.ndbc.noaa.gov/
- Coastal Data Information Program (CDIP) http://cdip.ucsd.edu/

Data Collected

- Wave Height (Hs)
- Wave Period (Tp
- Wave Direction (θ)
- Wind data (U_{mean}, U_{max} and θ)
- Wave Spectra (energy content)
- And more…

CDIP Wind Buoy

http://cdip.ucsd.edu/

NDBC Directional Buoy

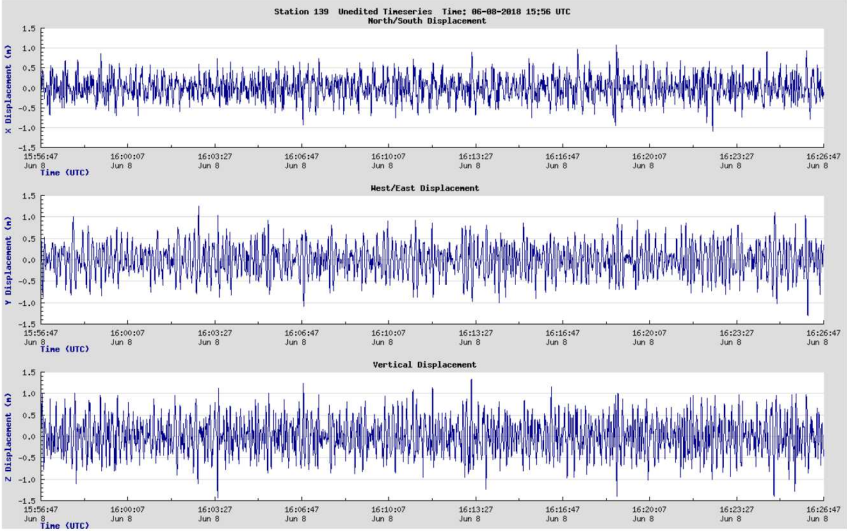
http://www.ndbc.noaa.gov/

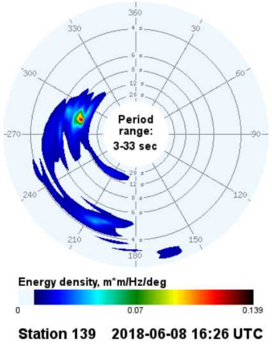
Umpqua Offshore, OR

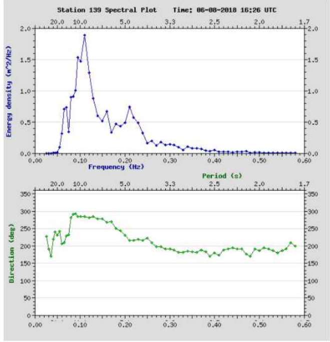
CDIP 139

- Maintains time-series of data buoy
- Generates wave spectra and wave rose

http://cdip.ucsd.edu/?nav=historic&stn=139





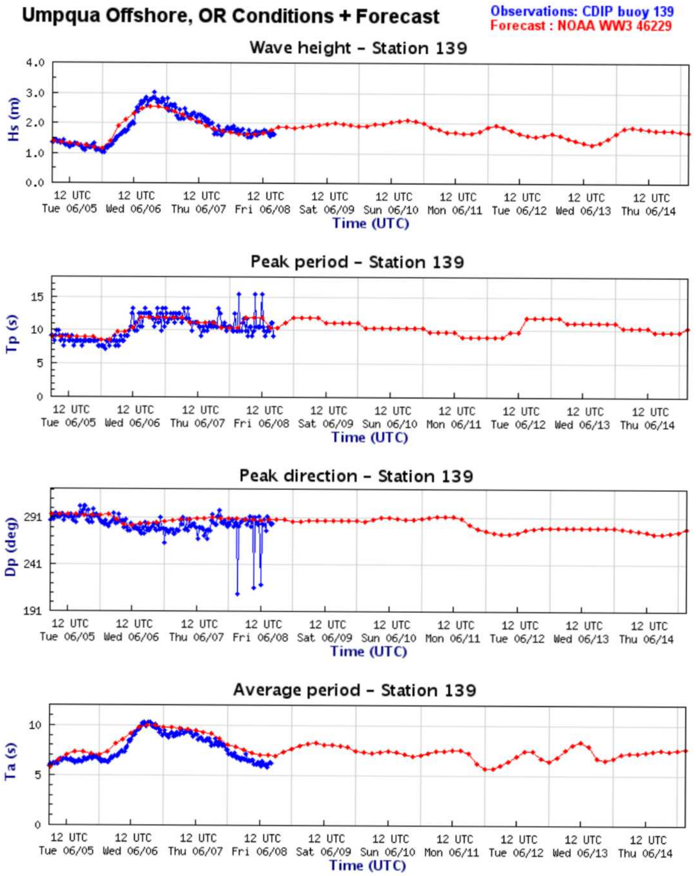


Umpqua Offshore, OR

CDIP 139

- Maintains time-series of data buoy
- Generates wave spectra and wave rose
- Compares data to WW3 Forecast

http://cdip.ucsd.edu/?nav=historic&stn=139



Umpqua Offshore, OR

NDBC 46229

- Data binned every 30min
- Maintains wave statistics
  - Peak Period
  - Significant Wave Height
  - Spectral Energy Content
- Generates data plots

http://www.ndbc.noaa.gov/station_page.php?station=46229


Wave Height at 46229

Image Credit: NOAA/NWS/NDBC

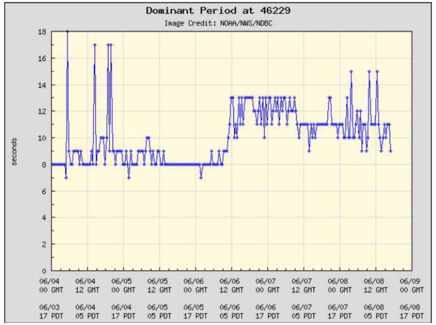

Dominant Period at 46229

Image Credit: NOAA/NWS/NDBC

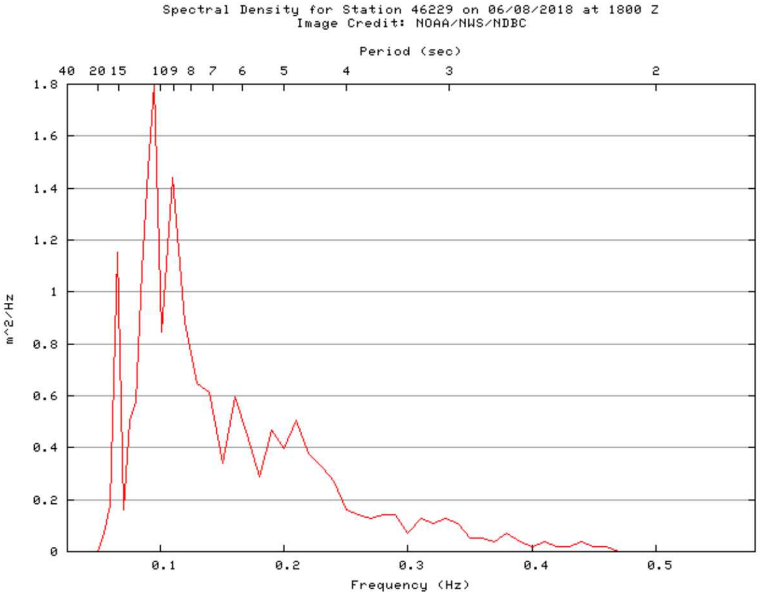
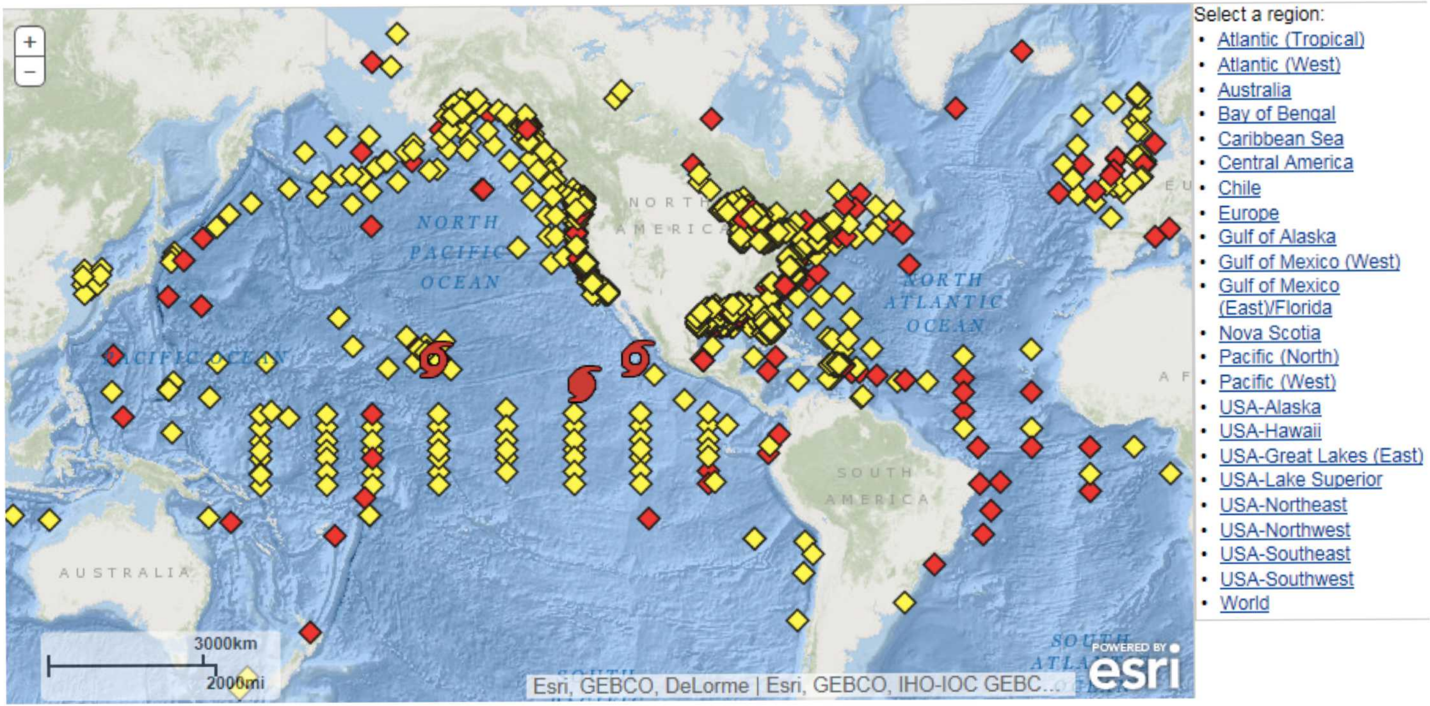

Spectral Density for Station 46229 on 06/08/2018 at 1800 Z

Image Credit: NOAA/NWS/NDBC

NDBC Worldwide Buoy Map

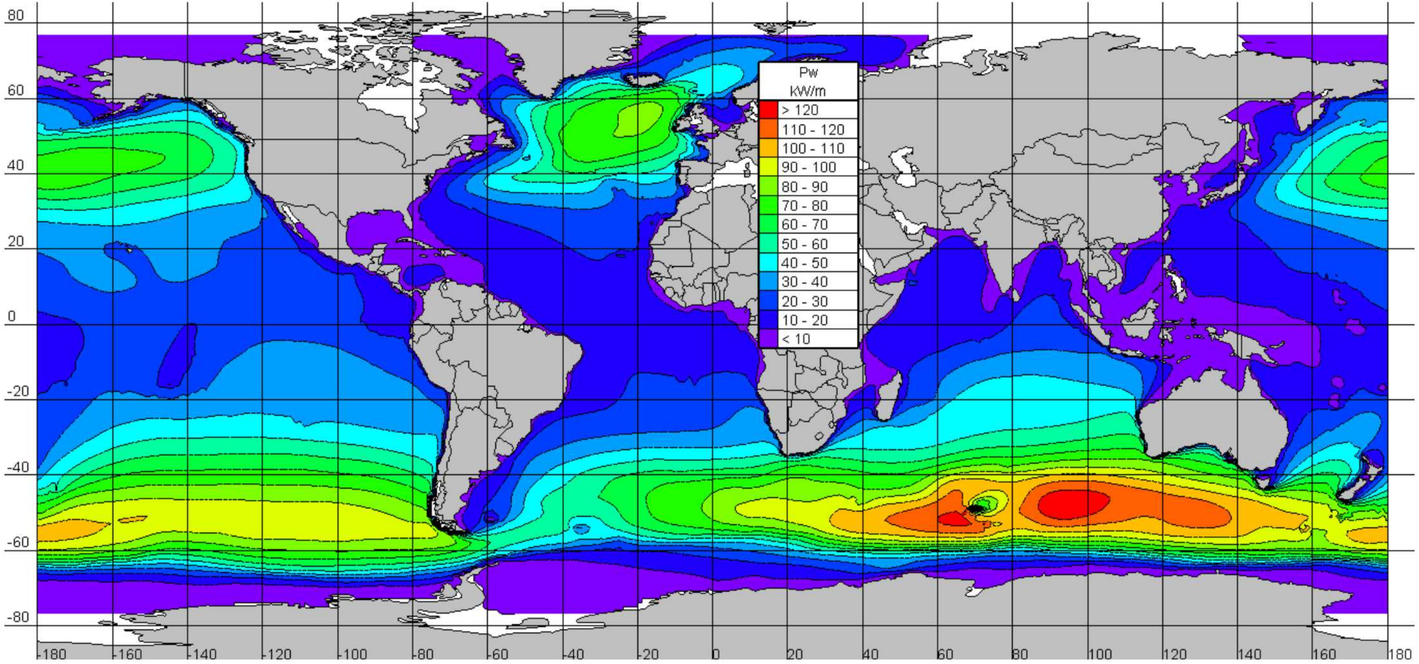


Select a region:

- Atlantic (Tropical)
- Atlantic (West)
- Australia
- Bay of Bengal
- Caribbean Sea
- Central America
- Chile
- Europe
- Gulf of Alaska
- Gulf of Mexico (West)
- Gulf of Mexico (East)/Florida
- Nova Scotia
- Pacific (North)
- Pacific (West)
- USA-Alaska
- USA-Hawaii
- USA-Great Lakes (East)
- USA-Lake Superior
- USA-Northeast
- USA-Northwest
- USA-Southeast
- USA-Southwest
- World

http://www.ndbc.noaa.gov/

Wave Energy Resource



Cornett, Andrew. (2008). A Global Wave Energy Resource Assessment.
In: Proceedings of the eighteenth international offshore and polar conference. 50.

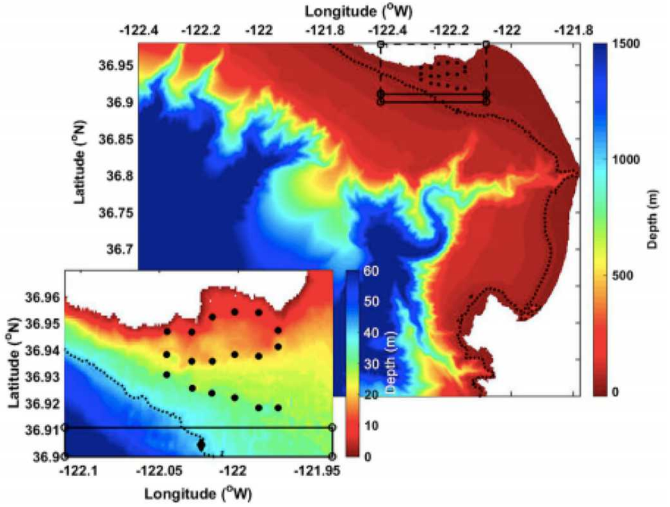
Wave propagation models

Spectral Wave Models

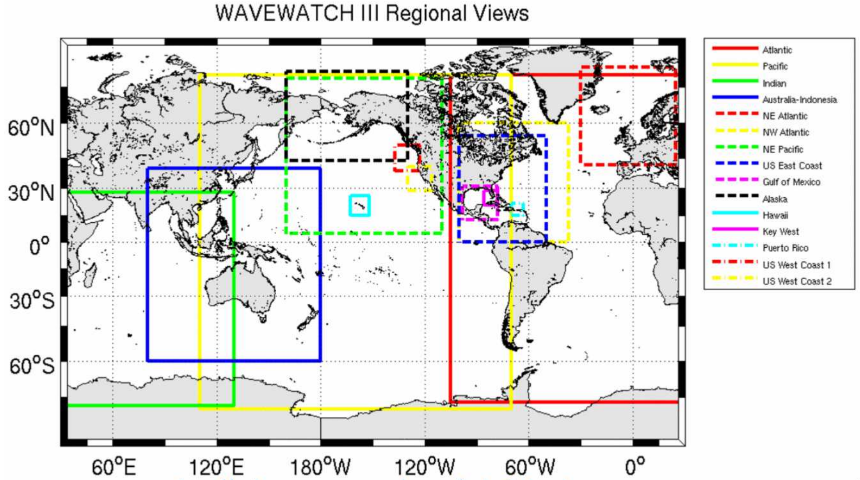
- SWAN (Simulating WAves Neashore)
- TOMAWAC

NOAA WAVEWATCH III

- Maintains 30 year hindcast
- Generates forecast based on wind data

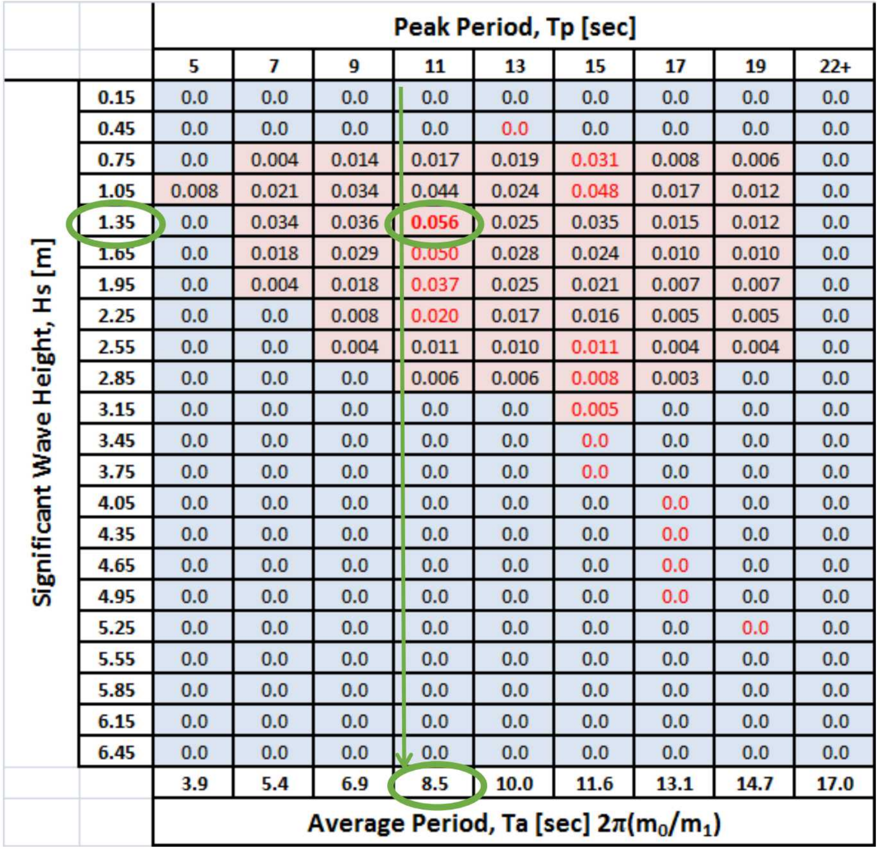


G. Chang, K. Ruehl, C. A. Jones, J. Roberts, and C. Chartrand, "Numerical modeling of the effects of wave energy converter characteristics on nearshore wave conditions," *Renewable Energy*, vol. 89, pp. 636–648, 2016.



http://polar.ncep.noaa.gov/waves/index2.shtml

Joint Probability Distribution



		Peak Period, Tp [sec]								
		5	7	9	11	13	15	17	19	22+
Significant Wave Height, Hs [m]	0.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.75	0.0	0.004	0.014	0.017	0.019	0.031	0.008	0.006	0.0
	1.05	0.008	0.021	0.034	0.044	0.024	0.048	0.017	0.012	0.0
	1.35	0.0	0.034	0.036	0.056	0.025	0.035	0.015	0.012	0.0
	1.65	0.0	0.018	0.029	0.050	0.028	0.024	0.010	0.010	0.0
	1.95	0.0	0.004	0.018	0.037	0.025	0.021	0.007	0.007	0.0
	2.25	0.0	0.0	0.008	0.020	0.017	0.016	0.005	0.005	0.0
	2.55	0.0	0.0	0.004	0.011	0.010	0.011	0.004	0.004	0.0
	2.85	0.0	0.0	0.0	0.006	0.006	0.008	0.003	0.0	0.0
	3.15	0.0	0.0	0.0	0.0	0.0	0.005	0.0	0.0	0.0
	3.45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4.05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4.35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4.65	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4.95	0.0	0.0	0.0	0.0	0.0	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
	5.55	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	5.85	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	6.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	6.45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		3.9	5.4	6.9	8.5	10.0	11.6	13.1	14.7	17.0
		Average Period, Ta [sec] $2\pi(m_0/m_1)$								

Red Region Represents 95% of all possible sea conditions.

Red text depicts most common wave period for a given significant wave height.

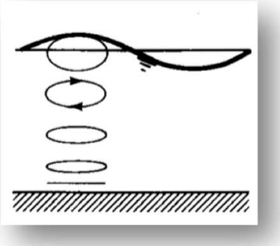
Using data summary products developed by CDIP for site

Depth Regions (from Linear Wave Theory)

WEC Type?

Shallow Water

- Water particle trajectories are elliptical
- Orbital size (energy content) is constant with depth

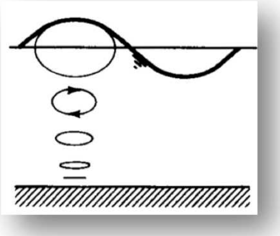


$$kh < \frac{\pi}{10}$$

$$\frac{h}{L} < \frac{1}{20}$$

Intermediate Water

- Water particle trajectories are elliptical
- Orbital size (energy content) decays with increasing water depth

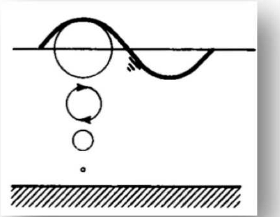


$$\frac{\pi}{10} < kh < \pi$$

$$\frac{1}{20} < \frac{h}{L} < \frac{1}{2}$$

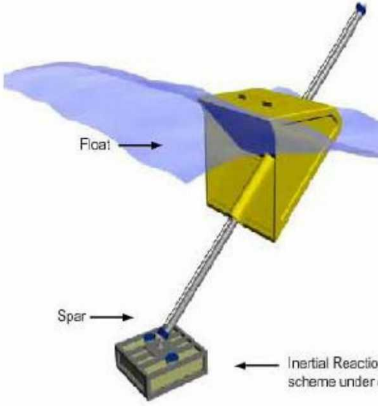
Deep Water

- Water particle trajectories are circular
- Orbital size (energy content) decays with increasing water depth



$$kh > \pi$$

$$\frac{h}{L} > \frac{1}{2}$$



Depth region has implications on LWT formulation → shallow/deep water assumptions

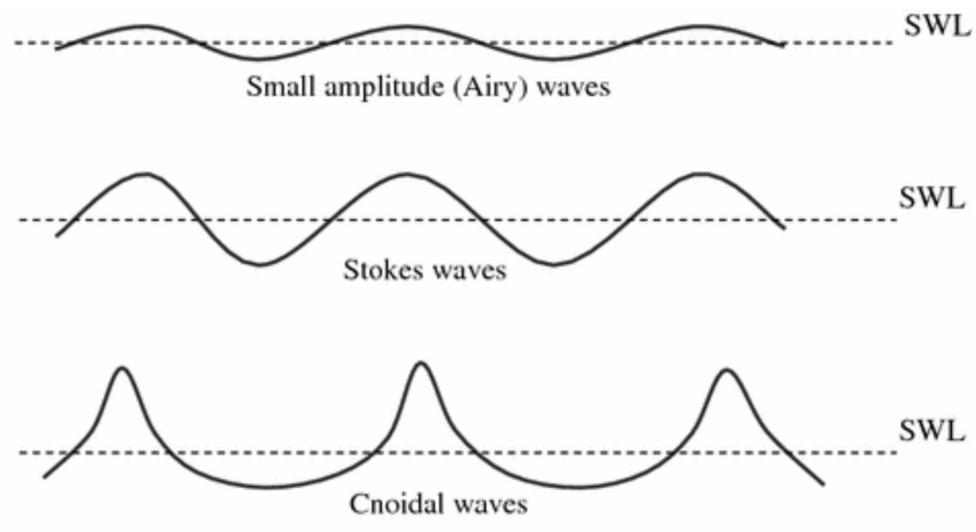
Water Wave Mechanics for Engineers and Scientists. Dean and Dalrymple. 1991. World Scientific. pg. 83

http://www.crses.sun.ac.za/files/technologies/ocean/WECs_2013_list.pdf http://www.aquamarinepower.com/

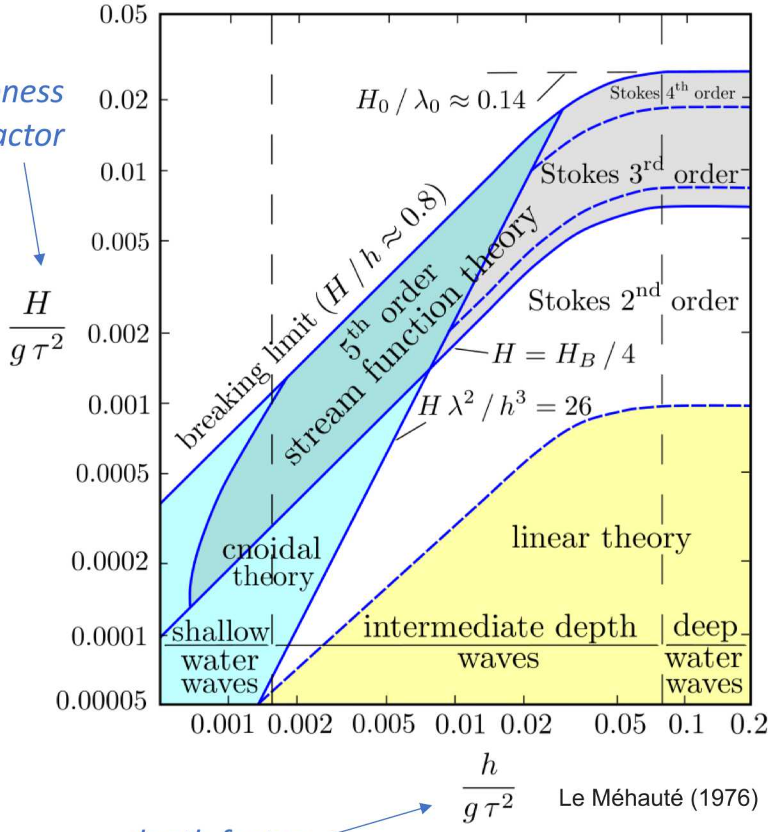
Wave Theory Formulations

Real ocean waves are not sinusoids…

we use different representations
based on some rough rules



steepness factor



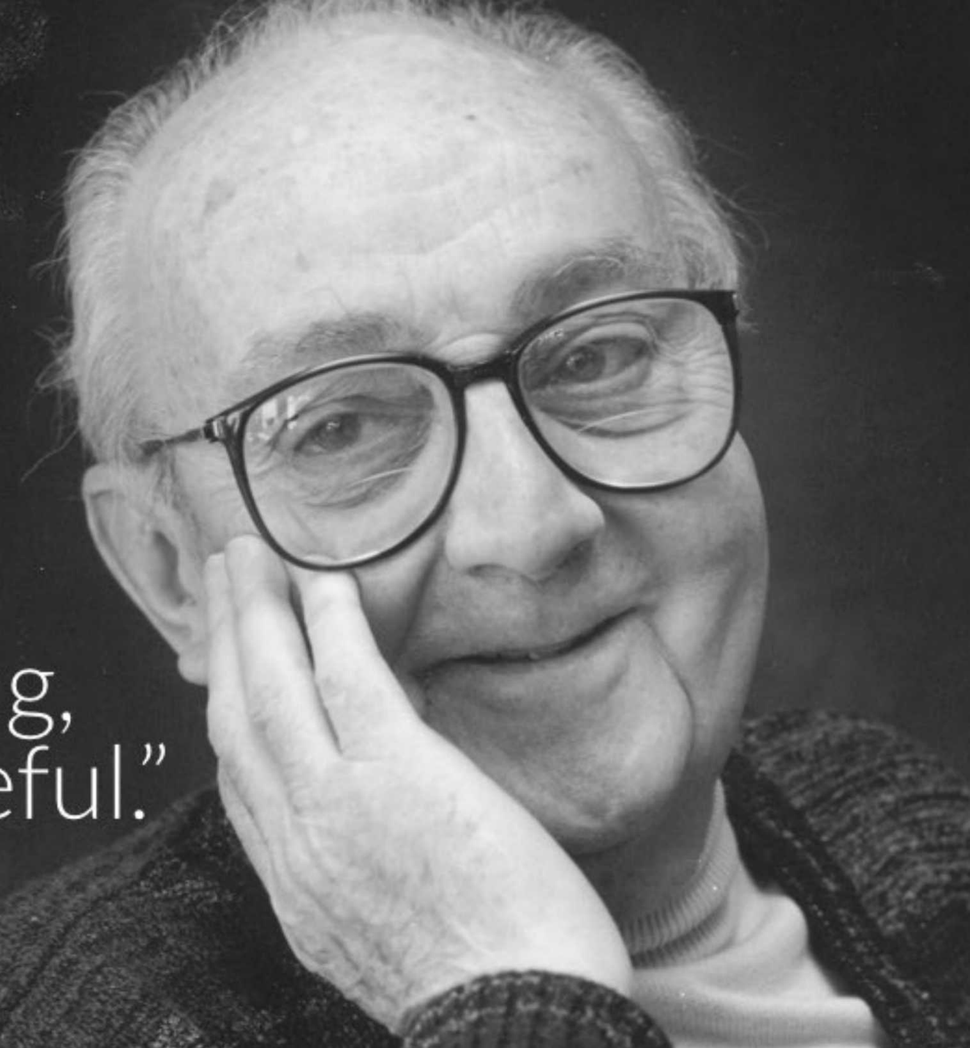
depth factor

Le Méhauté (1976)

WEC Design and Operation Requirement

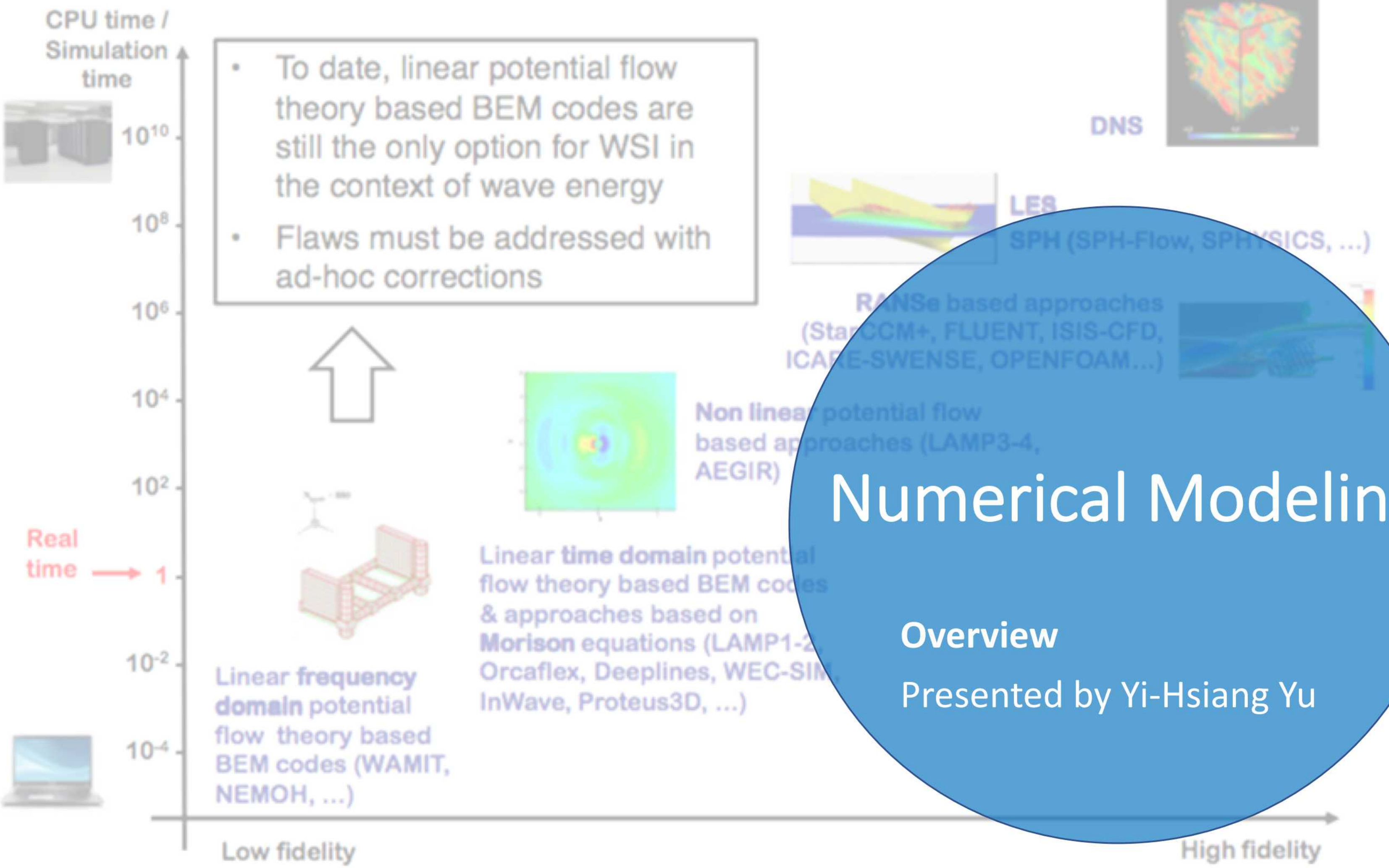
- WECs maximize energy capture and are often designed to resonate with waves (where viscous effects are essential).
- May result in large amplitude motion
- Need to survive in extreme, non-linear wave environments

http://www.oceanenergy.ie/ https://www.pelamiswave.com/



> “Essentially, all models are wrong, but some are useful.”
>
> —George E. P. Box

Coffee Break (15 mins)



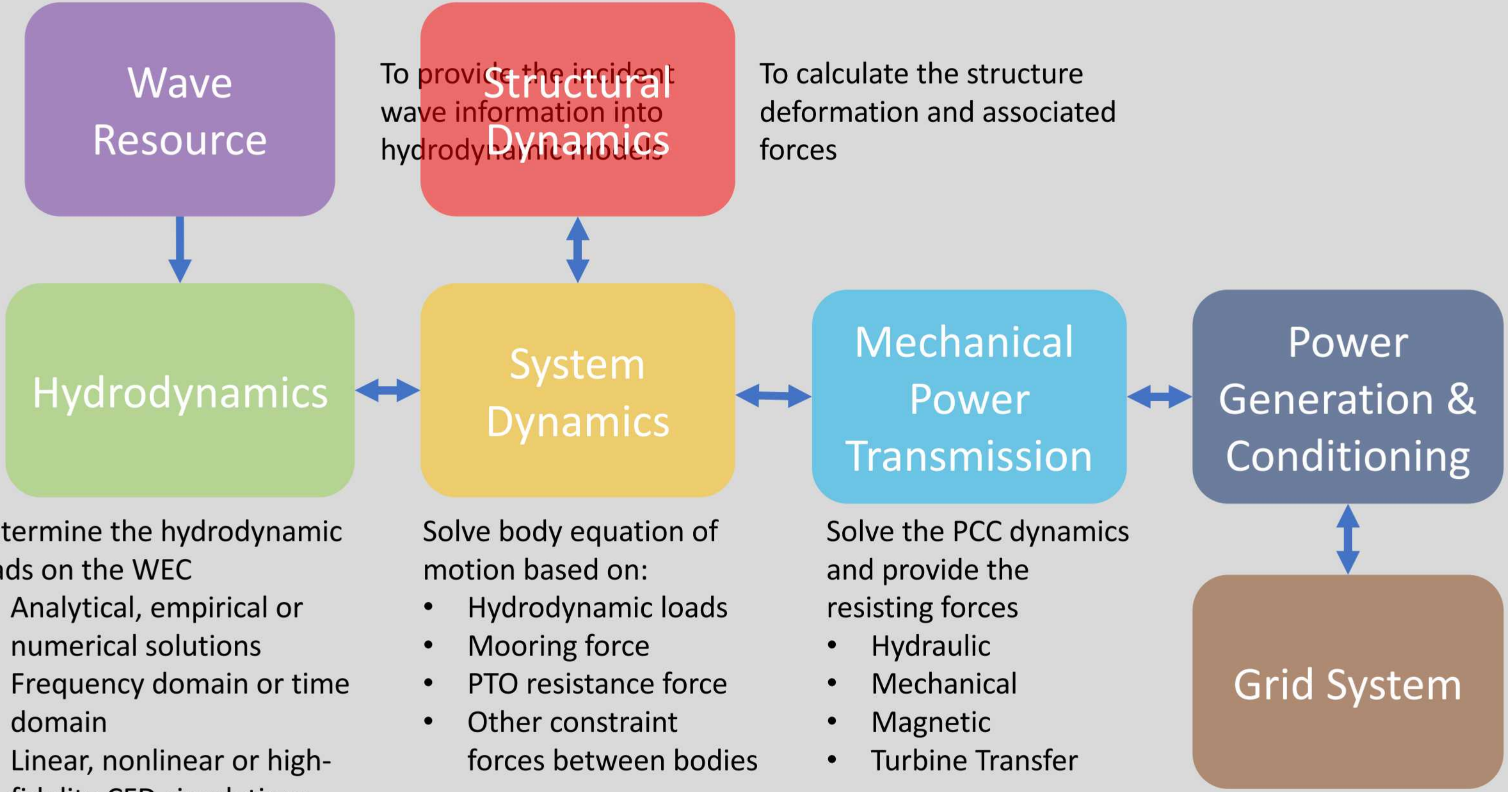
- To date, linear potential flow theory based BEM codes are still the only option for WSI in the context of wave energy
- Flaws must be addressed with ad-hoc corrections

Numerical Modeling

Overview

Presented by Yi-Hsiang Yu

WEC Simulations: Wave-To-Wire



Wave Resource

To provide the incident wave information into hydrodynamic models

Structural Dynamics

To calculate the structure deformation and associated forces

Hydrodynamics

System Dynamics

Mechanical Power Transmission

Power Generation & Conditioning

Grid System

Determine the hydrodynamic loads on the WEC

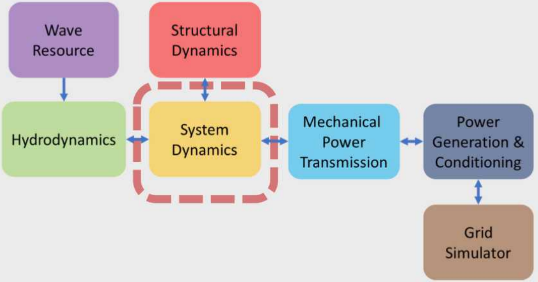
- Analytical, empirical or numerical solutions
- Frequency domain or time domain
- Linear, nonlinear or high-fidelity CFD simulations

Solve body equation of motion based on:

- Hydrodynamic loads
- Mooring force
- PTO resistance force
- Other constraint forces between bodies

Solve the PCC dynamics and provide the resisting forces

- Hydraulic
- Mechanical
- Magnetic
- Turbine Transfer



System Dynamics: Equation of motion

$$m\ddot{x}(t) = \boxed{f_{hd}(t)} + \boxed{f_{PTO}(t)} + \boxed{f_m(t)} + \boxed{f_c(t)} + \boxed{f_{st}(t)}$$

PTO forces

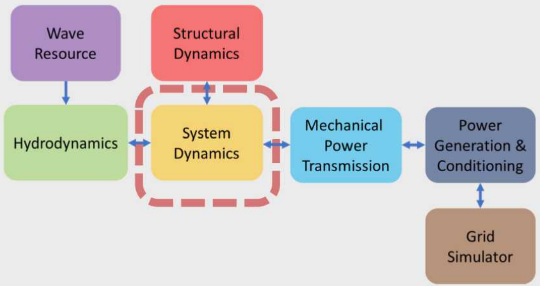
Mooring force

Constraint forces between bodies/reference frame

Forces from structure displacement

Hydrodynamic loads

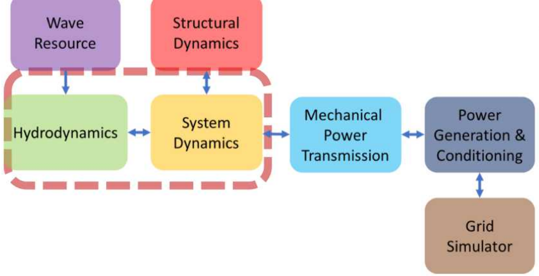
- Wave induced forces
- Body motion
- Gravity and buoyancy forces
- Including the effect of fluid viscosity



System Dynamics: Equation of motion

The resulting governing equations for the flow, PTO and the structure displacement can be combined and solved simultaneously using a single solver or more often solved separately and coupled through iterations.

The iterative approach allows the use of more efficient numerical approaches for solving fluid dynamics and structural dynamics, such as different time step sizes and time marching methods.



Wave Resource

Structural Dynamics

Hydrodynamics

System Dynamics

Mechanical Power Transmission

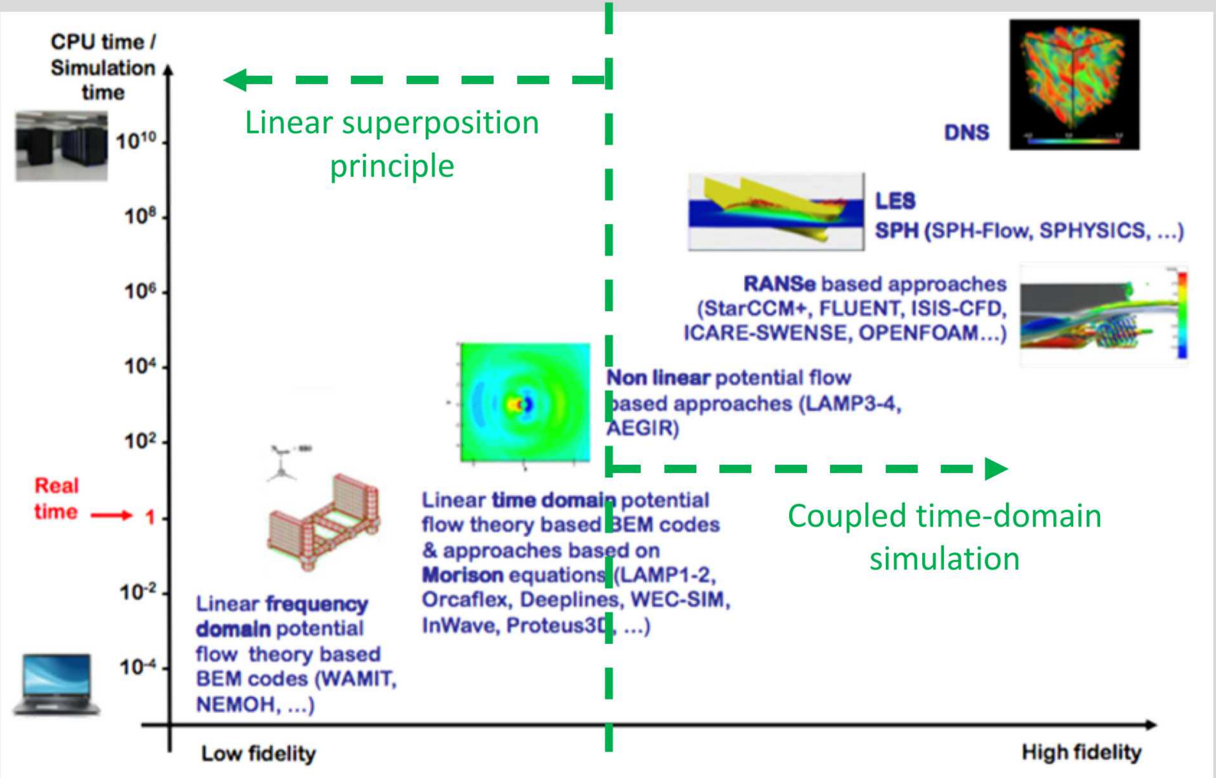
Power Generation & Conditioning

Grid Simulator

Wave and Floating Body Interaction:

Linear superposition principle
Vs
Coupled time-domain simulation

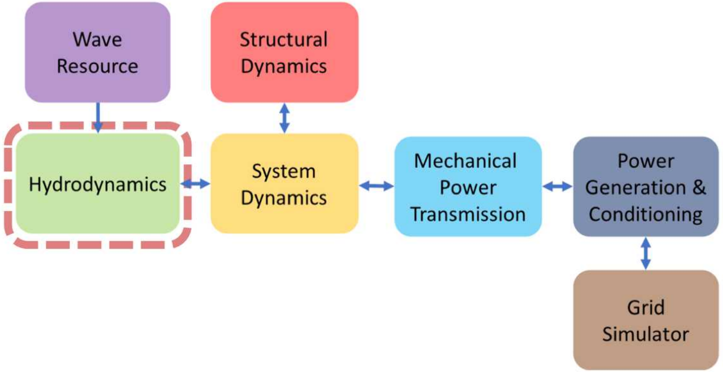
Hydrodynamics and system dynamic model fidelity versus computational time

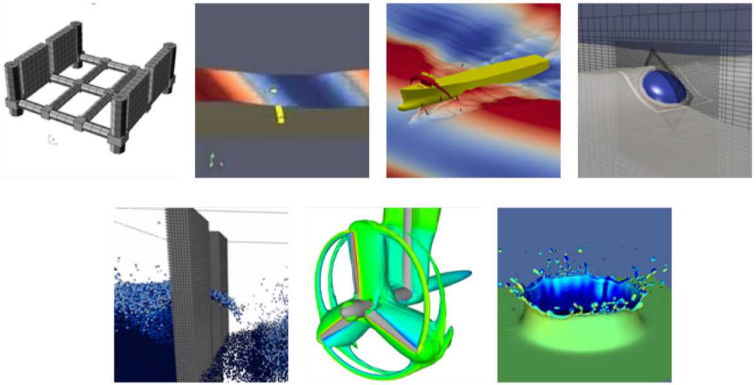


Hydrodynamics Simulation

Determine the hydrodynamic loads on the WEC

- Analytical, empirical or numerical solutions
- Frequency domain or time domain
- Linear, nonlinear or high-fidelity CFD simulations

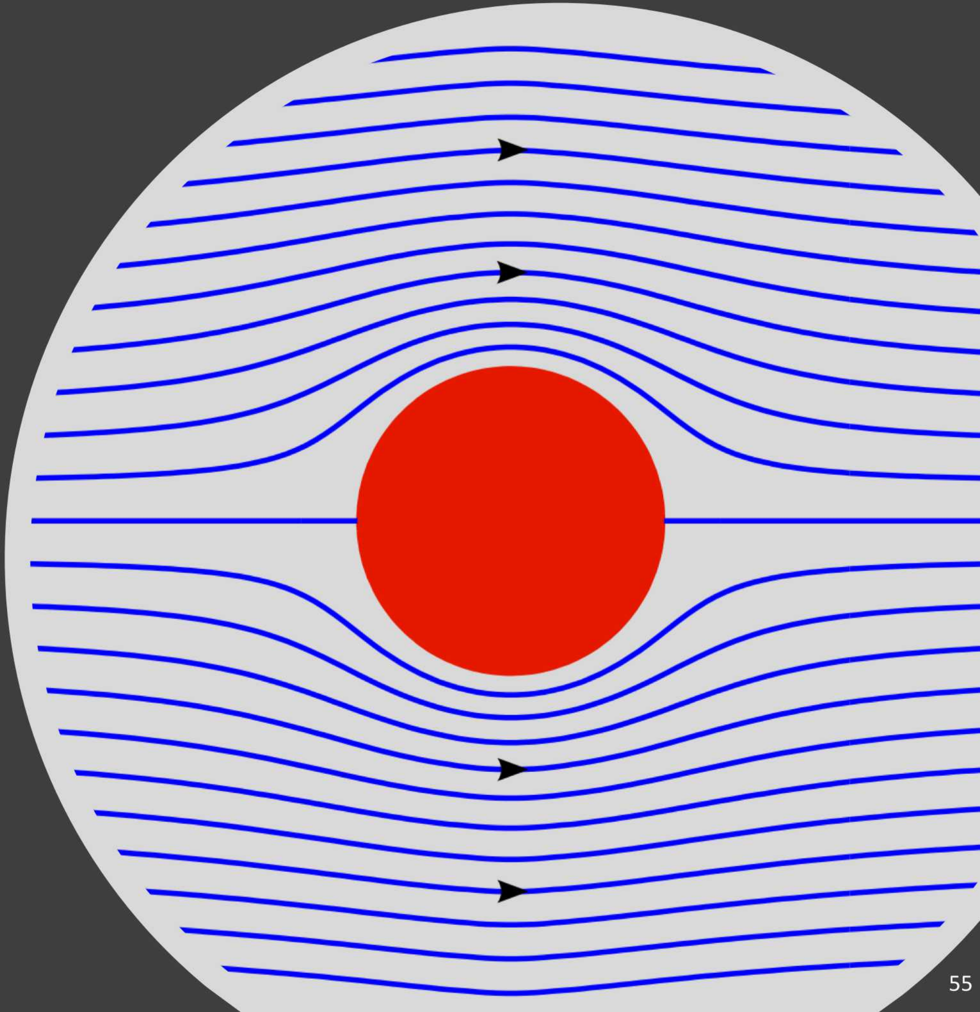




Potential flow

Presented by Ryan Coe

Hydrodynamics Simulation



Potential flow

ϕ Scalar function describing flow kinematics (velocity)

$$u_i = \partial\phi/\partial x_i$$

$$\vec{v} = \nabla\phi$$

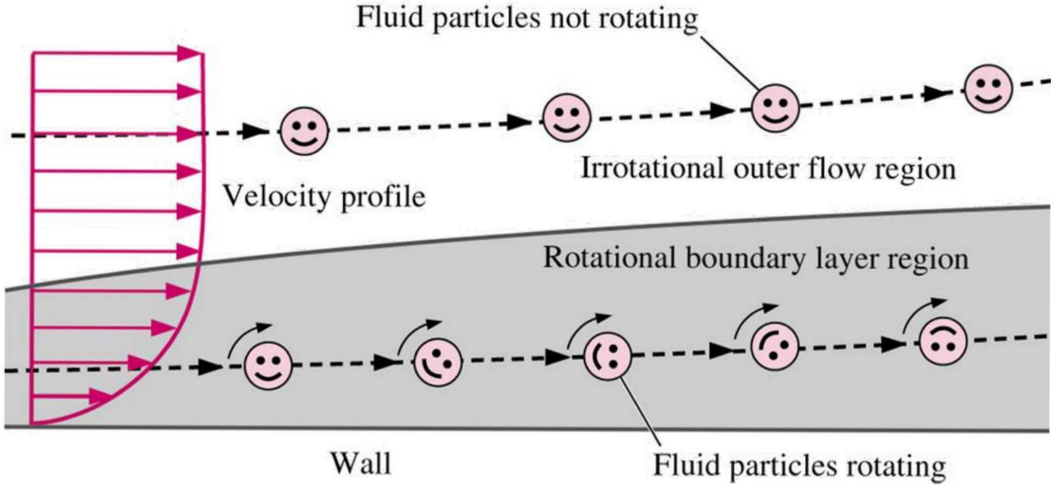
$$\nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2}$$

Potential flow - Irrotational

$$\nabla \times \nabla\phi = 0$$

True for <u>any</u> scalar

$$\nabla \times \vec{v} = 0$$



The internet (source unknown)

Potential flow - incompressible

$$\nabla \cdot \vec{v} = 0$$

$$\nabla \cdot \nabla \phi = 0$$

$$\boxed{\nabla^2 \phi = 0}$$

"continuity"

1 equation
1 unknown

Also…

pressure is decoupled, so we can solve for it independently!

$$p = f(\vec{v}) = f(\nabla \phi)$$

Potential flow – Bernoulli's eq.

$$\boxed{p = -\rho\left(\frac{\partial\phi}{\partial t} + \frac{1}{2}\left|\nabla\phi\right|^2 + \frac{p}{\rho} + gz\right) + F(t)}$$

https://en.wikipedia.org/wiki/Cavitation#/media/File:Cavitating-prop.jpg

https://en.wikipedia.org/wiki/Contrail#/media/File:A340-313X.jpg

https://commons.wikimedia.org/wiki/File:Cloud_over_A340_wing.JPG

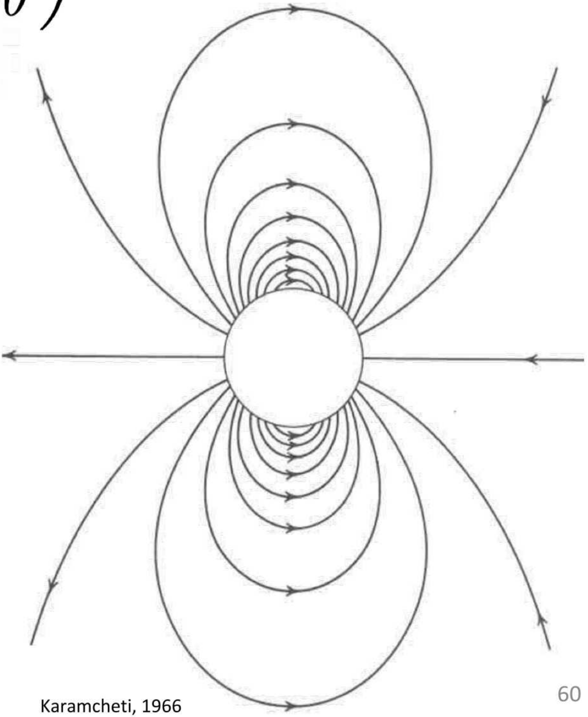
Potential flow – simple problem

$$\nabla^2\phi = 0 \quad \Rightarrow \quad \frac{\partial}{\partial r}\left(r^2 \sin(\theta)\frac{\partial \phi}{\partial r}\right) + \frac{\partial}{\partial \theta}\left(\sin(\theta)\frac{\partial \phi}{\partial \theta}\right) = 0$$

$$\vec{v} = \nabla\phi \quad \Rightarrow \quad \frac{\partial \phi}{\partial r} = -U\cos(\theta), \quad \text{on } r = a$$

$$\phi(r,\theta,t) = \frac{U(t)a^3\cos(\theta)}{2r^2}$$

$$= -\frac{a\vec{U}(t)\cdot\vec{r}}{2r^3}$$



Karamcheti, 1966

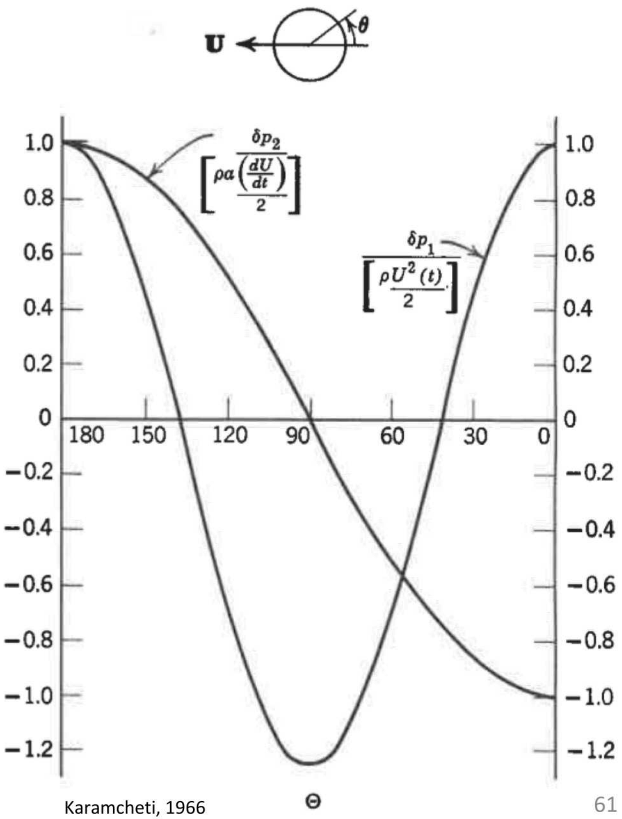
Potential flow – simple problem

$$p(a,\theta,t) = p_\infty + \frac{\rho}{2}\left(\underbrace{\frac{U^2(t)}{4}\left(9\cos^2(\theta)-5\right)}_{\textit{Steady}} - \underbrace{a\frac{dU}{dt}\cos\left(\theta\right)}_{\textit{Unsteady}}\right)$$

$$\vec{F} = \frac{\rho a}{2}\frac{dU}{dt}\int\int \hat{n}\cos\theta a^2 \sin\theta \, d\theta d\varphi$$

$$\boxed{F_x = -\frac{2}{3}\pi a^3 \rho \frac{dU}{dt}}$$

Only force is caused by acceleration!



Karamcheti, 1966

Potential flow – waves

$$\text{at } z = \eta(t)$$

kinematic boundary condition

$$\boxed{\underbrace{\frac{\partial \phi}{\partial z}}_{\text{velocity of a particle at free surface}} = \underbrace{\frac{\partial \eta}{\partial t}}_{\text{velocity of free surface interface}}}$$

→ ***Vertical velocity or free surface and particles are equal***

$$\text{at } z = \eta(t)$$

dynamic boundary condition

$$\boxed{\eta = -\frac{1}{g}\frac{\partial \phi}{\partial t}}$$

→ ***Pressure is constant across the free surface interface***

Potential flow – waves, linearized

$$\text{at } z = 0$$

kinematic boundary condition

$$\boxed{\frac{\partial \phi}{\partial z} = \frac{\partial \eta}{\partial t}}$$

Small waves!
(with wavelength much larger than amplitude)

$$\text{at } z = 0$$

dynamic boundary condition

$$\boxed{\eta = -\frac{1}{g}\frac{\partial \phi}{\partial t}}$$

Potential flow – waves, linear

differentiating the dynamic boundary condition with time and combining with the kinematic boundary condition…

$$\text{at } z = 0$$

$$\boxed{\frac{\partial^2 \phi}{\partial t^2} + g\frac{\partial \phi}{\partial z} = 0}$$

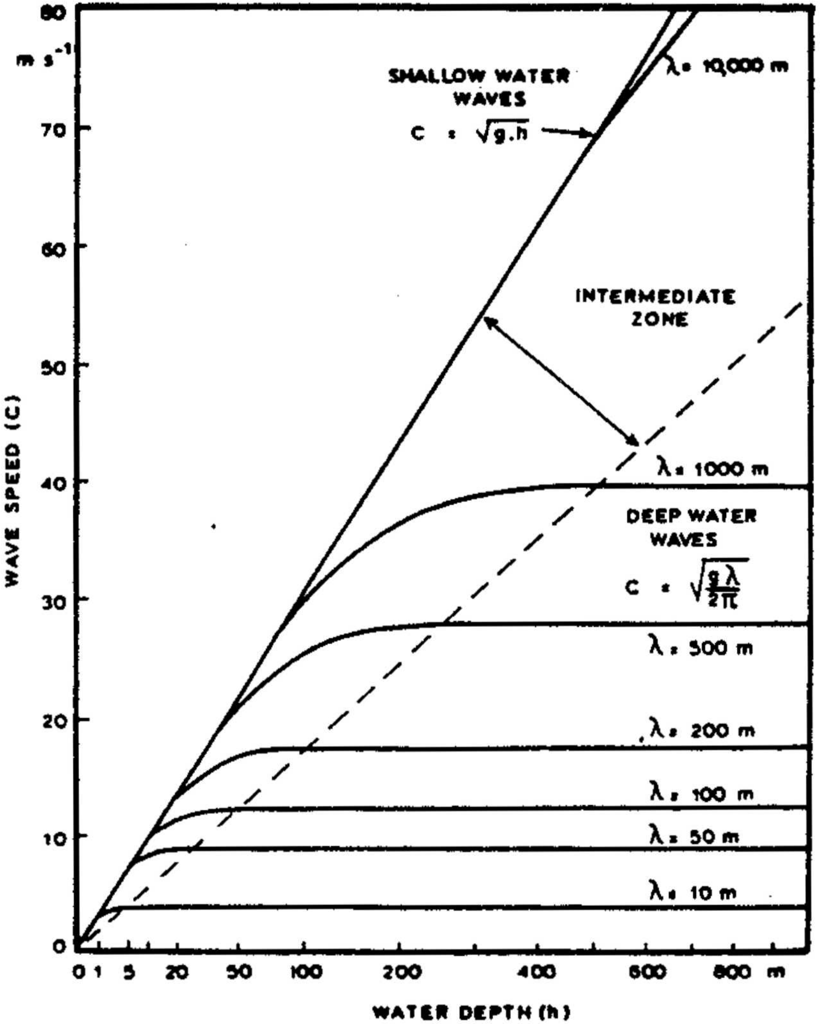
Potential flow – waves

$$\frac{\partial^2 \phi}{\partial t^2} + g\frac{\partial \phi}{\partial z} = 0$$

the "dispersion relation"

$$\boxed{\omega^2 = gk\tanh kh}$$

Phase speed $c = \frac{\omega}{k}$



Bowden, 1983

Potential flow – waves, energy

Considering the energy in waves…

We can quantify the average energy passing through a plane

$$P_p = \int_{-h}^{0} \rho g z \frac{\partial \phi}{\partial x} dz$$

$$P_k = \int_{-h}^{0} \frac{1}{2} \rho \left| \nabla \phi \right|^2 \frac{\partial \phi}{\partial x} dz$$

$$P = P_p + P_k = E \underbrace{c_g}_{}$$

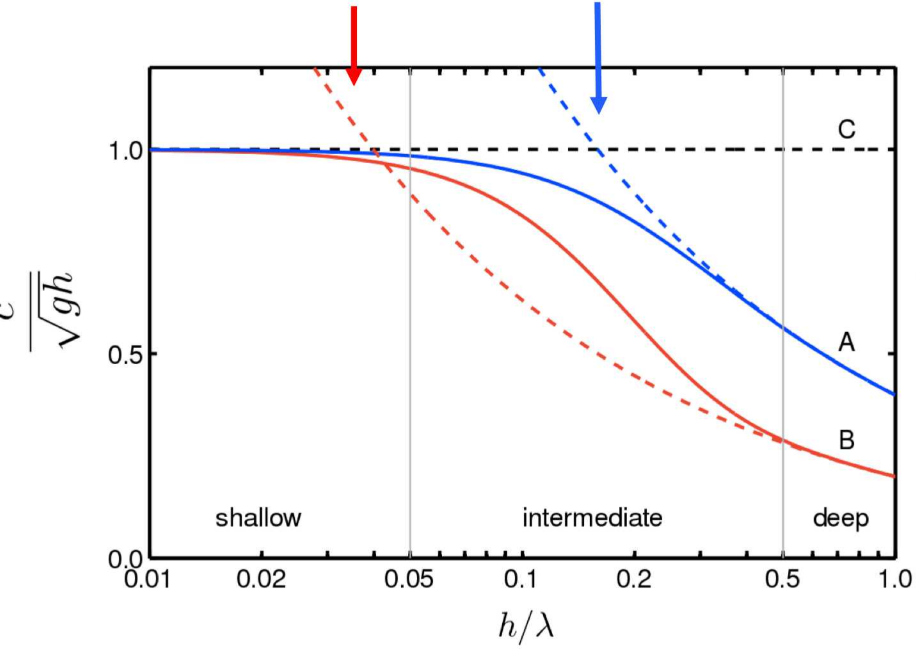
Energy transport speed
(“group velocity”)

$$E = \frac{1}{2} \rho g A^2$$

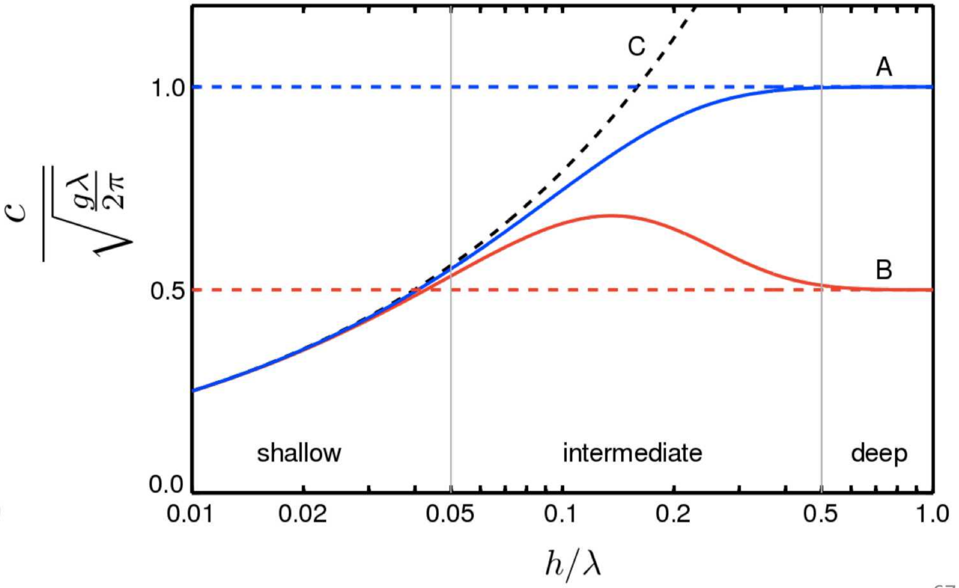
Potential flow – waves, energy

Group velocity

$$c_g = \frac{1}{2}\underbrace{\frac{\omega}{k}}_{\textit{Phase velocity}}\left(1 + \frac{2kh}{\sinh 2kh}\right)$$


group vel.

phase vel.



https://en.wikipedia.org/wiki/Dispersion_(water_waves)

Potential flow – waves, energy

In deep water…

Energy in waves travels more slowly than the crests

$$\begin{aligned} c_g &= \frac{1}{2}c \\ &= \frac{1}{2}\omega k \\ &= \frac{gT}{4\pi} \end{aligned}$$

$$P = E c_g$$

$$\boxed{P = \frac{1}{8\pi}\rho g^2 A^2 T}$$

Boundary element model

Linear (frequency domain)

WAMIT INC

The State of the Art in Wave Interaction Analysis

LHEEA CENTRALE NANTES

NEMOH

- Small motion around mean position, small steepness
- Linearized boundary conditions
- Harmonic solutions (frequency domain)

Nonlinear

- LAMP4
- AEGIR
- Xwave

- Various levels of nonlinearity
- Time-domain
- Limited to single solution (no wave breaking)

Boundary element model - linear

- The free-surface and body-boundary conditions are linearized
- A harmonic time dependence is adopted for ϕ

$$\Phi = \mathrm{Re}(\varphi e^{i\omega t})$$

The linearization of the problem permits decomposition of φ into the ***radiation*** and ***diffraction*** components

$$\varphi = \varphi_R + \varphi_D$$

$$\varphi_R = i\omega \sum_{j=1}^{6} \xi_i \varphi_i$$

$$\varphi_D = \varphi_0 + \varphi_S$$

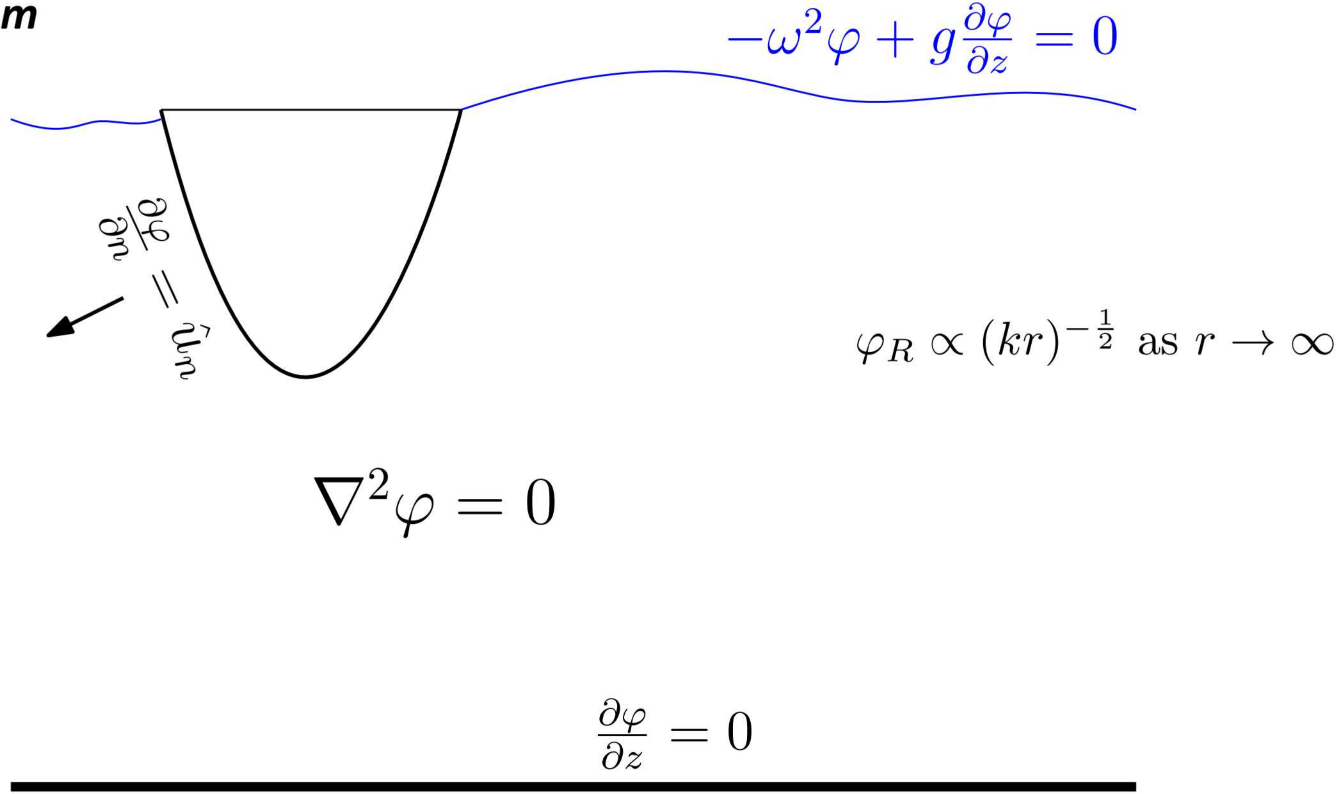
Boundary element model - linear

Now our free surface boundary condition simplifies to

$$\overset{\text{at } z=0}{\boxed{\frac{\partial^2\phi}{\partial t^2}+g\frac{\partial\phi}{\partial z}=0}}\quad\Longrightarrow\quad\overset{\text{at } z=0}{\boxed{-\omega^2\varphi+g\frac{\partial\varphi}{\partial z}=0}}$$

Boundary element model - linear

Boundary value problem



$$-\omega^2\varphi + g\frac{\partial\varphi}{\partial z} = 0$$

$$\frac{\partial\varphi}{\partial n} = \hat{u}_n$$

$$\varphi_R \propto (kr)^{-\frac{1}{2}} \text{ as } r \to \infty$$

$$\nabla^2\varphi = 0$$

$$\frac{\partial\varphi}{\partial z} = 0$$

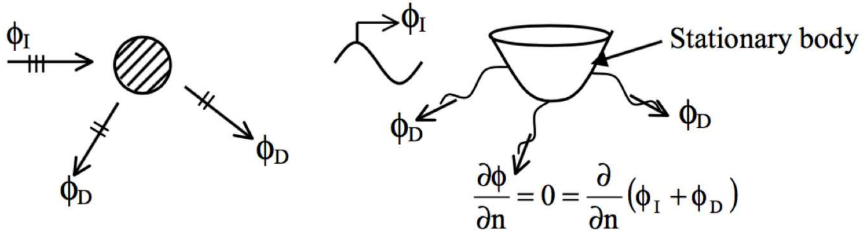
Boundary element model - linear

Diffraction

On the ***undisturbed*** position of the body boundary, the radiation and diffraction potentials are

$$\varphi_{jn} = n_j,$$

$$\varphi_{Dn} = 0,$$



$$\frac{\partial\phi}{\partial n} = 0 = \frac{\partial}{\partial n}(\phi_I + \phi_D)$$

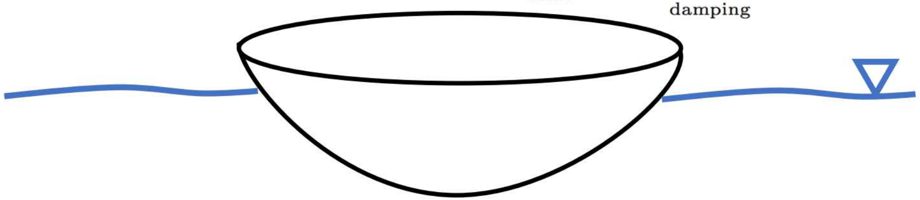
$$\text{or} \quad \frac{\partial\phi_D}{\partial n} = -\frac{\partial\phi_I}{\partial n} \leftarrow \text{given}$$

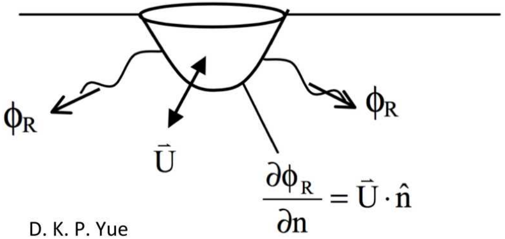
$$\vec{F}_D = \underset{\substack{\text{body}\\\text{surface}}}{\iint} -\rho\left(\frac{\partial\phi_D}{\partial t}\right)\hat{n}dS$$

D. K. P. Yue

Radiation

$$\vec{F}_R = \underset{\substack{\text{body}\\\text{surface}}}{\iint} -\rho\left(\frac{\partial\phi_R}{\partial t}\right)\hat{n}dS = -\underbrace{m_{ij}}_{\substack{\text{added}\\\text{mass}}}\dot{U}_j - \underbrace{d_{ij}}_{\substack{\text{wave}\\\text{radiation}\\\text{damping}}}U_j$$





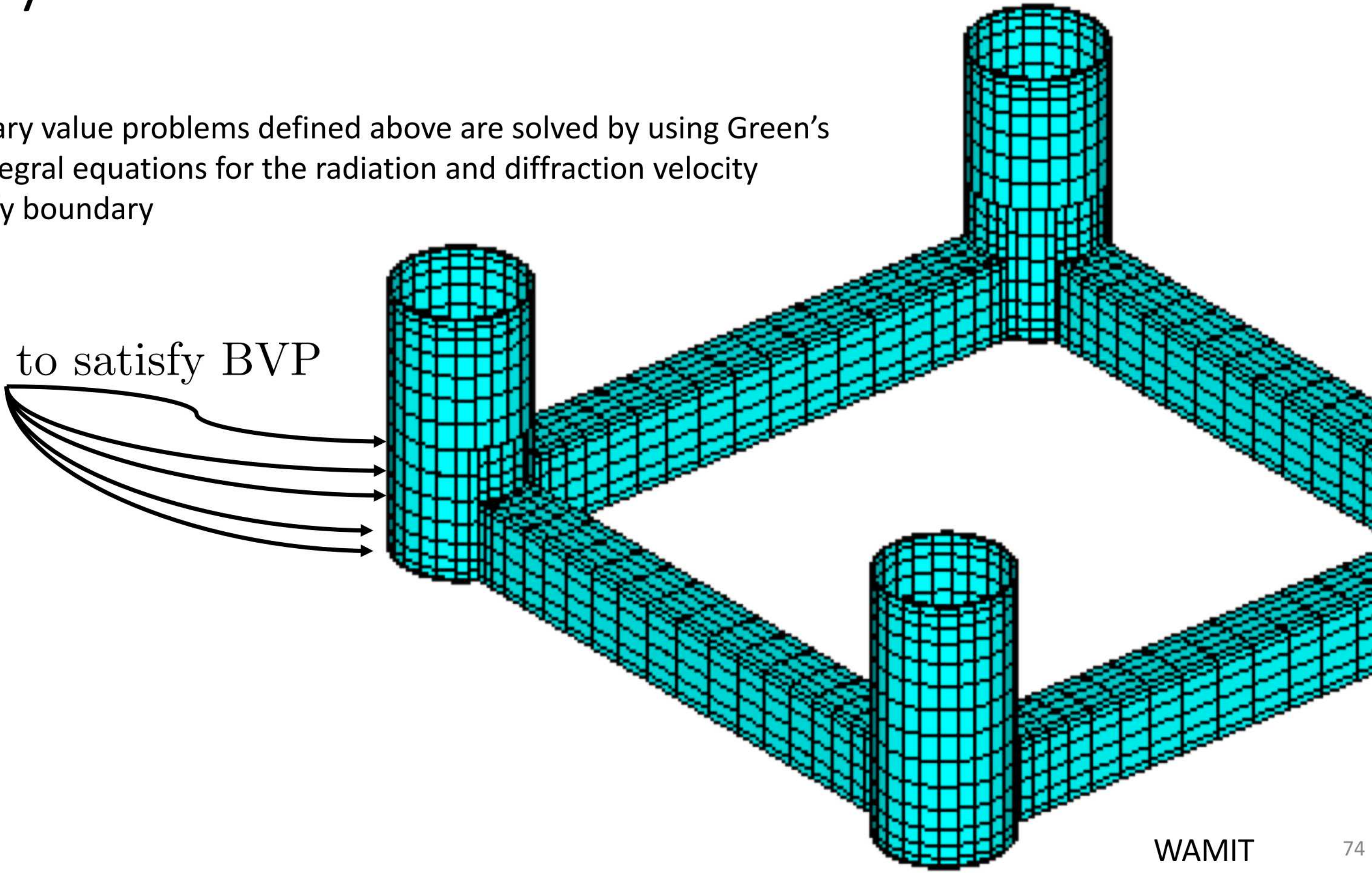
$$\frac{\partial\phi_R}{\partial n} = \vec{U}\cdot\hat{n}$$

D. K. P. Yue

Boundary element model - linear

In WAMIT the boundary value problems defined above are solved by using Green's theorem to derive integral equations for the radiation and diffraction velocity potentials on the body boundary

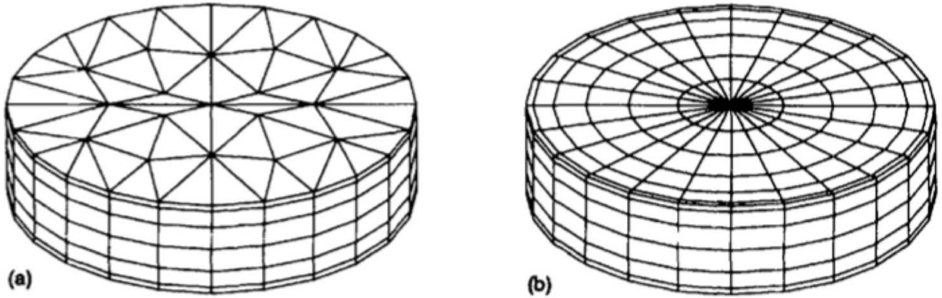
Set φ_R and φ_S to satisfy BVP

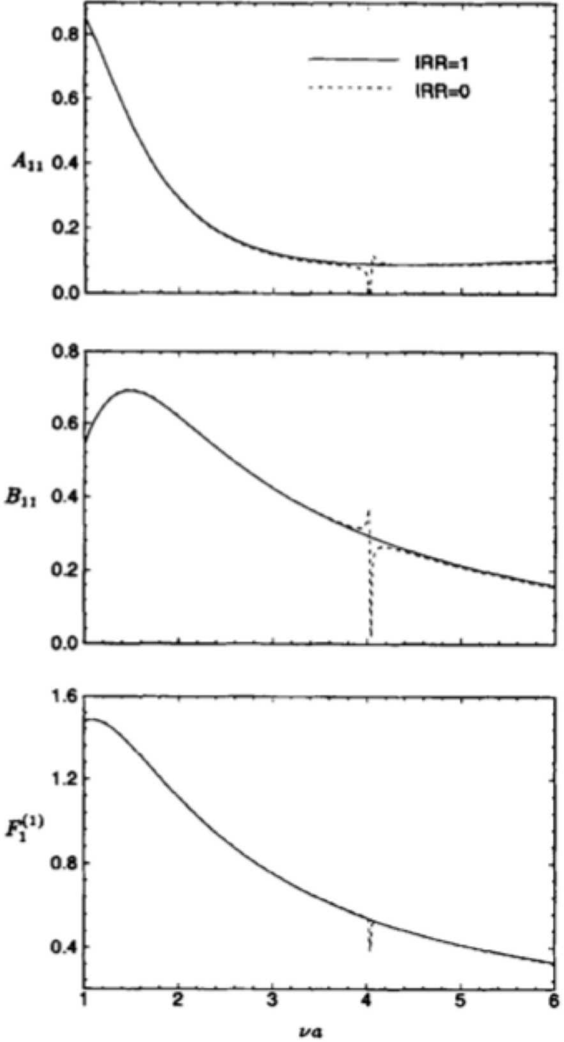


WAMIT

Boundary element model - Linear, usage

- Meshing (diminishing returns and dependence on wave length)
- Only mesh the wetted surface below the SWL
- Irregular frequencies
- High order vs low order method

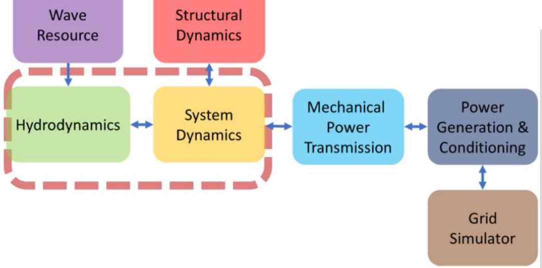




Lee, C-H., J. N. Newman, and X. Zhu. "An extended boundary integral equation method for the removal of irregular frequency effects." *International Journal for Numerical Methods in Fluids23.7* (1996): 637-660.

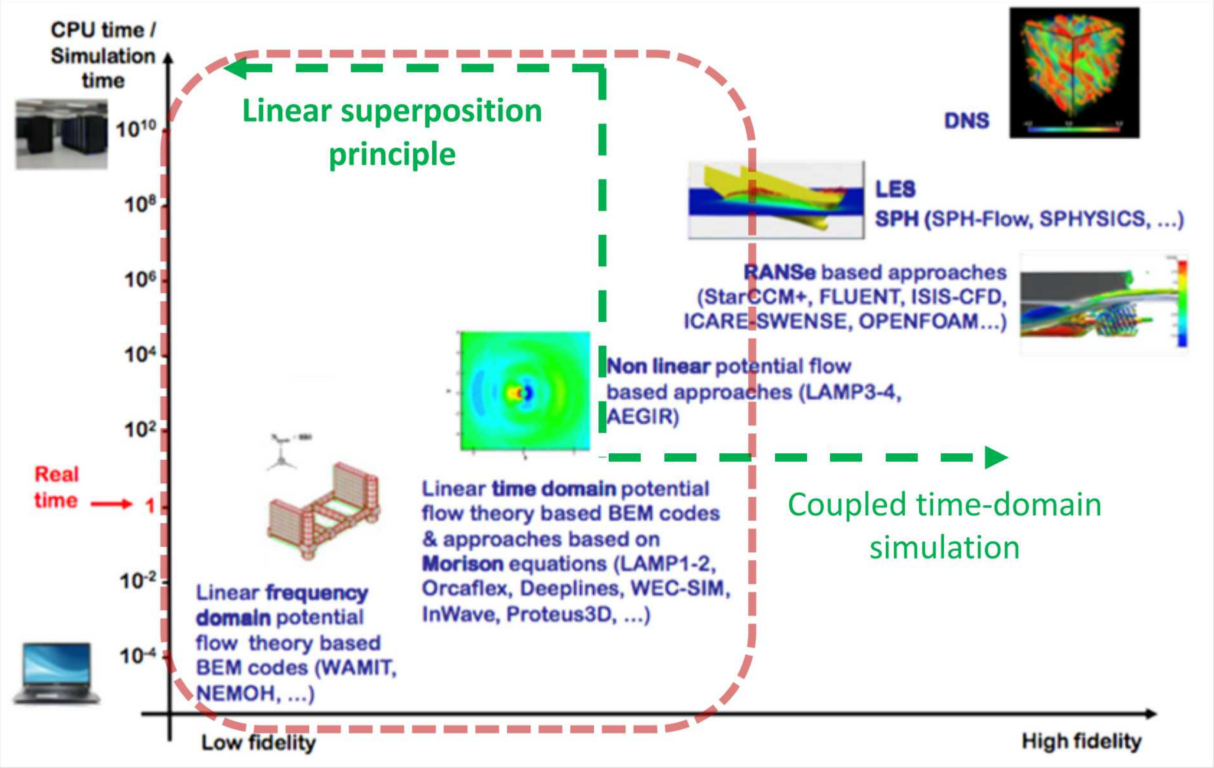
Linear Hydrodynamic Theory

Presented by Kelley Ruehl and Ryan Coe



Hydrodynamics and system dynamic model fidelity versus computational time

Wave and Floating Body Interaction:



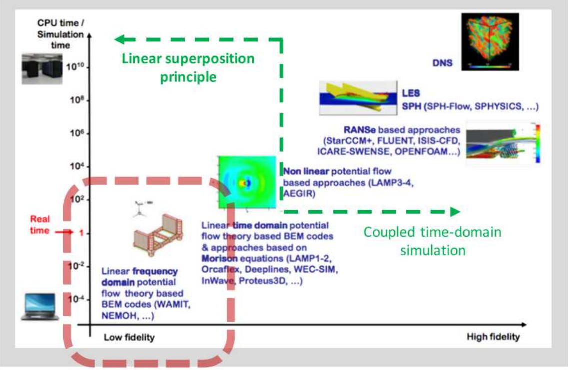
Aurelien Babarit

Linear superposition principle

Vs

Coupled time-domain simulation

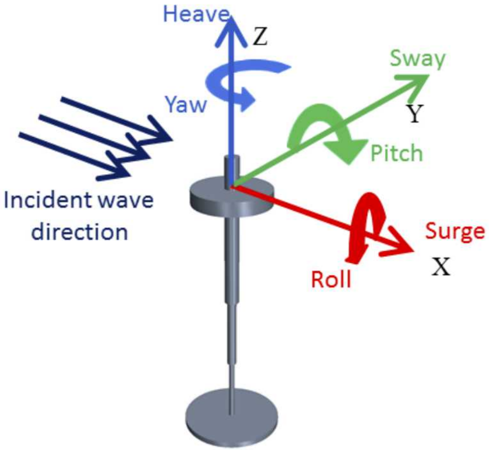
WEC Equation of Motion (Frequency-Domain)



Aurelien Babarit

$$F_{e,i}(\omega) = \sum_{i=1}^{6} \boldsymbol{X_i}(\omega)\left[-\omega^2(m + A_{ii}) + j\omega\left(B_{ii} + \Lambda_{pto,i}\right) + k_{ii}\right]$$

where i = 1-6 for 6DOF



- Hydrodynamics based on BEM solution from Linear Wave Theory (small amplitude motion, inviscid, irrotational flow)
- Linearity assumption, aka linear superposition

WEC Equation of Motion

Time-domain

- Hydrodynamics based in linear potential flow, but allows additional of non-linear forcing
- i.e. realistic PTO, real-time control, drag, non-linear hydrostatics, etc

$$F_{e,i}(t) = (m + A_{\infty,ii})\ddot{X}_i + \int_{0}^{t} \dot{X}_i(\tau)k_{r,ii}(t-\tau)d\tau$$
$$+k_{ii}X_i + F_{pto,i} + B_{v,i}|\dot{X}_i|\dot{X}_i + F_{ext,i}$$

Fourier Transform

Inverse Fourier Transform

Fourier Transform

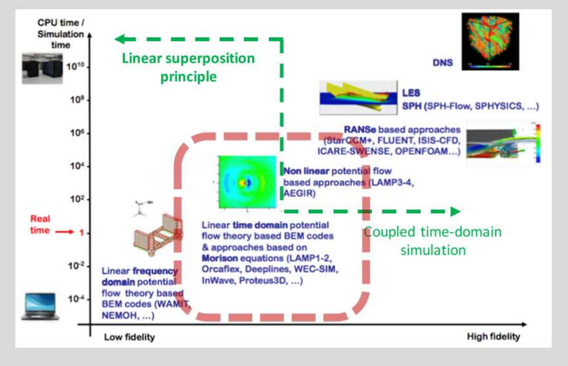
Inverse Fourier Transform

Frequency-domain

- Linearity assumption, aka linear superposition
- i.e. linear damping for PTO, linear mooring, linear hydrostatics, etc

$$F_{e,i}(\omega) = \sum_{i=1}^{6} \boldsymbol{X_i}(\omega)\left[-\omega^2(m + A_{ii}) + j\omega\left(B_{ii} + \Lambda_{pto,i}\right) + k_{ii}\right]$$

WEC Equation of Motion (Time-Domain)



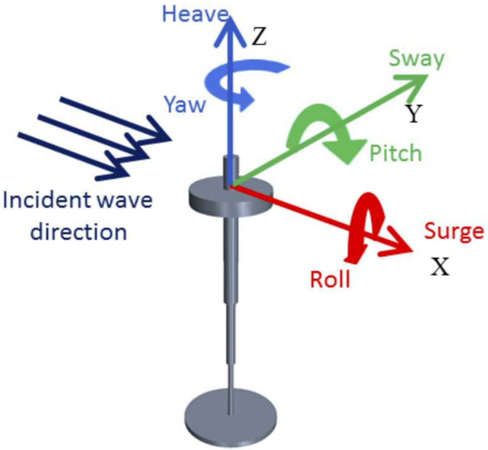
Aurelien Babarit

$$F_{e,i}(t) = (m + A_{\infty,ii})\ddot{X}_i + \int_0^t \dot{X}_i(\tau) k_{r,ii}(t-\tau)d\tau + k_{ii}X_i$$

$$\boxed{+ F_{pto,i} + B_{v,i}\left|\dot{X}_i\right|\dot{X}_i + \ F_{ext,i}}$$

Non-linearities

where i = 1-6 for 6DOF



- Hydrodynamics based on BEM solution from Linear Wave Theory (small amplitude motion, inviscid, irrotational flow)
- Quasi-nonlinear, addition of non-linear drag, pto, and external forcing

WEC Equation of Motion (Time-Domain)

$$\underbrace{F_{e,i}(t)}_{\text{Excitation Force}} = (m + \underbrace{A_{\infty,ii}}_{\text{Added Mass}})\ddot{X}_i + \underbrace{\int_0^t \dot{X}_i(\tau)k_{r,ii}(t-\tau)d\tau}_{\text{Radiation Force}} + \underbrace{k_{ii}X_i}_{\text{Hydrostatic Force}} + \underbrace{F_{pto,i}}_{\text{PTO Force}} + \underbrace{B_{v,i}|\dot{X}_i|\dot{X}_i}_{\text{Viscous Drag}} + \underbrace{F_{ext,i}}_{\text{External Forcing}}$$

- Excitation Force $F_e(t) = \int_{-\infty}^{\infty} \eta(\tau)\underbrace{f_e(t-\tau)}_{\text{Excitation IRF}}d\tau$
- Radiation Force $F_r(t) = \int_0^t \dot{x}(\tau)\underbrace{k_r(t-\tau)}_{\text{Radiation IRF}}d\tau$
- Added Mass
- Hydrostatic Force (linear/non-linear)
- PTO Force (linear/non-linear)
- Viscous Damping and Drag (linear/non-linear)
- External Forcing (linear/non-linear mooring, control, end stops, etc)

Impulse Response Functions (IRFs) in Hydrodynamics

Radiation Force:

$$F_r(t) = \int_0^t \dot{x}(\tau)\boxed{k_r(t-\tau)}d\tau$$

Radiation IRF

Radiation IRF:

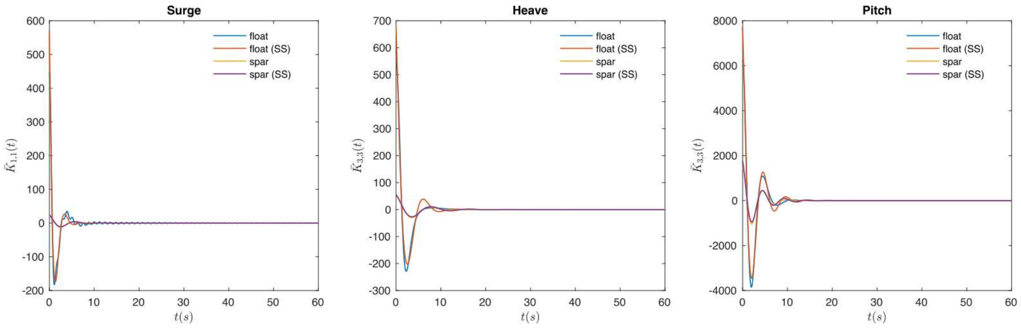
$$k_r(t) = \frac{2}{\pi}\int_0^\infty \boxed{B(\omega)}cos(\omega t)d\omega$$

Radiation Damping

Fourier Transform

Inverse Fourier Transform

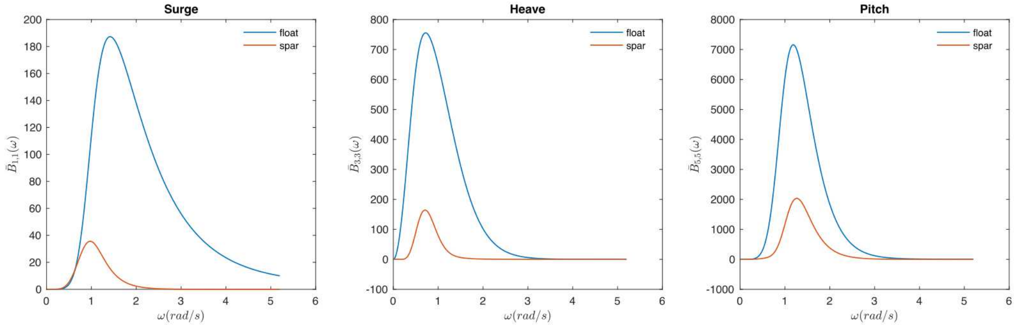
Normalized Radiation Impulse Response Functions: $\bar{K}_{i,j}(t) = \frac{2}{\pi}\int_0^\infty \frac{B_{i,j}(\omega)}{\rho}\cos(\omega t)d\omega$



Notes:

- The IRF should tend towards zero within the specified timeframe. If it does not, attempt to correct this by adjusting the ω and t range and/or step size used in the IRF calculation.
- Only the IRFs for the surge, heave, and pitch DOFs are plotted here. If another DOF is significant to the system, that IRF should also be plotted and verified before proceeding.

Normalized Radiation Damping: $\bar{B}_{i,j}(\omega) = \frac{B_{i,j}(\omega)}{\rho\omega}$

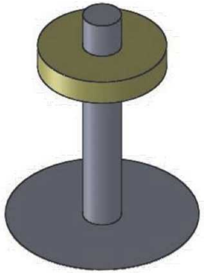


Notes:

- $\bar{B}_{i,j}(\omega)$ should tend towards zero within the specified ω range.
- Only $\bar{B}_{i,j}(\omega)$ for the surge, heave, and pitch DOFs are plotted here. If another DOF is significant to the system that $\bar{B}_{i,j}(\omega)$ should also be plotted and verified before proceeding.

Fourier Transform

Inverse Fourier Transform



Impulse Response Functions (IRFs) in Hydrodynamics

Excitation Force:

$$F_e(t) = \int_{-\infty}^{\infty} \eta(\tau) f_e(t-\tau) d\tau$$

Excitation IRF

Excitation IRF:

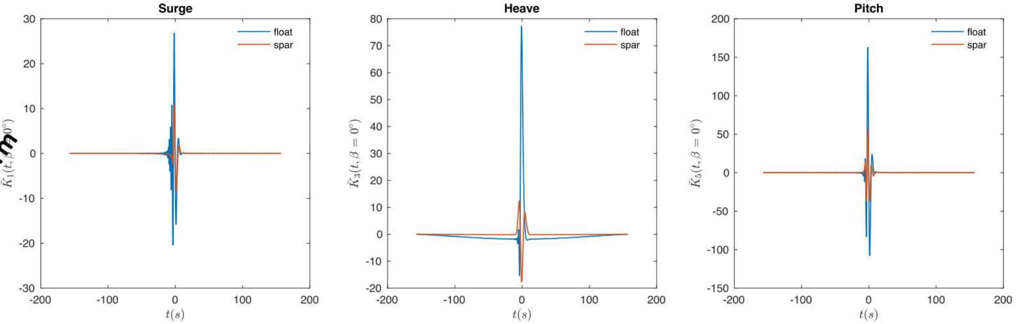
$$k_e(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} X(i\omega) e^{i\omega t} d\omega$$

Excitation Coefficient

Fourier Transform

Inverse Fourier Transform

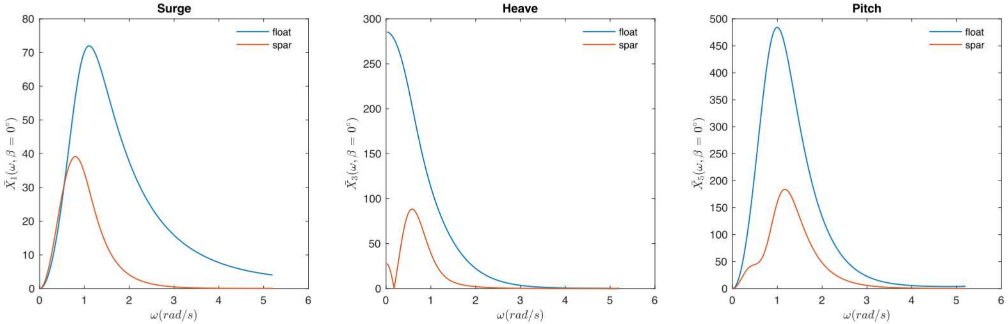
Normalized Excitation Impulse Response Functions: $\bar{K}_i(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{X_i(\omega,\beta)e^{i\omega t}}{\rho g} d\omega$



Notes:

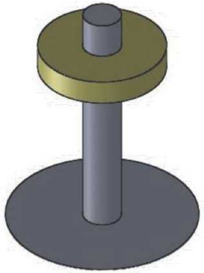
- The IRF should tend towards zero within the specified timeframe. If it does not, attempt to correct this by adjusting the ω and t range and/or step size used in the IRF calculation.
- Only the IRFs for the first wave heading, surge, heave, and pitch DOFs are plotted here. If another wave heading or DOF is significant to the system, that IRF should also be plotted and verified before proceeding.

Normalized Excitation Force Magnitude: $\bar{X}_i(\omega,\beta) = \frac{X_i(\omega,\beta)}{\rho g}$



Fourier Transform

Inverse Fourier Transform



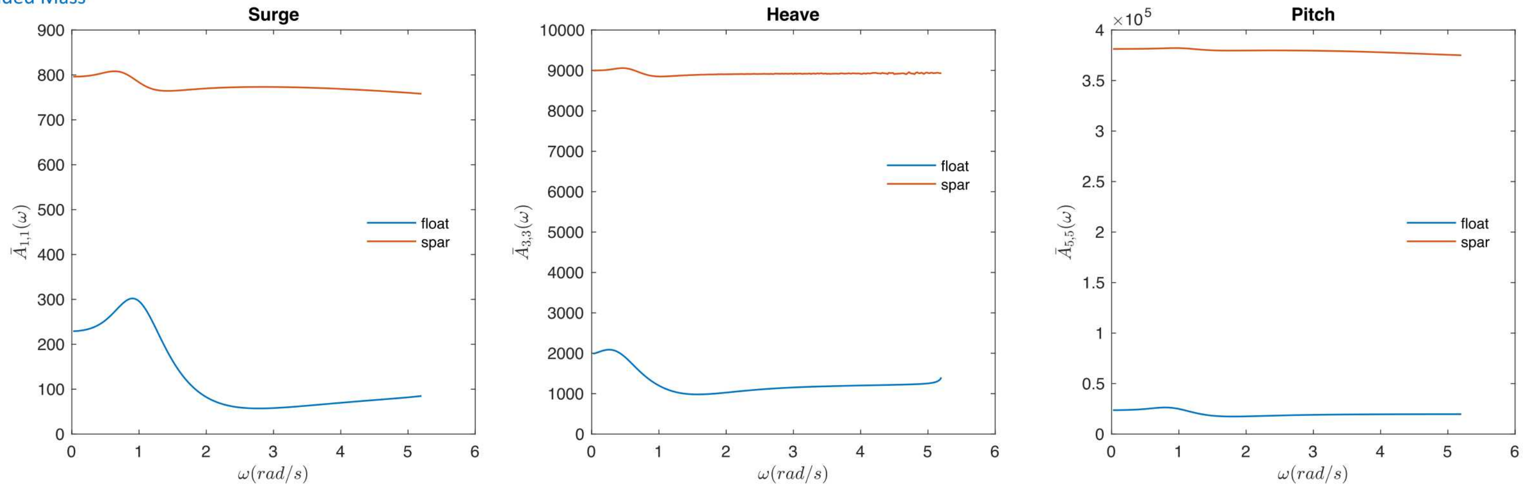
Impulse Response Functions (IRFs) in Hydrodynamics

Infinite Added Mass

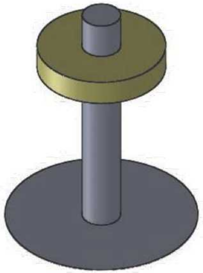
$$\boxed{(m + A_{\infty,ii})\ddot{X}_i}$$

Added Mass

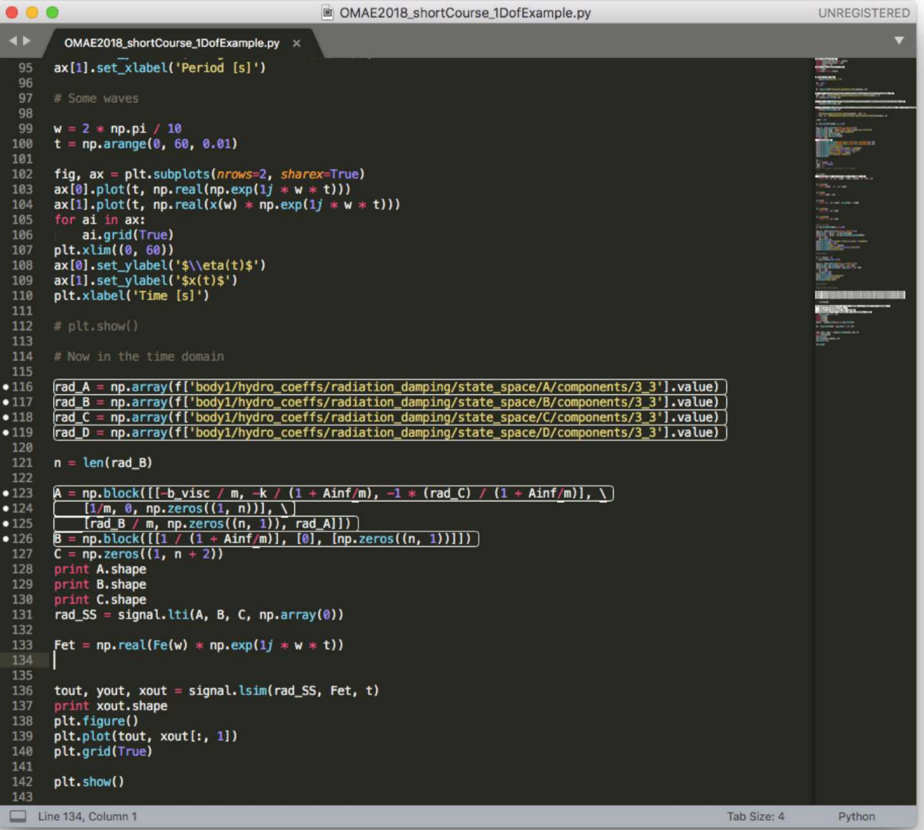
Normalized Added Mass: $\bar{A}_{i,j}(\omega) = \dfrac{A_{i,j}(\omega)}{\rho}$



Notes:
- $\bar{A}_{i,j}(\omega)$ should tend towards a constant, A_∞, within the specified ω range.
- Only $\bar{A}_{i,j}(\omega)$ for the surge, heave, and pitch DOFs are plotted here. If another DOF is significant to the system, that $\bar{A}_{i,j}(\omega)$ should also be plotted and verified before proceeding.

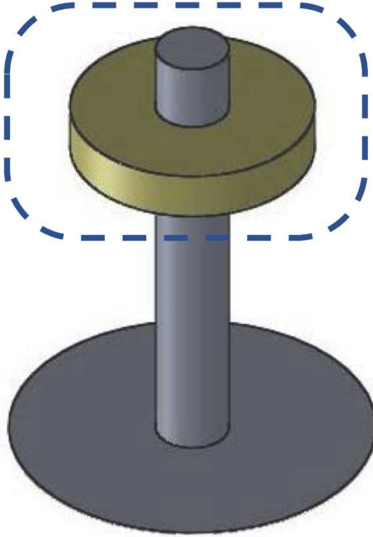


1DOF example

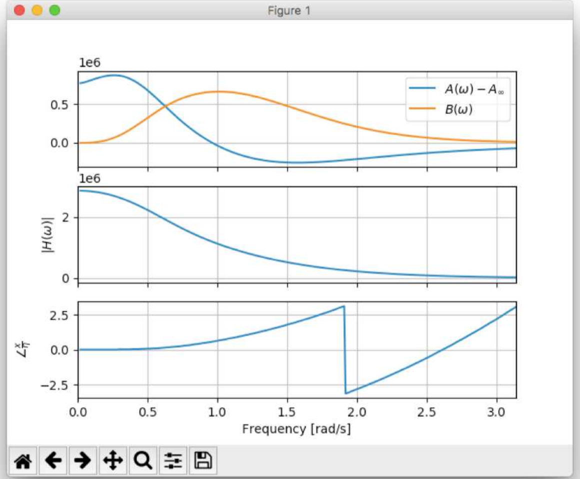


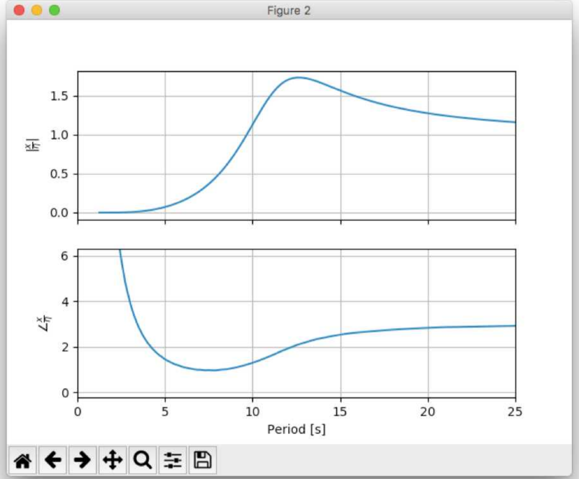
```python
ax[1].set_xlabel('Period [s]')

# Some waves

w = 2 * np.pi / 10
t = np.arange(0, 60, 0.01)

fig, ax = plt.subplots(nrows=2, sharex=True)
ax[0].plot(t, np.real(np.exp(1j * w * t)))
ax[1].plot(t, np.real(x(w) * np.exp(1j * w * t)))
for ai in ax:
    ai.grid(True)
plt.xlim((0, 60))
ax[0].set_ylabel('$\\eta(t)$')
ax[1].set_ylabel('$x(t)$')
plt.xlabel('Time [s]')

# plt.show()

# Now in the time domain

rad_A = np.array(f['body1/hydro_coeffs/radiation_damping/state_space/A/components/3_3'].value)
rad_B = np.array(f['body1/hydro_coeffs/radiation_damping/state_space/B/components/3_3'].value)
rad_C = np.array(f['body1/hydro_coeffs/radiation_damping/state_space/C/components/3_3'].value)
rad_D = np.array(f['body1/hydro_coeffs/radiation_damping/state_space/D/components/3_3'].value)

n = len(rad_B)

A = np.block([[-b_visc / m, -k / (1 + Ainf/m), -1 * (rad_C) / (1 + Ainf/m)], \
    [1/m, 0, np.zeros((1, n))], \
    [rad_B / m, np.zeros((n, 1)), rad_A]])
B = np.block([[1 / (1 + Ainf/m)], [0], [np.zeros((n, 1))]])
C = np.zeros((1, n + 2))
print A.shape
print B.shape
print C.shape
rad_SS = signal.lti(A, B, C, np.array(0))

Fet = np.real(Fe(w) * np.exp(1j * w * t))


tout, yout, xout = signal.lsim(rad_SS, Fet, t)
print xout.shape
plt.figure()
plt.plot(tout, xout[:, 1])
plt.grid(True)

plt.show()
```

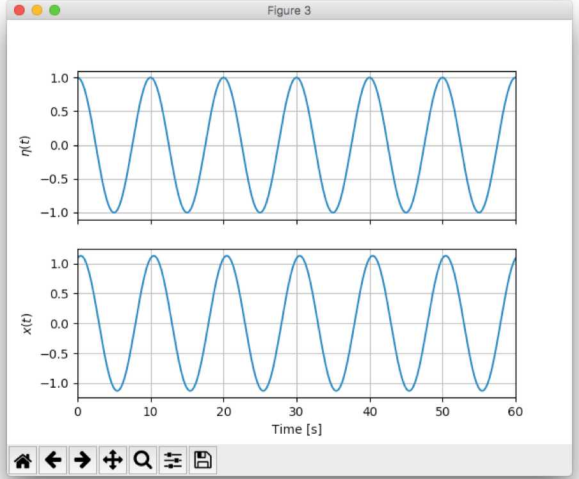
1. Import BEM data
2. Check BEM data
3. Freq. domain model
4. Time domain model



1DOF example - FD







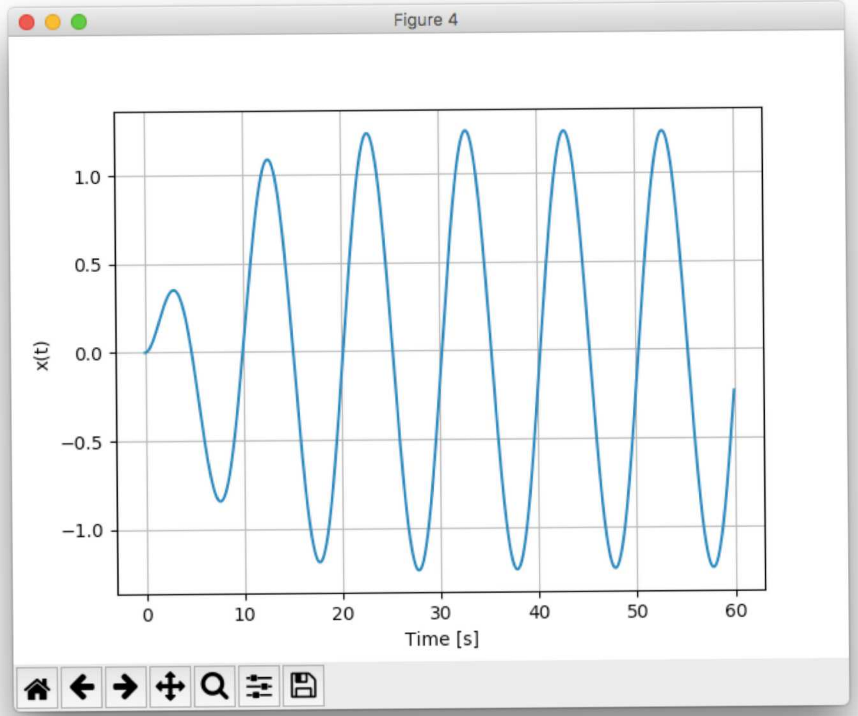
$$Z_i(\omega) = B(\omega) + B_f + i\left(\omega\left(M + A(\omega)\right) - K/\omega\right)$$

$$\hat{x} = \frac{\hat{F}_e}{\hat{Z}_i}$$

1DOF example - TD

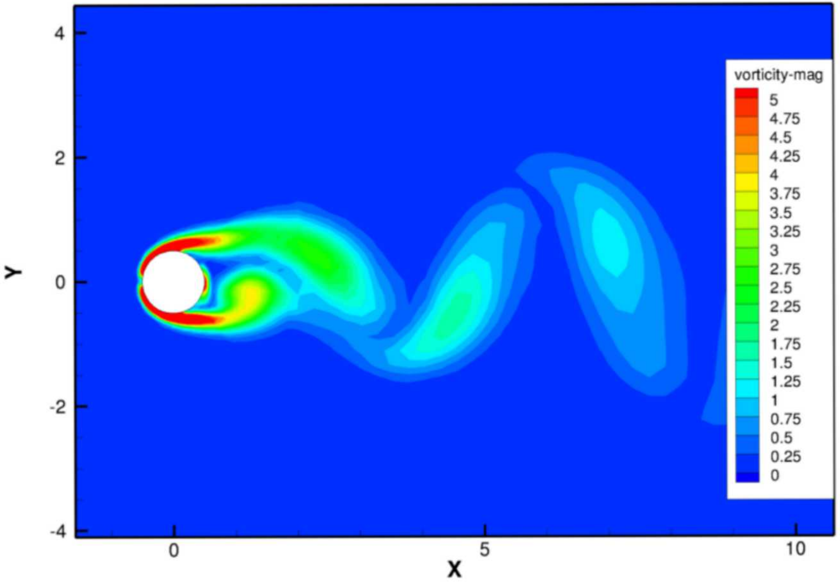
$$
\begin{aligned}
\dot{\mathbf{x}}(t) &= \begin{bmatrix} 0 & \frac{-C_b}{1+m_\infty/m_b} & \frac{-\mathbf{C}_r}{1+m_\infty/m_b} \\ 1/m_b & 0 & \mathbf{0}_{1\times4} \\ \mathbf{B}_r/m_b & \mathbf{0}_{4\times1} & \mathbf{A}_r \end{bmatrix} \mathbf{x}(t) \\
&\quad + \begin{bmatrix} \frac{1}{1+m_\infty/m_b} \\ 0 \\ \mathbf{0}_{4\times1} \end{bmatrix} F_m(t) + \begin{bmatrix} \frac{1}{1+m_\infty/m_b} \\ 0 \\ \mathbf{0}_{4\times1} \end{bmatrix} F_e(t) \\
&\equiv \mathbf{A}\,\mathbf{x}(t) + \mathbf{B}\,F_m(t) + \mathbf{B}\,F_e(t) \\
\mathbf{y}(t) &= \mathbf{C}\,\mathbf{x}(t)
\end{aligned}
$$

$$x_1 = m\dot{\eta},\ x_2 = \eta \text{ and } [x_3, \dots x_N]^{\mathrm{T}} = \mathbf{z}$$



Hydrodynamics Simulation
Viscous flow

Presented by Yi-Hsiang Yu



$$\text{Continuity: } \nabla \cdot \vec{v} = 0$$

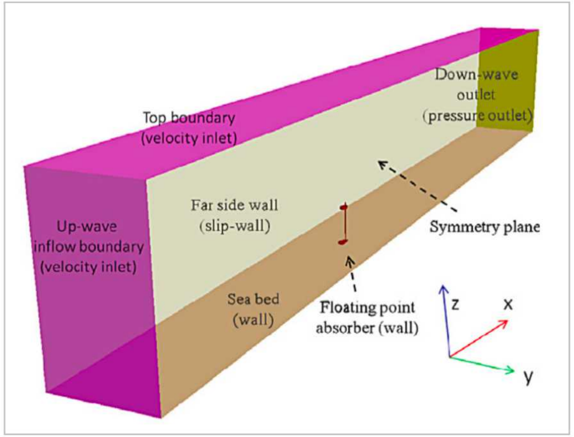
$$\text{Navier-Stokes}: \underbrace{\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}} = \frac{1}{\rho} \frac{\partial \tau_{ij}}{\partial x_j} + \frac{1}{\rho} F_i$$

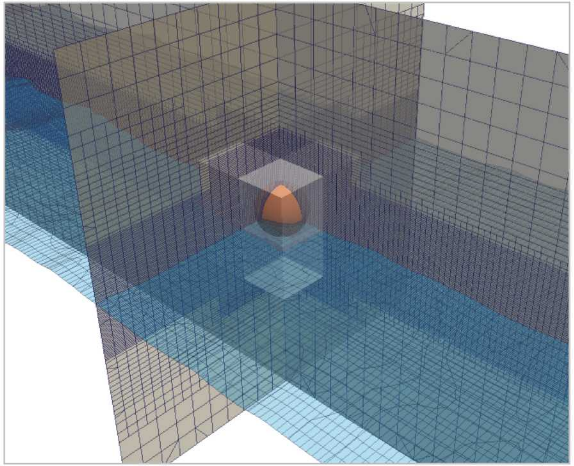
substantial derivative
(time rate change of cord-sys moving w/ particle)

Fundamental CFD

The most fundamental consideration in CFD is how one treats *a continuous fluid in a discretized fashion* on a computer?

- Mesh-based method
    - Finite Difference Method (FDM)
    - Finite Volume Method (FVM)
    - Finite Element Method (FEM): More often used for structure analysis



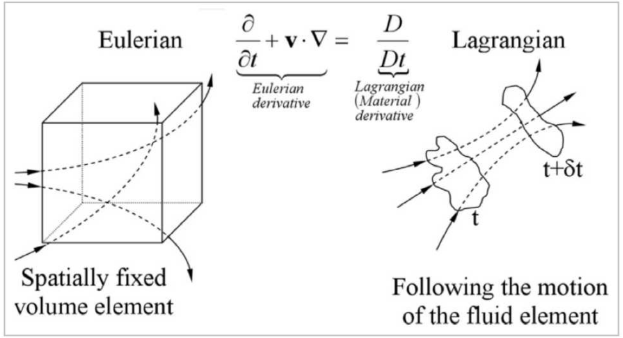


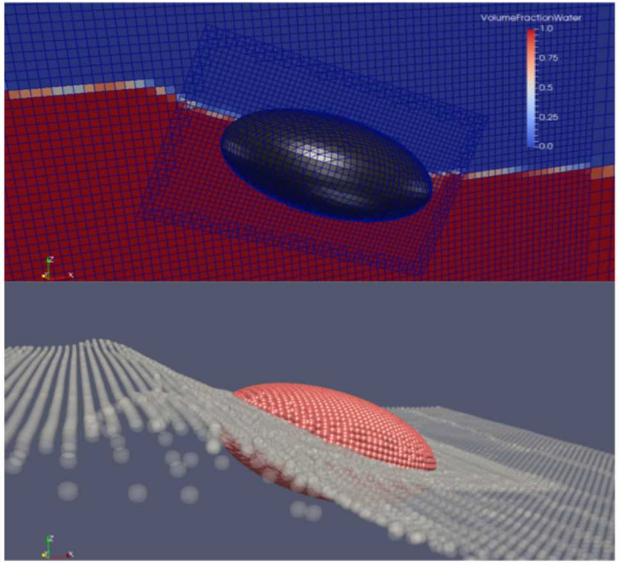
Fundamental CFD

The most fundamental consideration in CFD is how one treats *a continuous fluid in a discretized fashion* on a computer?

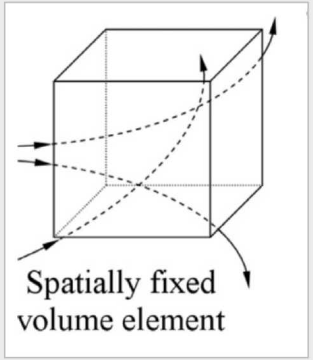
- Mesh-free method

  Lagrangian (particle-based) method: a mesh free approach that solves the equations of continuity for any continuum media, including both solids and fluids, using a set of particles in which the coordinates move with the particles.





Finite Volume Method (FVM)



- FVM is the "classical" or standard approach used in commercial software (e.g., ANSYS_FLUENT, StarCCM+) and open source code (e.g., OpenFOAM).

- FVM discretize the partial differential equations of the N-S equation in the conservative form, which guarantees the conservation of fluxes through a particular control volume.

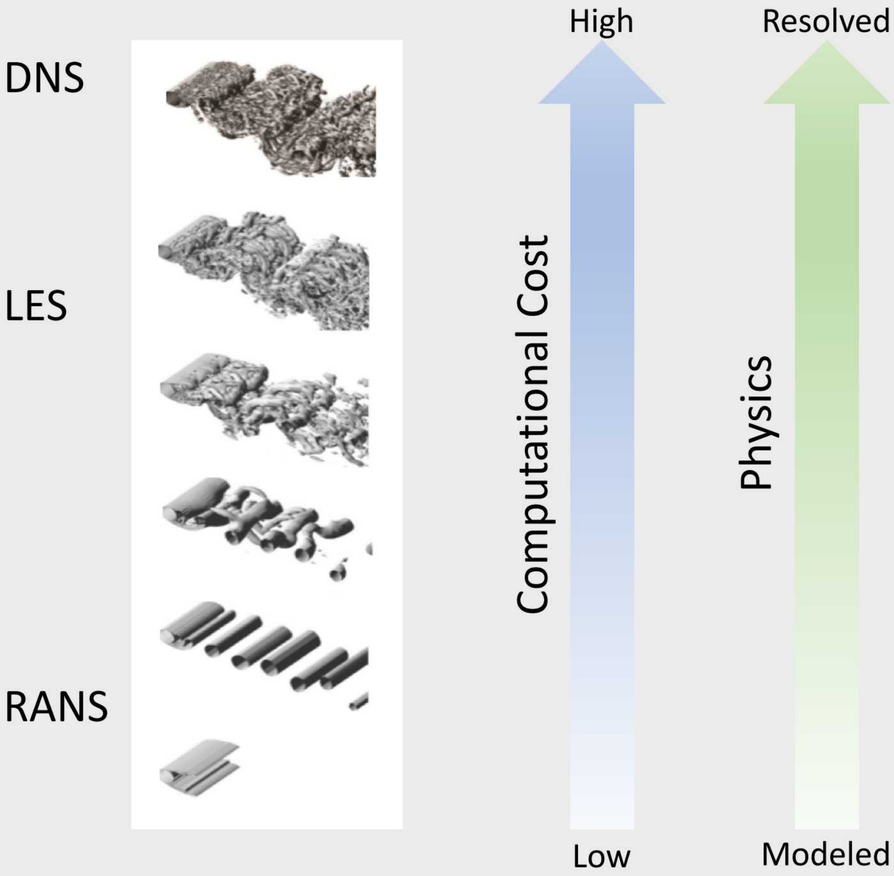
$$\frac{\partial}{\partial t}\int Q\,dV + \int F\,dA = 0$$

where *Q* is the vector of conserved variables, *F* is the vector of fluxes, *V* is the cell volume, and is the cell surface area.

Turbulent flow modeling:

Turbulence or turbulent flow is a fluid regime characterized by chaotic, random property changes. This includes low momentum diffusion, high momentum convection, and rapid variation of pressure and velocity in space and time.

"An ideal model should introduce the minimum amount of complexity while capturing the essence of the relevant physics" **(Wilcox, 1993, p. 1)**



DNS

LES

RANS

High

Computational Cost

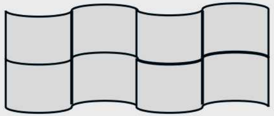
Low

Resolved

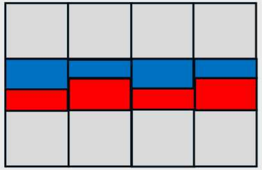
Physics

Modeled

Modeling of Free-Surface Flows



3D top view



Side view

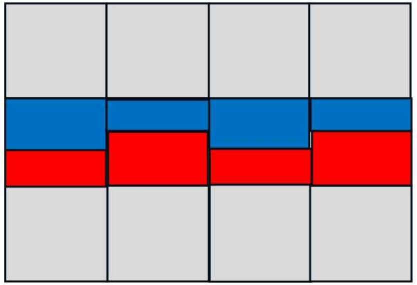
- Free-surface flows are driven by gravity and surface tension
- Majority of hydrodynamic problems do not require a sophisticated model for air (can be modelled as ideal gas)
- FVM are based on either
  - Interface-tracking methods
    - Moving, boundary-fitted grid

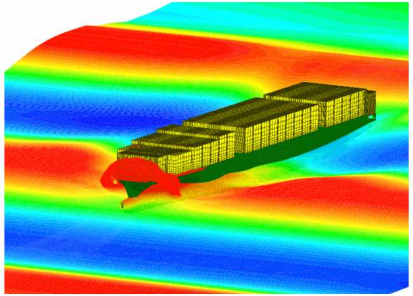
  - Interface-capturing methods
    - Fixed grid, volume share dynamics based on transport equation

Interface-Capturing Method

- Suitable for complex geometries, multi-phase flows
- The α-equation is coupled to the Navier-Stokes equations; thus accounts for **nonlinear and viscous free-surface effects**

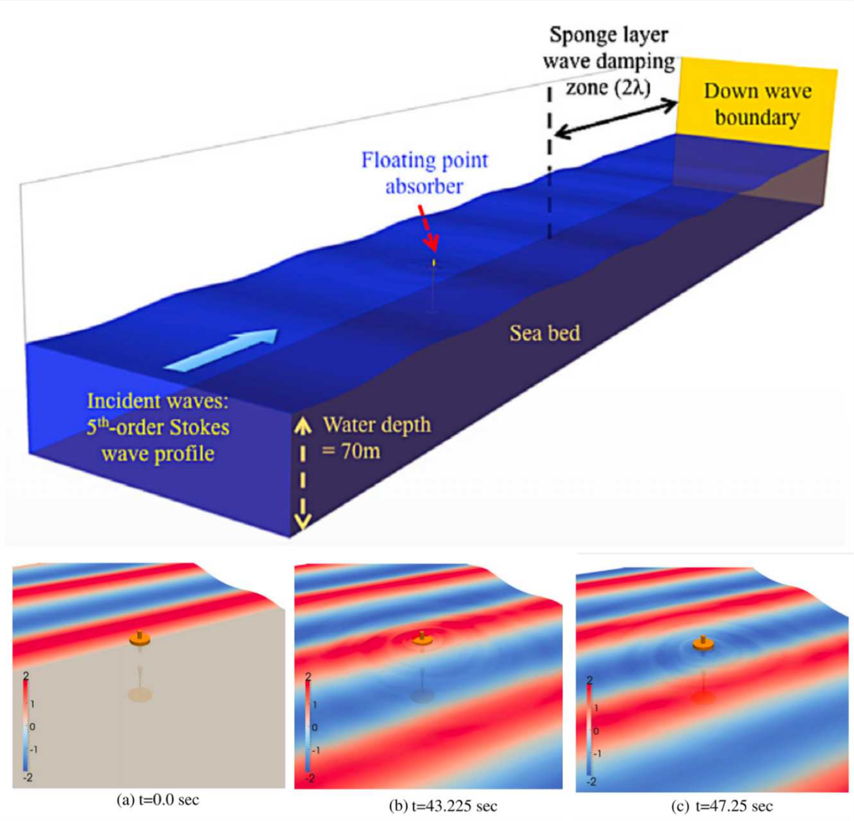
$$\frac{\partial}{\partial t}\int_V \alpha \, \mathrm{d}V + \int_S \alpha \boldsymbol{v} \cdot \boldsymbol{n} \, \mathrm{d}S = 0$$





Numerical Wave Tank

Just like “physical” wave tank, waves are generated on one side and need to be absorbed on the other end.



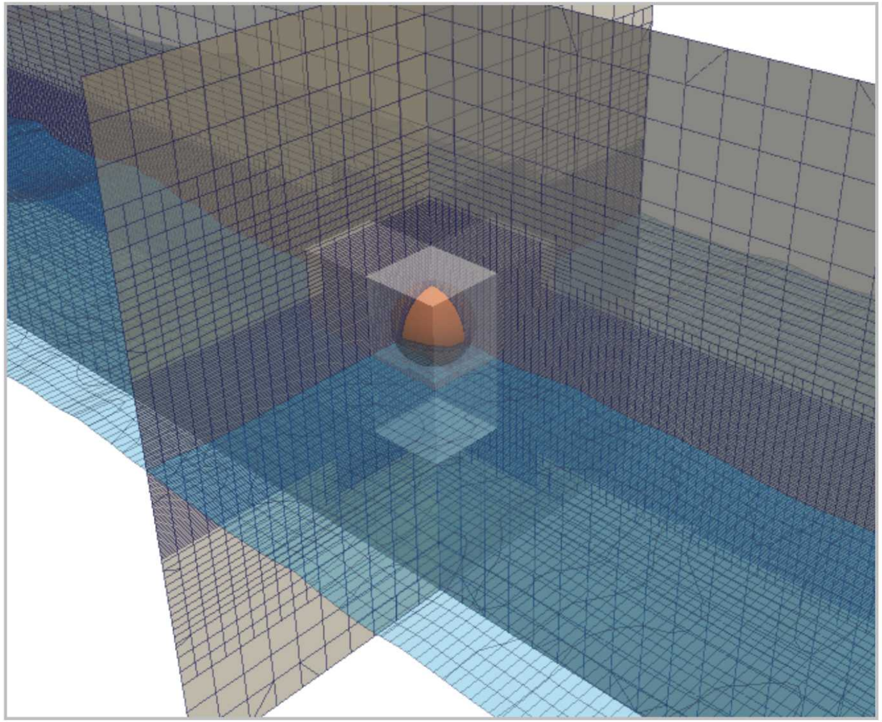
(a) t=0.0 sec

(b) t=43.225 sec

(c) t=47.25 sec

Numerical Wave Tank

- Capture wave propagation and the dynamic interaction between waves and the floating body
- Space and temporal resolutions are function of H, T and λ
- Like experimental tank test, it is recommended to resolve the space and temporal resolutions that is needed without the present of the device

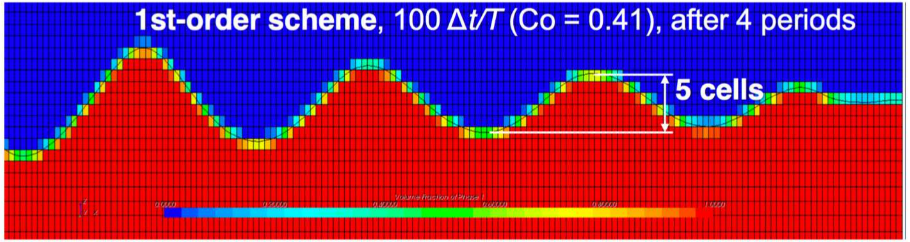


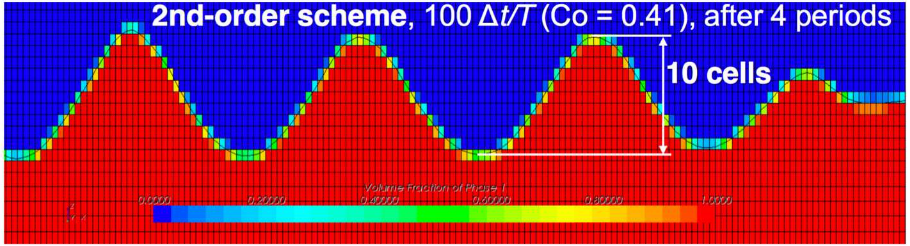
Numerical Wave Tank

With Insufficient Resolution

- Induced by numerical damping
- Wave amplitude decays as waves propagate through the domain
- Wave propagation speed will be inaccurate
- Unrealistic wave breaking

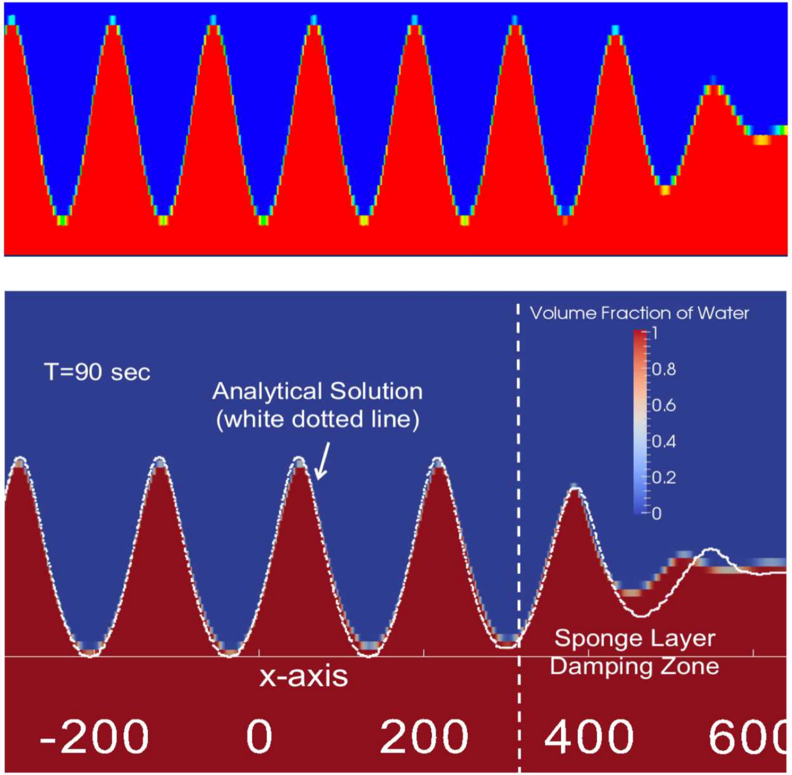
Example: H=5m and T=8sec and wave damping zone was applied over the last 100 m 41 cells per wave length, 11.5 cells per wave height (Δx = 2.5 m, Δz = 0.5 m)





Numerical Wave Tank

- Wave train initialized using Stokes 5th-order theory
- Damping Zone: 1~2 λ
- $\Delta z > H/20$; $\Delta x > \lambda/80$
- Second-order time integration scheme
- Higher space and temporal resolutions maybe needed for larger and steeper waves and longer domain/duration cases



Operational Waves

Extreme Waves

Hydrodynamics Simulation

It is all about using the right tool for what we want to investigate

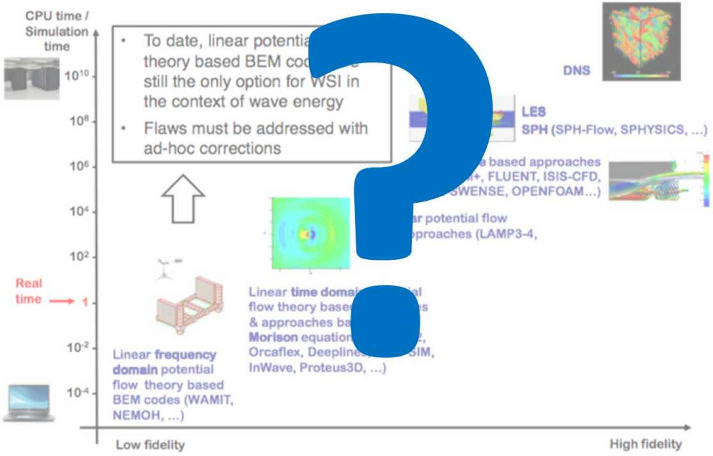
Hydrodynamics Simulation

Typically:

- Linear model -> System design and optimization
- High-fidelity model -> Extreme condition modeling and viscous drag coefficient calculation

However:

- What numerical model to use depends on the complexity of the fundamental physics
- Don’t use a sledgehammer to crack a nut



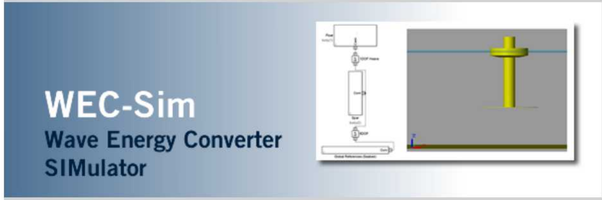
Lunch (12:30 ~ 13:30)

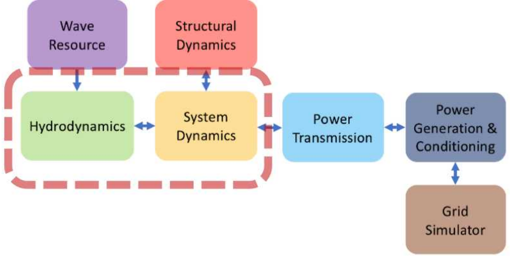
Agenda

1. Introduction
2. WEC fundamentals
3. Ocean waves
4. Numerical methods
5. Experimental methods
6. WEC control
7. Extreme response and fatigue

Numerical Methods
WEC-Sim

Presented by Kelley Ruehl and Yi-Hsiang Yu





Wave Resource

Structural Dynamics

Hydrodynamics

System Dynamics

Power Transmission

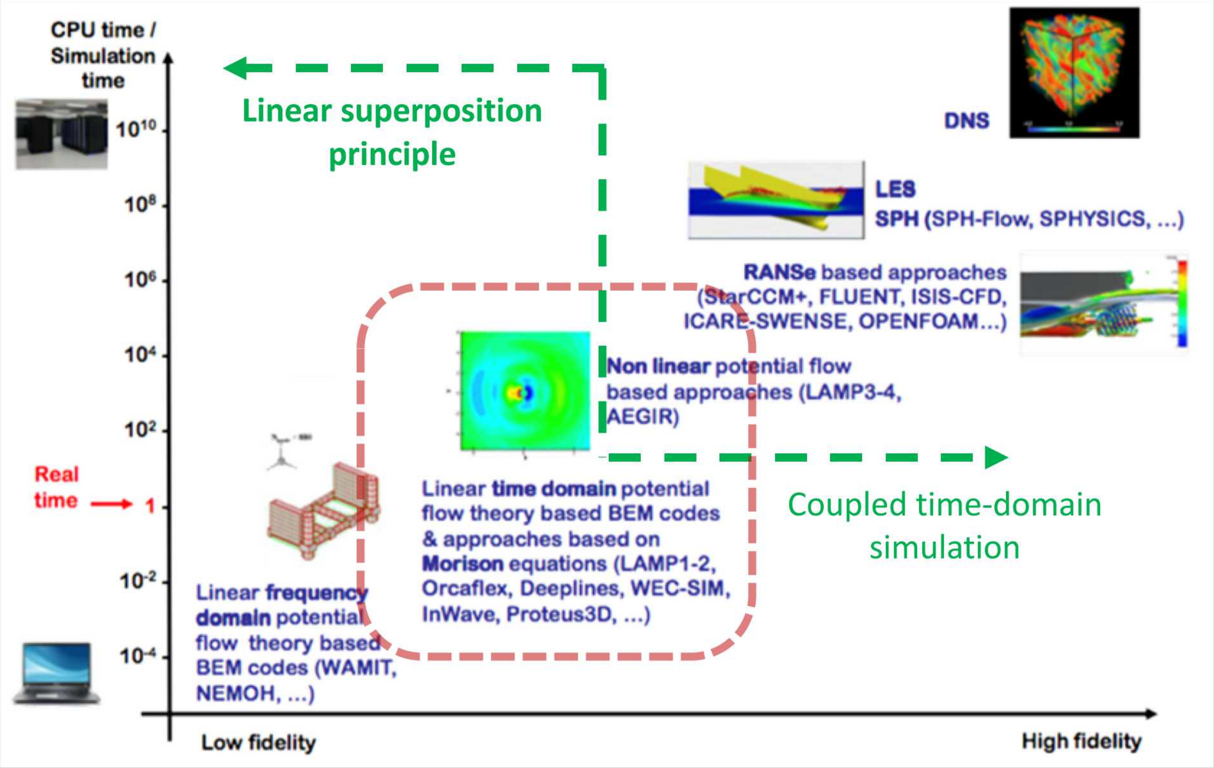
Power Generation & Conditioning

Grid Simulator

Wave and Floating Body Interaction:

Linear superposition principle
Vs
Coupled time-domain simulation

Hydrodynamics and system dynamic model fidelity versus computational time



Aurelien Babarit

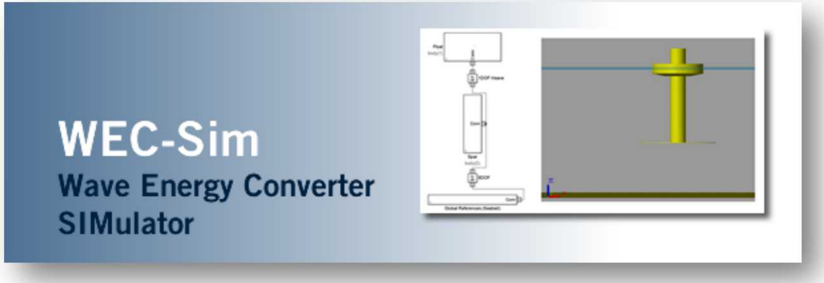
What is WEC-Sim?

- WEC-Sim (Wave Energy Converter Simulator)
  - Simulates wave energy converter dynamics in operational waves
  - Time-domain rigid body equation of motion solver based on Cummins' formulation
  - Open source code developed in MATLAB/SIMULINK
  - Joint NREL/Sandia project funded by the US Department of Energy
  - First Release: v1.0 in June 2014
  - Current Release: v3.0 in December 2017

U.S. DEPARTMENT OF ENERGY

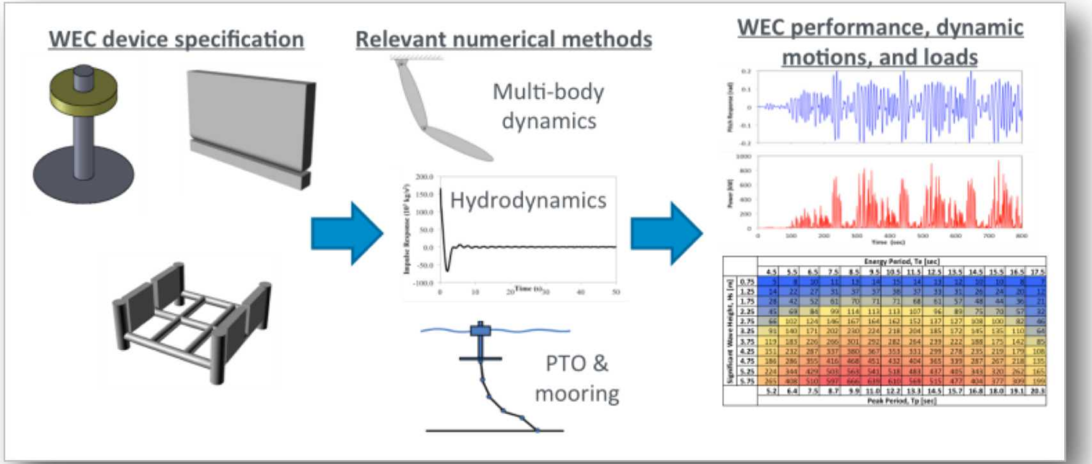
Sandia National Laboratories

NREL NATIONAL RENEWABLE ENERGY LABORATORY



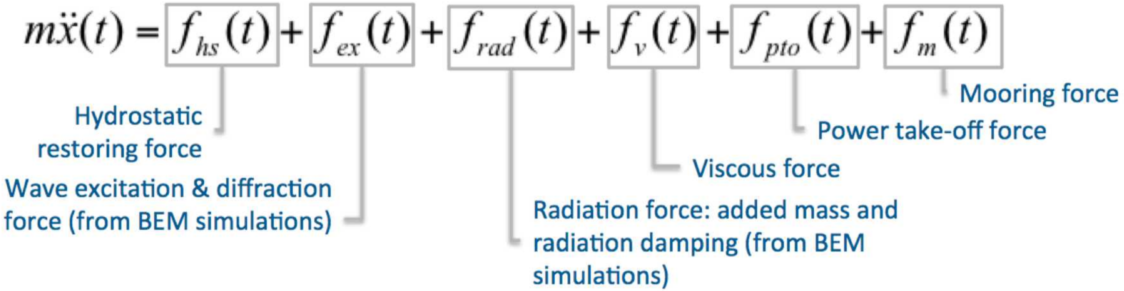
Why use WEC-Sim?

- WEC-Sim has the ability to model the dynamics of devices that are comprised of rigid bodies, power-take-off (PTO) systems, and mooring systems.
- WEC-Sim uses hydrodynamic coefficients derived from frequency-domain boundary element (BEM) simulations to model the relevant hydrodynamics.
- Time-domain simulations are performed by solving the governing WEC equations of motion in 6 degrees-of-freedom.



WEC-Sim Theory

- Dynamics simulated by solving time-domain equation of motion (Cummins, 1962)



$$m\ddot{x}(t) = \boxed{f_{hs}(t)} + \boxed{f_{ex}(t)} + \boxed{f_{rad}(t)} + \boxed{f_{v}(t)} + \boxed{f_{pto}(t)} + \boxed{f_{m}(t)}$$

Hydrostatic restoring force

Wave excitation & diffraction force (from BEM simulations)

Radiation force: added mass and radiation damping (from BEM simulations)

Viscous force

Power take-off force

Mooring force

- Use radiation and diffraction method and calculate the hydrodynamic forces from frequency-domain Boundary Element Method (BEM)

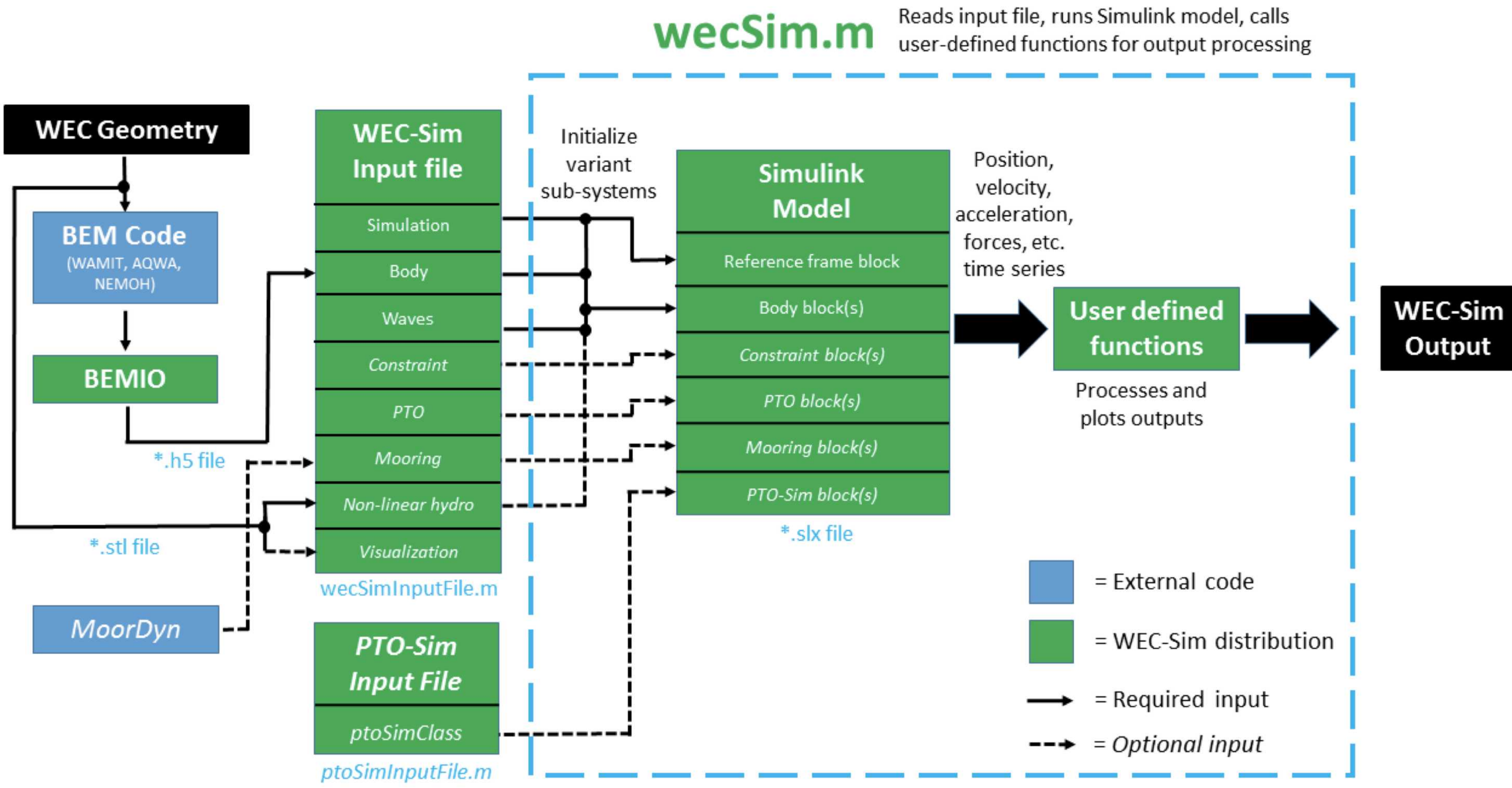
$$f_{rad}(t) = \underbrace{-A_{\infty}}_{\text{BEM}}\ddot{X} - \int_{0}^{t} \underbrace{K(t}_{\text{BEM}} - \tau)\dot{X}(\tau)d\tau$$

$$f_{ex}(t) = \Re\left[R_f \underbrace{F_X(\omega_r)}_{\text{BEM}} e^{i(\omega_r t+\phi)} \int_{0}^{\infty} \sqrt{2S(\omega_r)d\omega_r}\right]$$

$$= \int_{-\infty}^{\infty} \eta(\tau) \underbrace{f_e(t}_{\text{BEM}} - \tau)d\tau$$

WEC-Sim Software Requirements

- **CAD** (Computer-aided design), e.g. Rhinoceros, SolidWorks, ANSYS, etc.
- **BEM** (Boundary Element Method), e.g. WAMIT, NEMOH, AQWA
- **WEC-Sim** (Wave Energy Converter Simulator) and **BEMIO** (Boundary Element Method Input/Output)
  - http://wec-sim.github.io/WEC-Sim/
  - Requires MATLAB (R2015b), Simulink, Simscape and SimMechanics (Simscape Multibody in 2016a)
- **ParaView** (Optional)
  - http://www.paraview.org/
  - Optional, for additional visualization and analysis capabilities



wecSim.m Reads input file, runs Simulink model, calls user-defined functions for output processing

WEC Geometry

BEM Code
(WAMIT, AQWA, NEMOH)

BEMIO

*.h5 file

*.stl file

MoorDyn

WEC-Sim Input file
- Simulation
- Body
- Waves
- *Constraint*
- *PTO*
- *Mooring*
- *Non-linear hydro*
- *Visualization*

wecSimInputFile.m

PTO-Sim Input File
- *ptoSimClass*

ptoSimInputFile.m

Initialize variant sub-systems

Simulink Model
- Reference frame block
- Body block(s)
- *Constraint block(s)*
- *PTO block(s)*
- *Mooring block(s)*
- *PTO-Sim block(s)*

*.slx file

Position, velocity, acceleration, forces, etc. time series

User defined functions

Processes and plots outputs

WEC-Sim Output

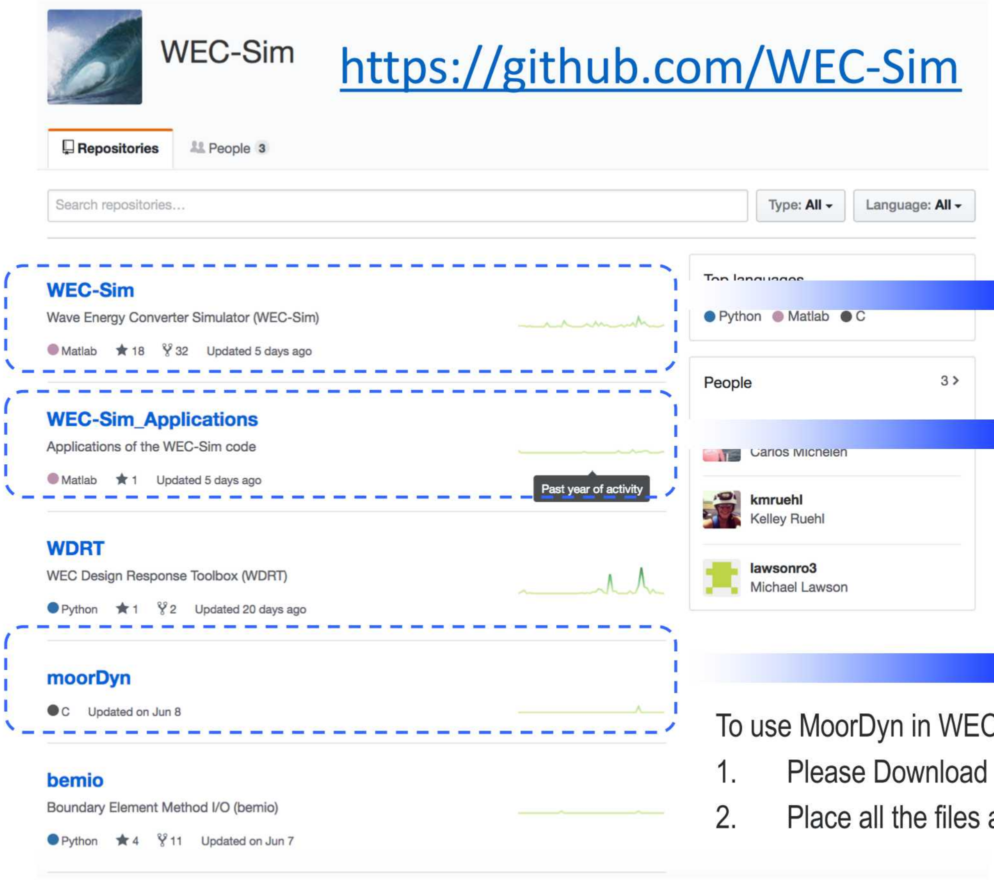
🟦 = External code

🟩 = WEC-Sim distribution

→ = Required input

⇢ = *Optional input*

WEC-Sim (GitHub) Repositories



WEC-Sim https://github.com/WEC-Sim

Repositories | People 3

Search repositories… | Type: All | Language: All

WEC-Sim
Wave Energy Converter Simulator (WEC-Sim)
● Matlab ★ 18 32 Updated 5 days ago

WEC-Sim_Applications
Applications of the WEC-Sim code
● Matlab ★ 1 Updated 5 days ago

WDRT
WEC Design Response Toolbox (WDRT)
● Python ★ 1 2 Updated 20 days ago

moorDyn
● C Updated on Jun 8

bemio
Boundary Element Method I/O (bemio)
● Python ★ 4 11 Updated on Jun 7

WEC-Sim Source Code

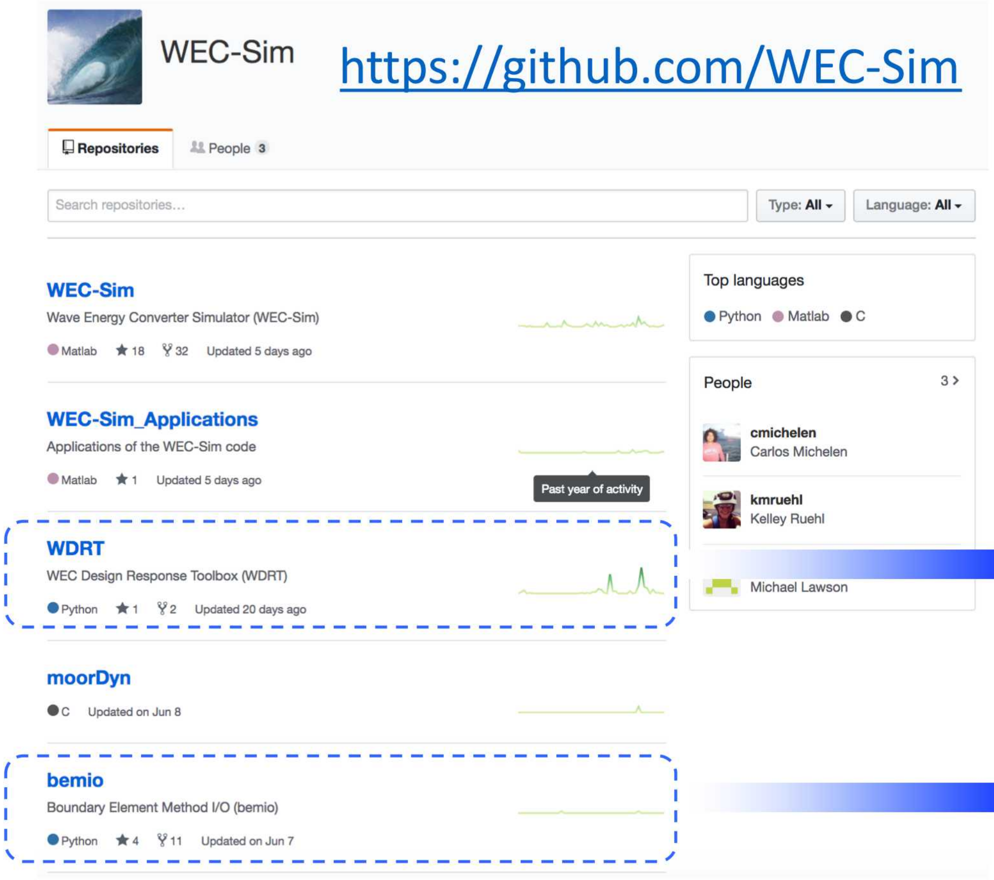
Additional Applications

Complied MoorDyn Library

To use MoorDyn in WEC-Sim,

1. Please Download MoorDyn from the repo https://github.com/WEC-Sim/moorDyn
2. Place all the files and folders under WEC-Sim/source/functions/moorDyn folder

WEC-Sim (GitHub) Repositories



WEC-Sim https://github.com/WEC-Sim

Repositories | People 3

Search repositories… | Type: All ▾ | Language: All ▾

WEC-Sim
Wave Energy Converter Simulator (WEC-Sim)
● Matlab ★ 18 ⑂ 32 Updated 5 days ago

WEC-Sim_Applications
Applications of the WEC-Sim code
● Matlab ★ 1 Updated 5 days ago

Past year of activity

WDRT
WEC Design Response Toolbox (WDRT)
● Python ★ 1 ⑂ 2 Updated 20 days ago

moorDyn
● C Updated on Jun 8

bemio
Boundary Element Method I/O (bemio)
● Python ★ 4 ⑂ 11 Updated on Jun 7

Top languages
● Python ● Matlab ● C

People 3 >

cmichelen
Carlos Michelen

kmruehl
Kelley Ruehl

Michael Lawson

http://wec-sim.github.io/WDRT/

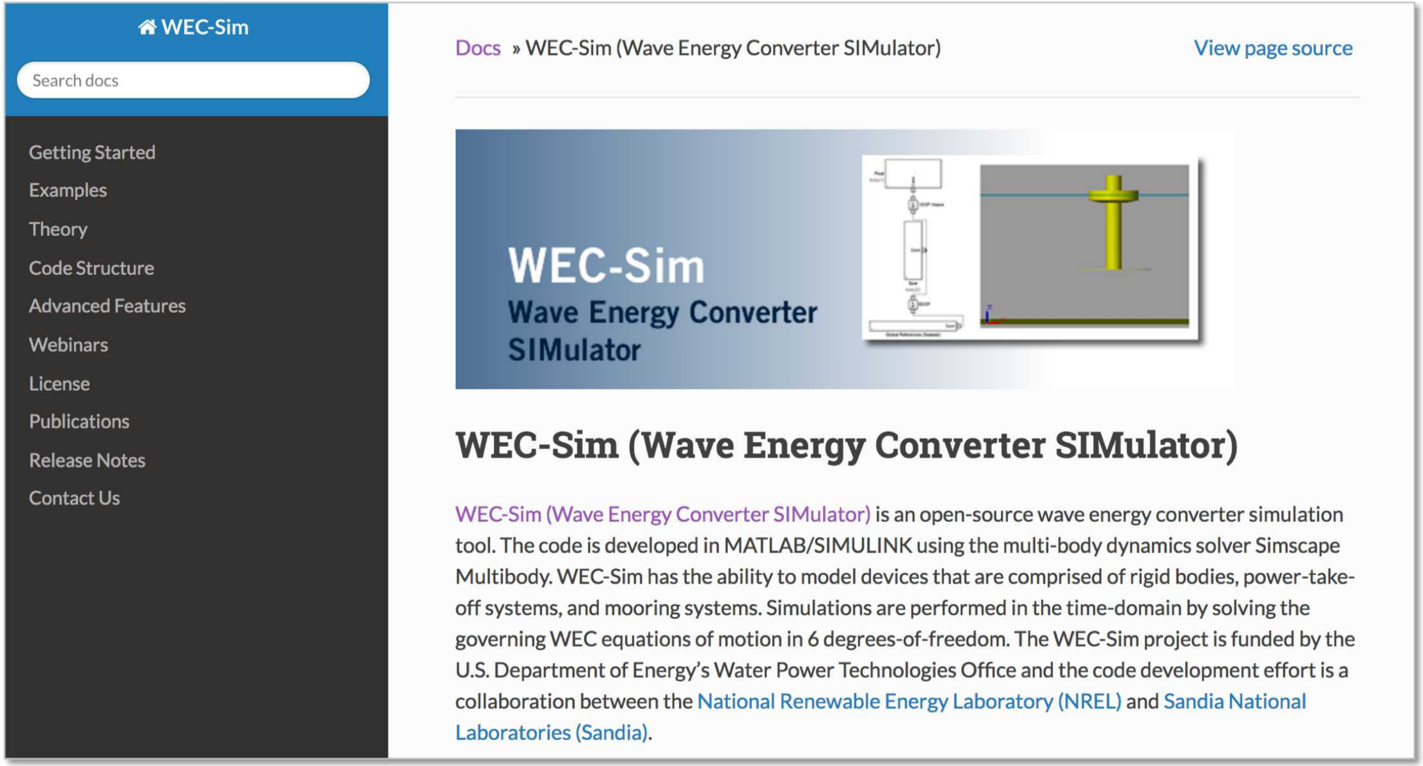
WDRT was developed by Sandia National Laboratories and the National Renewable Energy Laboratory (NREL) to provide extreme response and fatigue analysis tools, specifically for design analysis of ocean structures such as WECs.

WEC Design Response Toolbox

Old Python based BEMIO

Documentation

http://wec-sim.github.io/WEC-Sim/



- Getting Started
- Examples
- Theory
- Code Structure
- Advanced Features
- Webinars
- License
- Publications
- Release Notes
- Contact Us

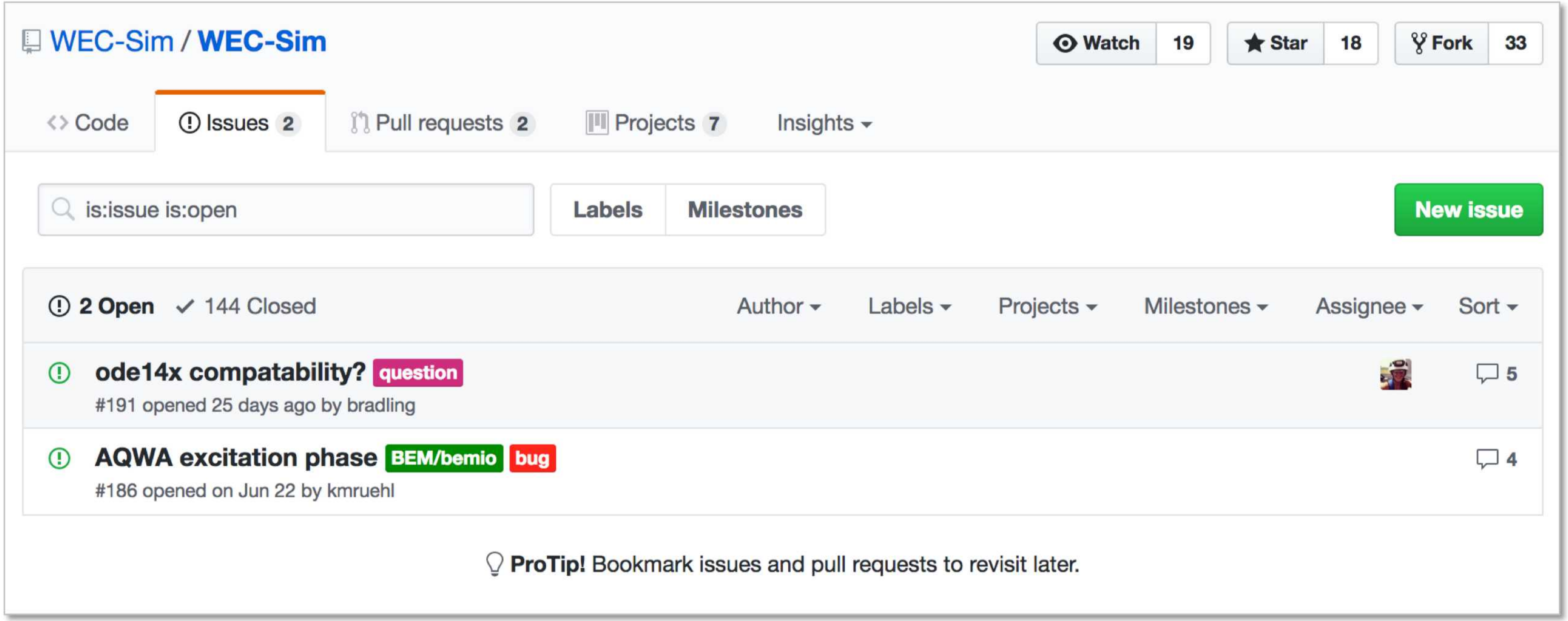
Docs » WEC-Sim (Wave Energy Converter SIMulator)

WEC-Sim (Wave Energy Converter SIMulator)

WEC-Sim (Wave Energy Converter SIMulator) is an open-source wave energy converter simulation tool. The code is developed in MATLAB/SIMULINK using the multi-body dynamics solver Simscape Multibody. WEC-Sim has the ability to model devices that are comprised of rigid bodies, power-take-off systems, and mooring systems. Simulations are performed in the time-domain by solving the governing WEC equations of motion in 6 degrees-of-freedom. The WEC-Sim project is funded by the U.S. Department of Energy's Water Power Technologies Office and the code development effort is a collaboration between the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (Sandia).

WEC-Sim Forum

https://github.com/WEC-Sim/WEC-Sim/issues



ode14x compatability? question
#191 opened 25 days ago by bradling
5

AQWA excitation phase BEM/bemio bug
#186 opened on Jun 22 by kmruehl
4

ProTip! Bookmark issues and pull requests to revisit later.

Numerical Assumptions and Nonlinearities

BEMIO	BEM (WAMIT, NEMOH, AQWA), Experimental, CFD, Geometry, Mesh

WEC-Sim

Body	Linear, Non-linear, Non-hydro, SS, B2B, Drag (Linear/Quadratic/Morison)
Waves	No Wave, Regular (Linear, CIC), Time-series, Irregular (PM/JS/BS/Imported Spectra)
Simu	Start-time, Time-step, Ramp-time, End-time, CI-time, Solver,
PTO	Linear, Non-linear, Control, PTO-Sim (Direct Drive, Hydraulic, User-defined)
Mooring	Linear, Non-linear, MoorDyn
Output	Visualization, MCR, Power Matrix, Optimization

IEA OES International Code Comparison

International Energy Agency Ocean Energy Systems Task 10 Wave Energy Converter Modeling Verification and Validation

Fabian Wendt[*], Yi-Hsiang Yu[*], Kim Nielsen[†], Kelley Ruehl[‡], Tim Bunnik[§], Imanol Touzon[¶], Bo Woo Nam[‖],
Jeong Seok Kim[‖], Kyong-Hwan Kim[‖], Carl Erik Janson[**], Ken-Robert Jakobsen[††], Sarah Crowley[‡‡], Luis Vega[x],
Krishnakumar Rajagopalan[x], Thomas Mathai[xi], Deborah Greaves[xii], Edward Ransley[xii], Paul Lamont-Kane[xiii],
Wanan Sheng[xiv], Ronan Costello[xv], Ben Kennedy[xv], Sarah Thomas[xvi], Pilar Heras[xvi], Harry Bingham[xvii],
Adi Kurniawan[xviii], Morten Mejlhede Kramer[xviii], David Ogden[xix], Samuel Girardin[xix], Aurélien Babarit[xx],
Pierre-Yves Wuillaume[xx], Dean Steinke[xxi], André Roy[xxi], Scott Beatty[xxii],
Paul Schofield[xxiii], Johan Jansson[xxiv, xxv], and Johan Hoffman[xxiv]

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E-mail: kelley.ruehl@sandia.gov
[§]MARIN, Netherlands [¶] Tecnalia, Spain [‖]KRISO, South Korea [**]Chalmers University, Sweden [††]EDRMedeso, Norway
[‡‡]WavEC, Portugal [x]Hawaii Natural Energy Institute, USA [xi]Glosten, USA [xii]Plymouth University, UK
[xiii]Queen's University Belfast, UK [xiv]University College Cork, Ireland [xv]Wave Venture, UK [xvi]Floating Power Plant, Denmark
[xvii]Technical University of Denmark [xviii]Aalborg University, Denmark [xix] INNOSEA, France
[xx]EC Nantes, France [xxi]Dynamic Systems Analysis, Canada
[xxii]Cascadia Coast Research, Canada [xxiii]ANSYS, USA [xxiv]KTH, Sweden [xxv]BCAM, Spain

Abstract—**This is the first joint reference paper for the Ocean Energy Systems (OES) Task 10 Wave Energy Converter modeling verification and validation group. The group is established under the OES Energy Technology Network program under the International Energy Agency. OES was founded in 2001 and Task 10 was proposed by Bob Thresher (National Renewable Energy Laboratory) in 2015 and approved by the OES Executive Committee EXCO in 2016. The kickoff workshop took place in September 2016, wherein the initial baseline task was defined. Experience from similar offshore wind validation/verification projects (OC3-OC5 conducted within the International Energy Agency Wind Task 30) [1], [2] showed that a simple test case would help the initial cooperation to present results in a comparable way. A heaving sphere was chosen as the first test case. The team of project participants simulated different numerical experiments, such as heave decay tests and regular and irregular wave cases. The simulation results are presented and discussed in this paper.**

Index Terms—**Wave power, numerical model, verification, validation, code comparison, international cooperation, IEA, OES, Task 10, BEM, CFD, heaving sphere, wave energy**

I. INTRODUCTION

Numerical modeling is an important aspect of the design of a wave energy converter (WEC). Designers use different simulation software packages (codes) that predict the response and loads of a WEC during operation and extreme events. These codes are based on different assumptions and numerical modeling approaches. The goal of the International Energy Agency (IEA) Offshore Energy Systems (OES) Task 10 is to gain confidence in using numerical models and assessing the accuracy of these codes. This project will eventually help to improve confidence levels in numerical predictions of power production and load estimates, which are important quantities for the development of reliable and cost-efficient WECs.

A total of 25 different organizations from 11 countries participated in the first phase of this project. The participants include universities, research laboratories, commercial software developers, and WEC developers.

The first phase focused on the relatively simple problem of a heaving, spherical body. The motivation behind the selection of this simplistic modeling problem was mitigating potential

1

F. Wendt and et al, "International Energy Agency Ocean Energy Systems Task 10 Wave Energy Converter Modeling Verification and Validation," in Proceedings of the 12th European Wave and Tidal Conference, Cork, Ireland, 2017.

International Energy Agency Ocean Energy Systems Task 10

- This task on WEC modeling verification and validation will internationally assess the accuracy and establish confidence in the use of numerical models for WECs.
- WEC-Sim was submitted by labs and also by other institutions
- Phase 1 results presented in EWTEC 2017 publication
- Currently modeling a new WEC geometry and looking for participants

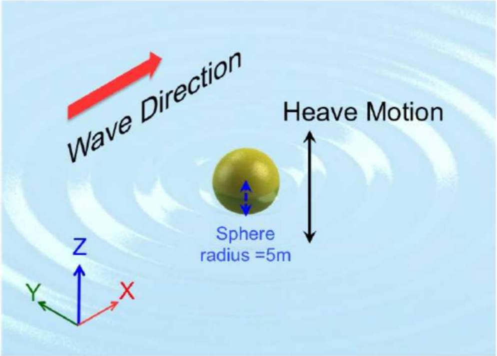


Fig. 1. Illustration of the heaving sphere used in the first phase of the project

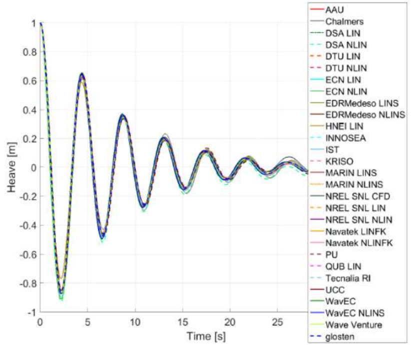


Fig. 3. Free-decay response in heave for the 1.0-m initial displacement.

WEC Control Competition (WECCCOMP)

- International competition to **maximize WEC benefit-to-cost ratio through innovative control strategies**
- First stage is **implementation of WEC control in a numerical simulation** at model scale using the WEC-Sim code
- Second stage involves **implementation of WEC control in an experimental wave tank**
- This paper details development and validation of a WEC-Sim representation of a 1-20th scale Wavestar model for WECCCOMP.

AVAILABLE AT

http://www.eeng.nuim.ie/coer/wec-control-competition-released/

ORGANIZED BY

COER Centre for Ocean Energy Research

NREL NATIONAL RENEWABLE ENERGY LABORATORY

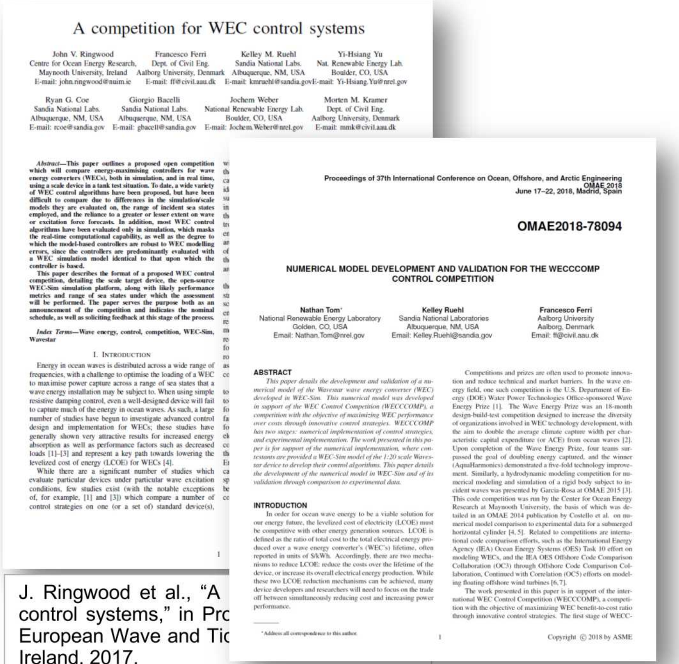
Sandia National Laboratories

AALBORG UNIVERSITY

WECCCOMP Timeline

1st Dec. 2017	Registration opens
1st Sept. 2018	Entry deadline
31st Oct. 2018	Shortlisting complete
15st Nov. 2018	Interactive implementation
31st Jan. 2019	Implementation evaluation
31st Mar. 2019	Final results published

WEC Control Competition (WECCCOMP)



A competition for WEC control systems

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Morten M. Kramer
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Abstract—This paper outlines a proposed open competition which will compare energy-maximising controllers for wave energy converters (WECs), both in simulation, and in real time, using a scale device in a tank test situation. To date, a wide variety of WEC control algorithms have been proposed, but have been difficult to compare due to differences in the simulation/scale models they are evaluated on, the range of incident sea states employed, and the reliance to a greater or lesser extent on wave or excitation force forecasts. In addition, most WEC control algorithms have been evaluated only in simulation, which masks the real-time computational capability, as well as the degree to which the model-based controllers are robust to WEC modelling errors, since the controllers are predominantly evaluated with a WEC simulation model identical to that upon which the controller is based.

This paper describes the format of a proposed WEC control competition, detailing the scale target device, the open-source WEC-Sim simulation platform, along with likely performance metrics and range of sea states under which the assessment will be performed. The paper serves the purpose both as an announcement of the competition and indicates the nominal schedule, as well as soliciting feedback at this stage of the process.

***Index Terms*—Wave energy, control, competition, WEC-Sim, Wavestar**

I. INTRODUCTION

Energy in ocean waves is distributed across a wide range of frequencies, with a challenge to optimise the loading of a WEC to maximise power capture across a range of sea states that a wave energy installation may be subject to. When using simple resistive damping control, even a well-designed device will fail to capture much of the energy in ocean waves. As such, a large number of studies have begun to investigate advanced control design and implementation for WECs; these studies have generally shown very attractive results for increased energy absorption as well as performance factors such as decreased loads [1]–[3] and represent a key path towards lowering the levelized cost of energy (LCOE) for WECs [4].

While there are a significant number of studies which evaluate particular devices under particular wave excitation conditions, few studies exist (with the notable exceptions of, for example, [1] and [3]) which compare a number of control strategies on one (or a set of) standard device(s),

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Proceedings of 37th International Conference on Ocean, Offshore, and Arctic Engineering
OMAE 2018
June 17–22, 2018, Madrid, Spain

OMAE2018-78094

NUMERICAL MODEL DEVELOPMENT AND VALIDATION FOR THE WECCCOMP CONTROL COMPETITION

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Aalborg, Denmark
Email: ff@civil.aau.dk

ABSTRACT

This paper details the development and validation of a numerical model of the Wavestar wave energy converter (WEC) developed in WEC-Sim. This numerical model was developed in support of the WEC Control Competition (WECCCOMP), a competition with the objective of maximizing WEC performance over costs through innovative control strategies. WECCCOMP has two stages: numerical implementation of control strategies, and experimental implementation. The work presented in this paper is for support of the numerical implementation, where contestants are provided a WEC-Sim model of the 1:20 scale Wavestar device to develop their control algorithms. This paper details the development of the numerical model in WEC-Sim and of its validation through comparison to experimental data.

INTRODUCTION

In order for ocean wave energy to be a viable solution for our energy future, the levelized cost of electricity (LCOE) must be competitive with other energy generation sources. LCOE is defined as the ratio of total cost to the total electrical energy produced over a wave energy converter's (WEC's) lifetime, often reported in units of $/kWh. Accordingly, there are two mechanisms to reduce LCOE: reduce the costs over the lifetime of the device, or increase its overall electrical energy production. While these two LCOE reduction mechanisms can be achieved, many device developers and researchers will need to focus on the trade off between simultaneously reducing cost and increasing power performance.

Competitions and prizes are often used to promote innovation and reduce technical and market barriers. In the wave energy field, one such competition is the U.S. Department of Energy (DOE) Water Power Technologies Office-sponsored Wave Energy Prize [1]. The Wave Energy Prize was an 18-month design-build-test competition designed to increase the diversity of organizations involved in WEC technology development, with the aim to double the average climate capture width per characteristic capital expenditure (or ACE) from ocean waves [2]. Upon completion of the Wave Energy Prize, four teams surpassed the goal of doubling energy captured, and the winner (AquaHarmonics) demonstrated a five-fold technology improvement. Similarly, a hydrodynamic modeling competition for numerical modeling and simulation of a rigid body subject to incident waves was presented by Garcia-Rosa at OMAE 2015 [3]. This code competition was run by the Center for Ocean Energy Research at Maynooth University, the basis of which was detailed in an OMAE 2014 publication by Costello et al. on numerical model comparison to experimental data for a submerged horizontal cylinder [4, 5]. Related to competitions are international code comparison efforts, such as the International Energy Agency (IEA) Ocean Energy Systems (OES) Task 10 effort on modeling WECs, and the IEA OES Offshore Code Comparison Collaboration (OC3) through Offshore Code Comparison Collaboration, Continued with Correlation (OC5) efforts on modeling floating offshore wind turbines [6, 7].

The work presented in this paper is in support of the international WEC Control Competition (WECCCOMP), a competition with the objective of maximizing WEC benefit-to-cost ratio through innovative control strategies. The first stage of WECC-

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*Address all correspondence to this author.

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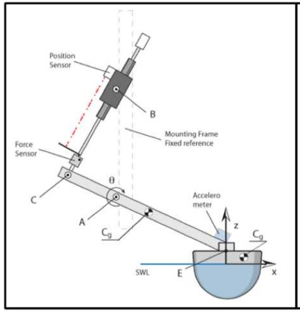
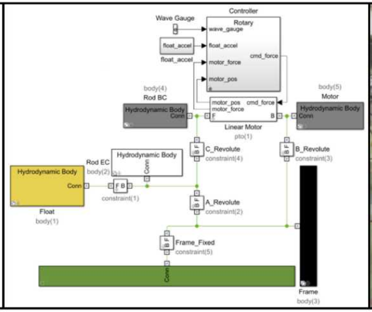
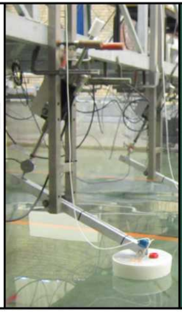
J. Ringwood et al., “A control systems,” in Pro European Wave and Tic Ireland, 2017.

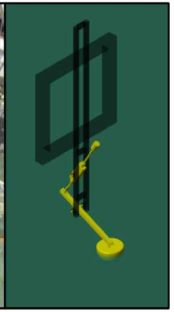
Tom, N., Ruehl, K., Ferri, F., “Numerical Model Development and Validation for the WECCCOMP Control Competition,” in Proceedings of OMAE 2018, Madrid, Spain, 2018.

- **Control competition announced in EWTEC 2017 publication**
- **Uses WEC-Sim as model for WaveStar controller development**
- **Development and validation of WEC-Sim model in OMAE 2018 publication**



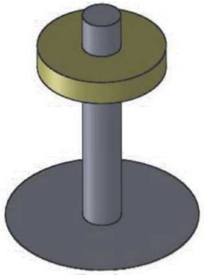


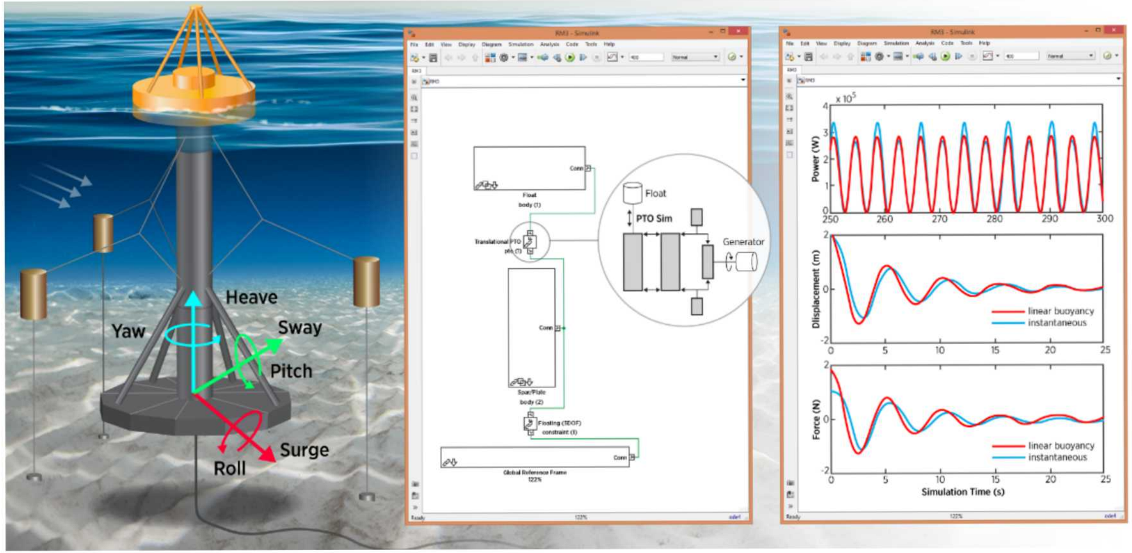




RM3 Tutorial

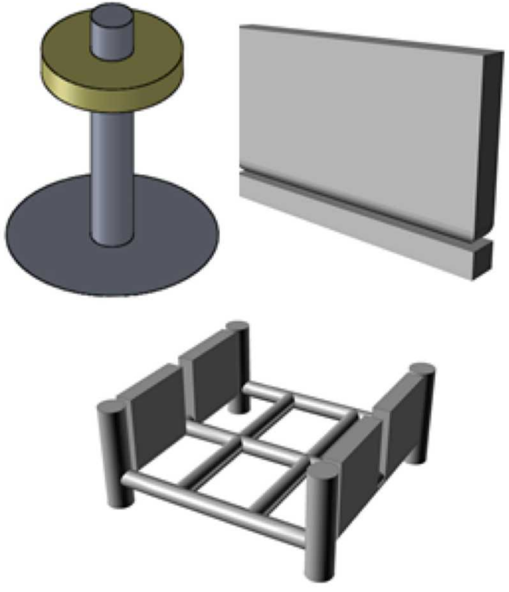
- Tutorial available online here:
  https://github.com/WEC-Sim/WEC-Sim/tree/master/tutorials/RM3
- Details available here:
  http://wec-sim.github.io/WEC-Sim/tutorials.html#two-body-point-absorber-rm3





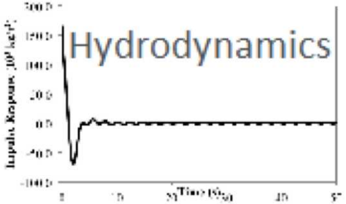
Analysis and Post-processing

WEC device specification

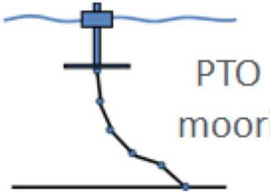


Relevant numerical methods

Multi-body dynamics

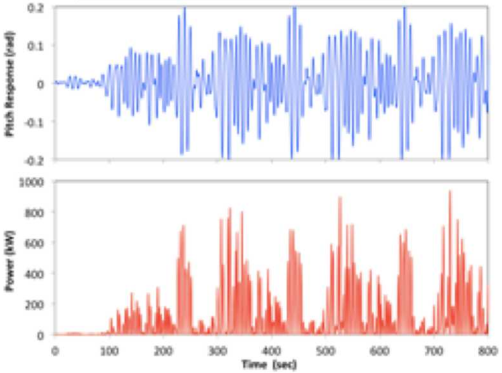


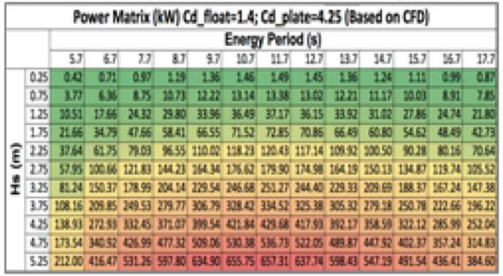
Hydrodynamics



PTO & mooring

WEC performance, motions, and loads





Power Matrix (kW) Cd_float=1.4; Cd_plate=4.25 (Based on CFD)

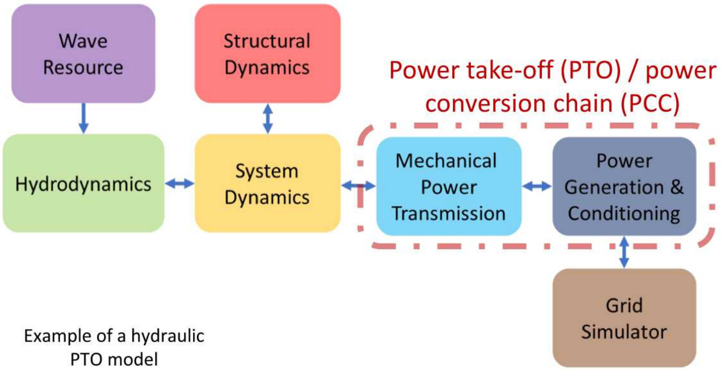
		Energy Period (s)												
		5.7	6.7	7.7	8.7	9.7	10.7	11.7	12.7	13.7	14.7	15.7	16.7	17.7
Hs (m)	0.25	0.42	0.71	0.97	1.19	1.36	1.46	1.49	1.45	1.36	1.24	1.11	0.99	0.87
	0.75	3.77	6.36	8.75	10.73	12.22	13.14	13.38	13.02	12.21	11.17	10.03	8.91	7.85
	1.25	10.51	17.66	24.32	29.80	33.96	36.49	37.17	36.15	33.92	31.02	27.86	24.74	21.80
	1.75	21.66	34.79	47.66	58.41	66.55	71.52	72.85	70.86	66.49	60.80	54.62	48.49	42.73
	2.25	37.64	61.75	79.03	96.55	110.02	118.23	120.43	117.14	109.92	100.50	90.28	80.16	70.64
	2.75	57.95	100.66	121.83	144.23	164.34	176.62	179.90	174.98	164.19	150.13	134.87	119.74	105.52
	3.25	81.24	150.37	178.99	204.14	229.54	246.68	251.27	244.40	229.33	209.69	188.37	167.24	147.38
	3.75	108.16	209.85	249.53	279.77	306.79	328.42	334.52	325.38	305.32	279.18	250.78	222.66	196.22
	4.25	138.93	272.93	332.45	371.07	399.54	421.84	429.68	417.93	392.17	358.59	322.12	285.99	252.04
	4.75	173.54	340.52	426.99	477.32	509.06	530.38	536.73	522.05	489.87	447.92	402.37	357.24	314.83
	5.25	212.00	416.47	531.26	597.80	634.90	655.75	657.31	637.74	598.43	547.19	491.54	436.41	384.60

Wave-To Wire Simulations

- Hydrodynamics simulation (including wave resource characterization) is important but is just half the battle.

- Mechanical power transmission and power electric and management (including grid impact) is the other half, which are essential to system design optimization and would affect the WEC hydrodynamics.

- Ultimately, WEC is a energy conversion system and cost efficiency is important.



Wave Resource

Structural Dynamics

Power take-off (PTO) / power conversion chain (PCC)

Hydrodynamics

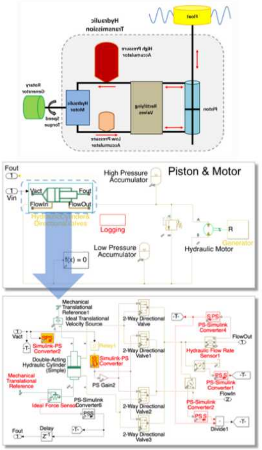
System Dynamics

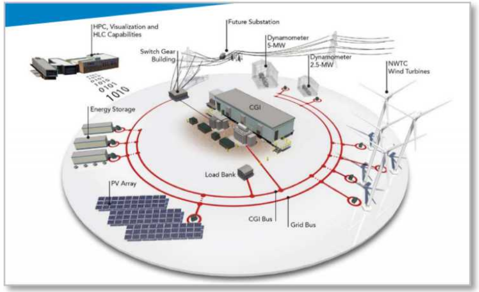
Mechanical Power Transmission

Power Generation & Conditioning

Grid Simulator

Example of a hydraulic PTO model

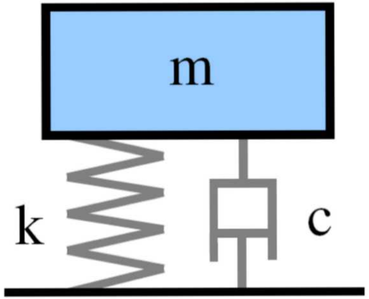


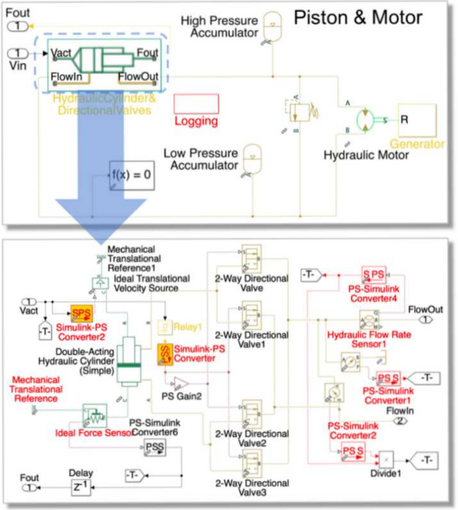


The NWTC's CGI allows manufacturers and system operators to test many aspects of grid integration for utility-scale wind and solar generation technologies and storage technologies.

PTO System Modeling

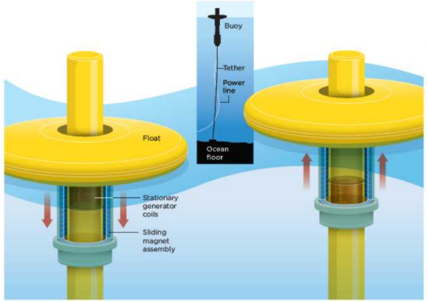
- Linear spring damper
- Coulomb damping
- Empirical correlation & lookup table
- PTO components simulation



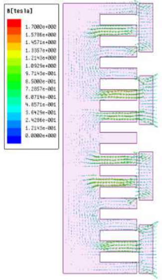


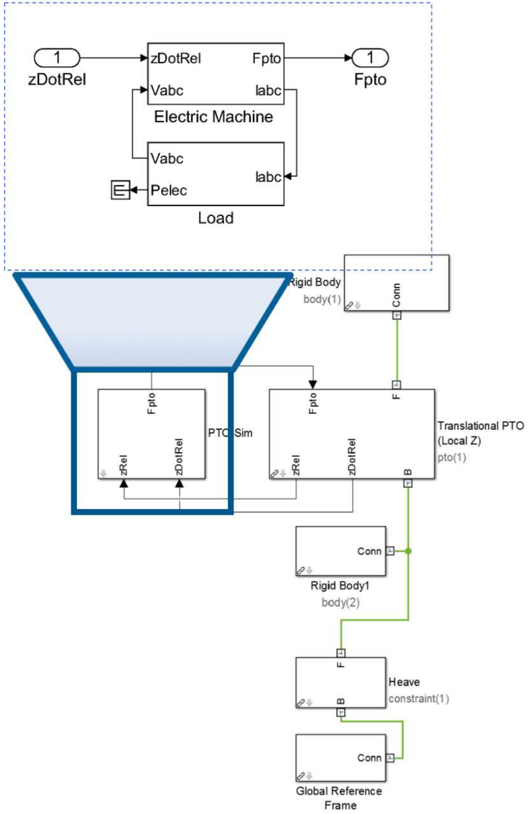
Case 1: Direct Drive PTO

- OSUL10: Two-body point absorber
- WEC-Sim using PTO-Sim

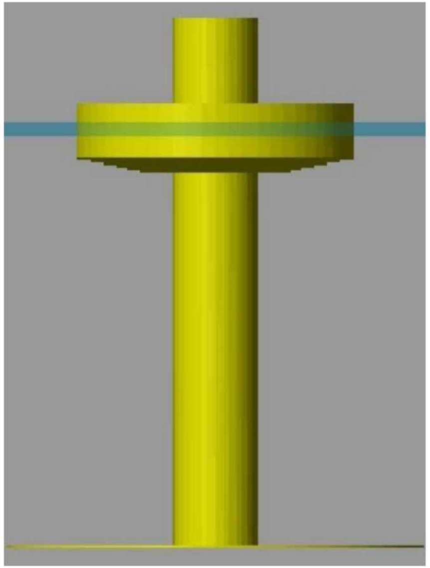


[Smithsonian]





So, R., Simmons, A., Brekken, T., Ruehl, K., and Michelen, C., 2015. “Development of PTO-Sim A power performance module for the open-source wave energy converter code WEC-Sim,” *34th International Conference on Ocean, Offshore and Arctic Engineering*.



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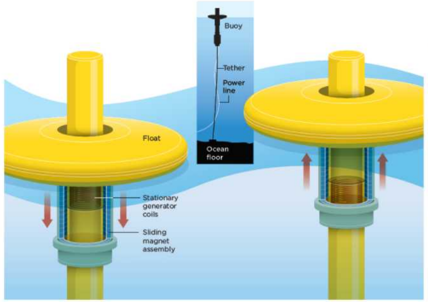

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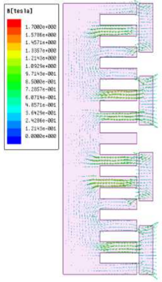

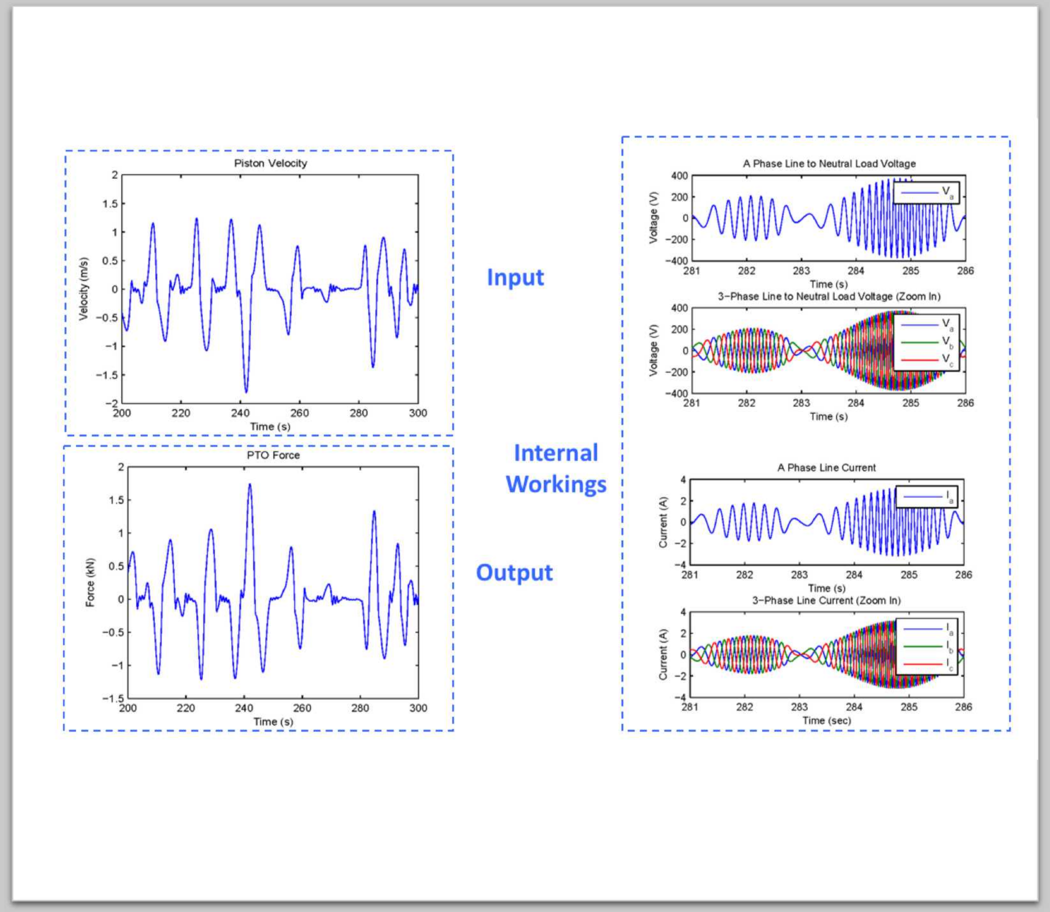

Case 1: Direct Drive PTO

- OSUL10: Two-body point absorber
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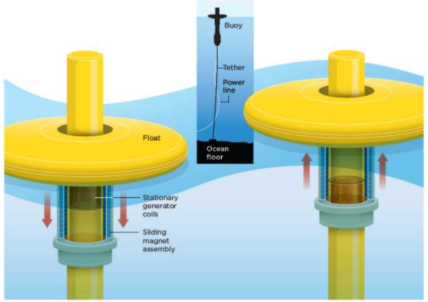
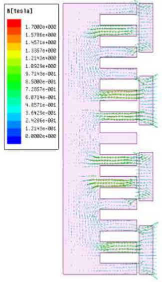
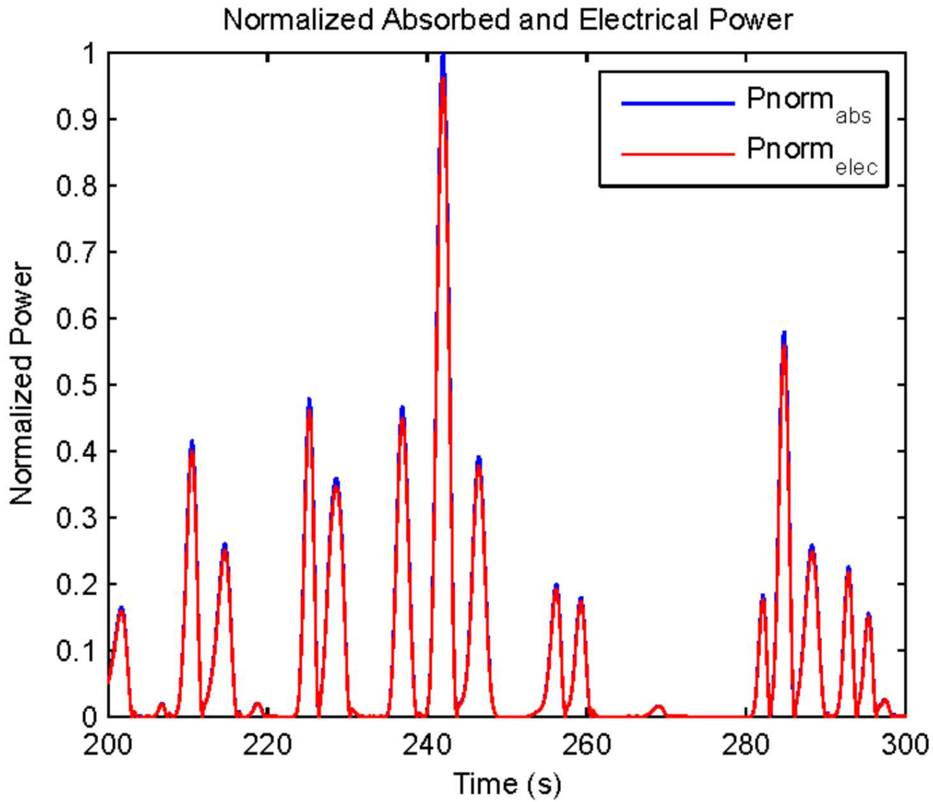


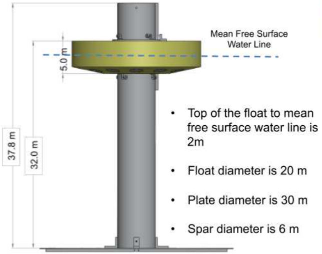
[Smithsonian]



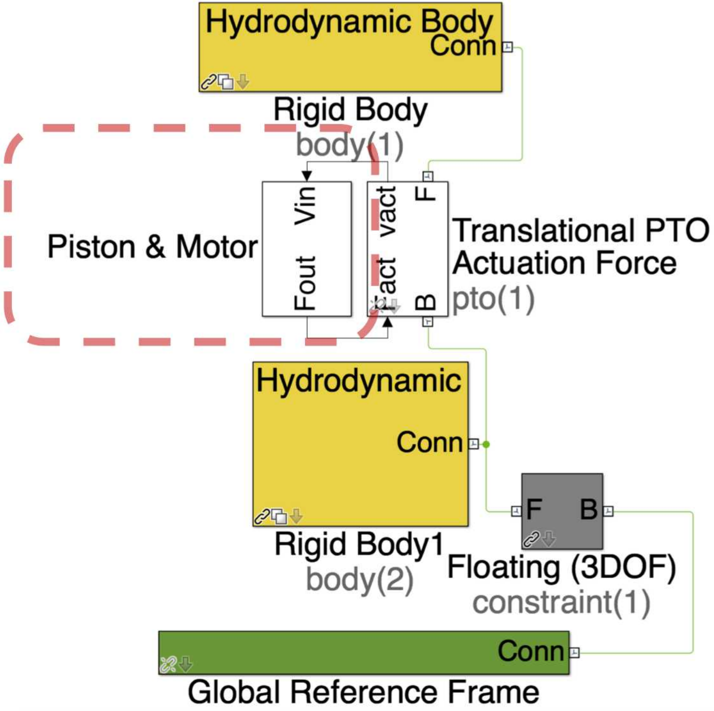


Case 2: Hydraulic PTO

- Reference Model 3: Two-body point absorber
- WEC-Sim + Simscape Fluids



- Top of the float to mean free surface water line is 2m
- Float diameter is 20 m
- Plate diameter is 30 m
- Spar diameter is 6 m



Yu Y.-H., Tom N., and Jenne D., 2018, “Numerical Analysis on Hydraulic Power Take-Off for Wave Energy Converter and Power Smoothing Methods,” 37th International Conference on Ocean, Offshore and Arctic Engineering, OMAE, Madrid, Spain.

Case 2: Hydraulic PTO

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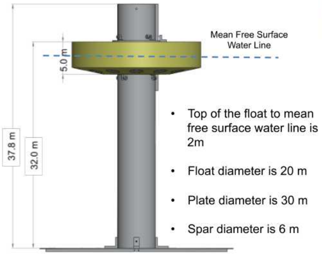

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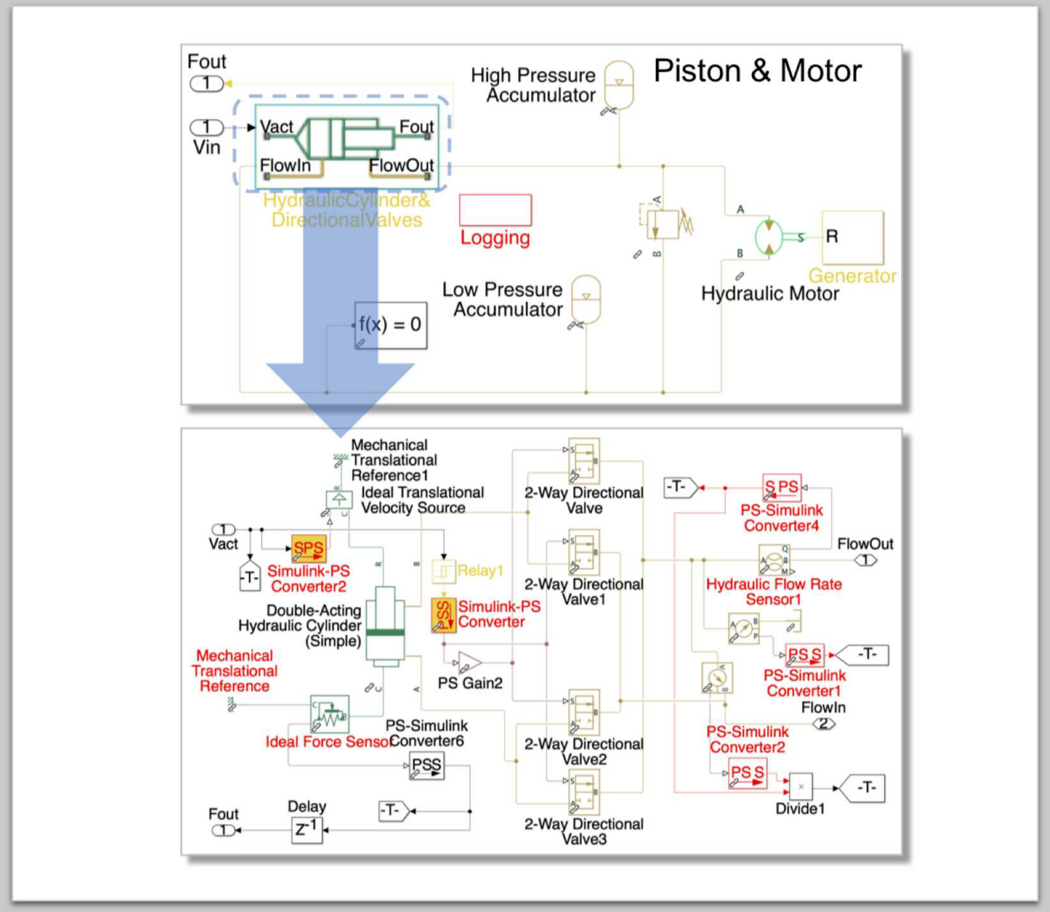
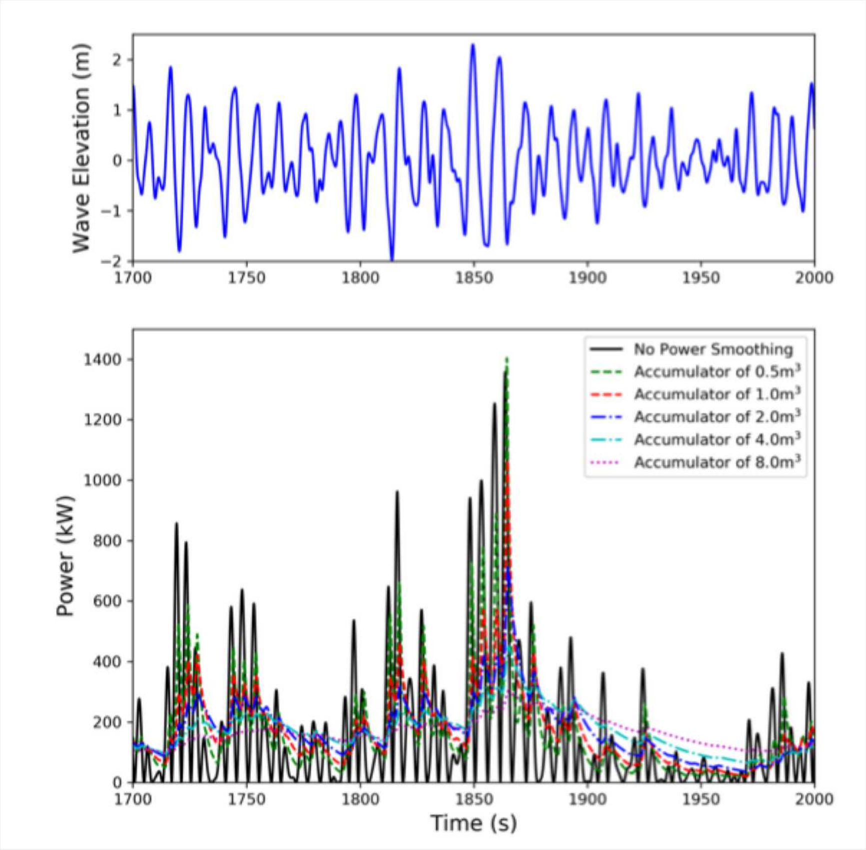
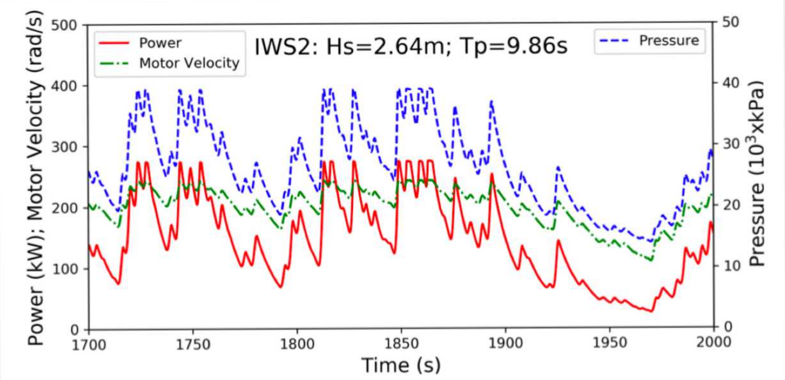


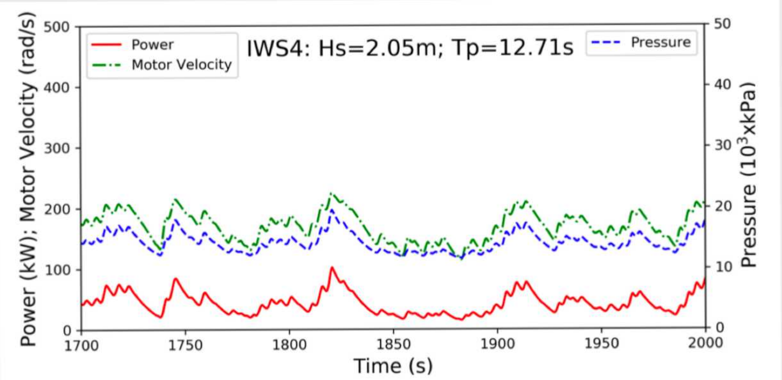
Case 2: Hydraulic PTO

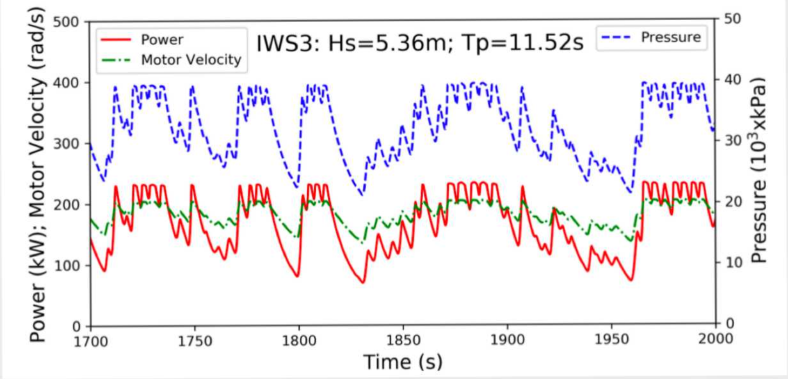
The variations of the power output (voltage, frequency, rate of change in power output) can be a problem which must be well understood as it drives additional design considerations for wider power system development.

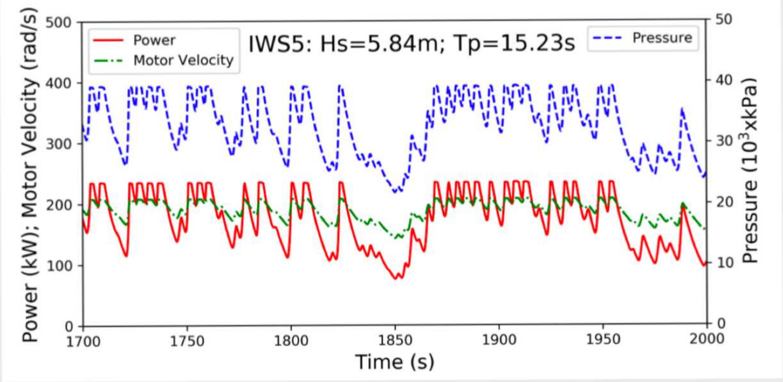


Case 2: Hydraulic PTO







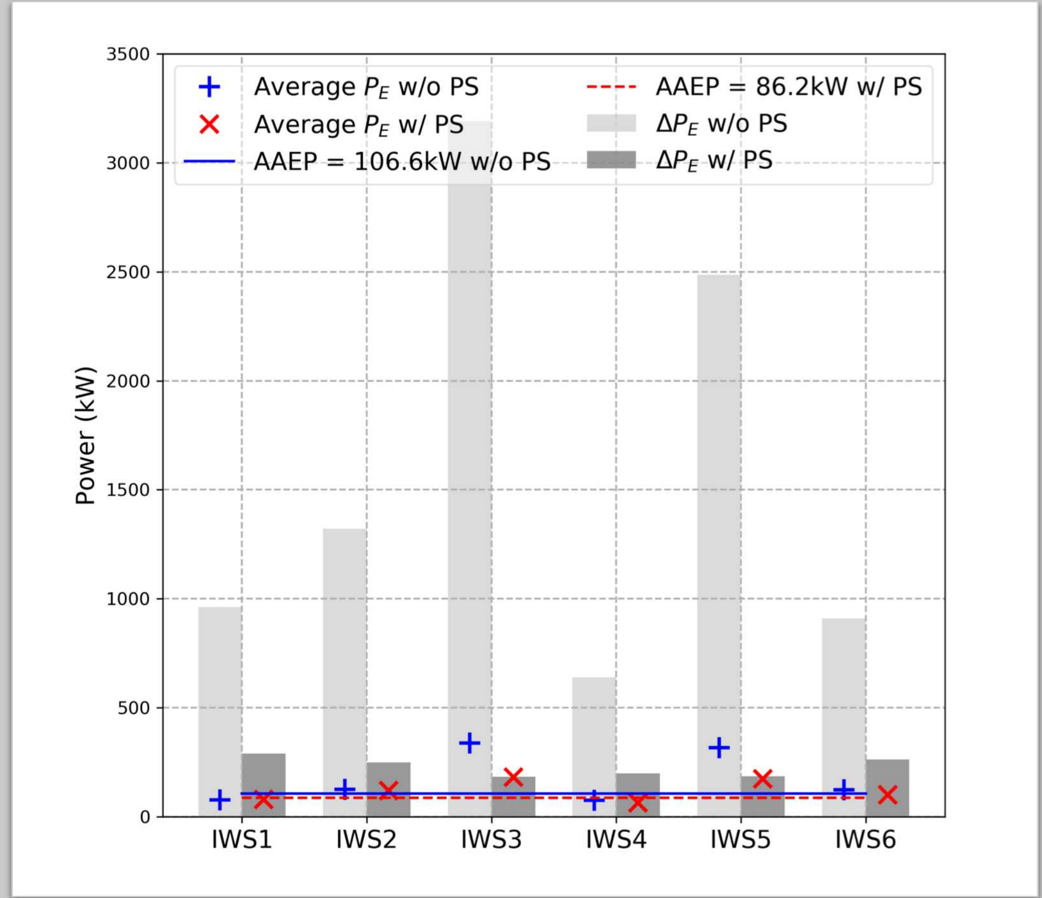


Case 2: Hydraulic PTO

Control for Power Smoothing

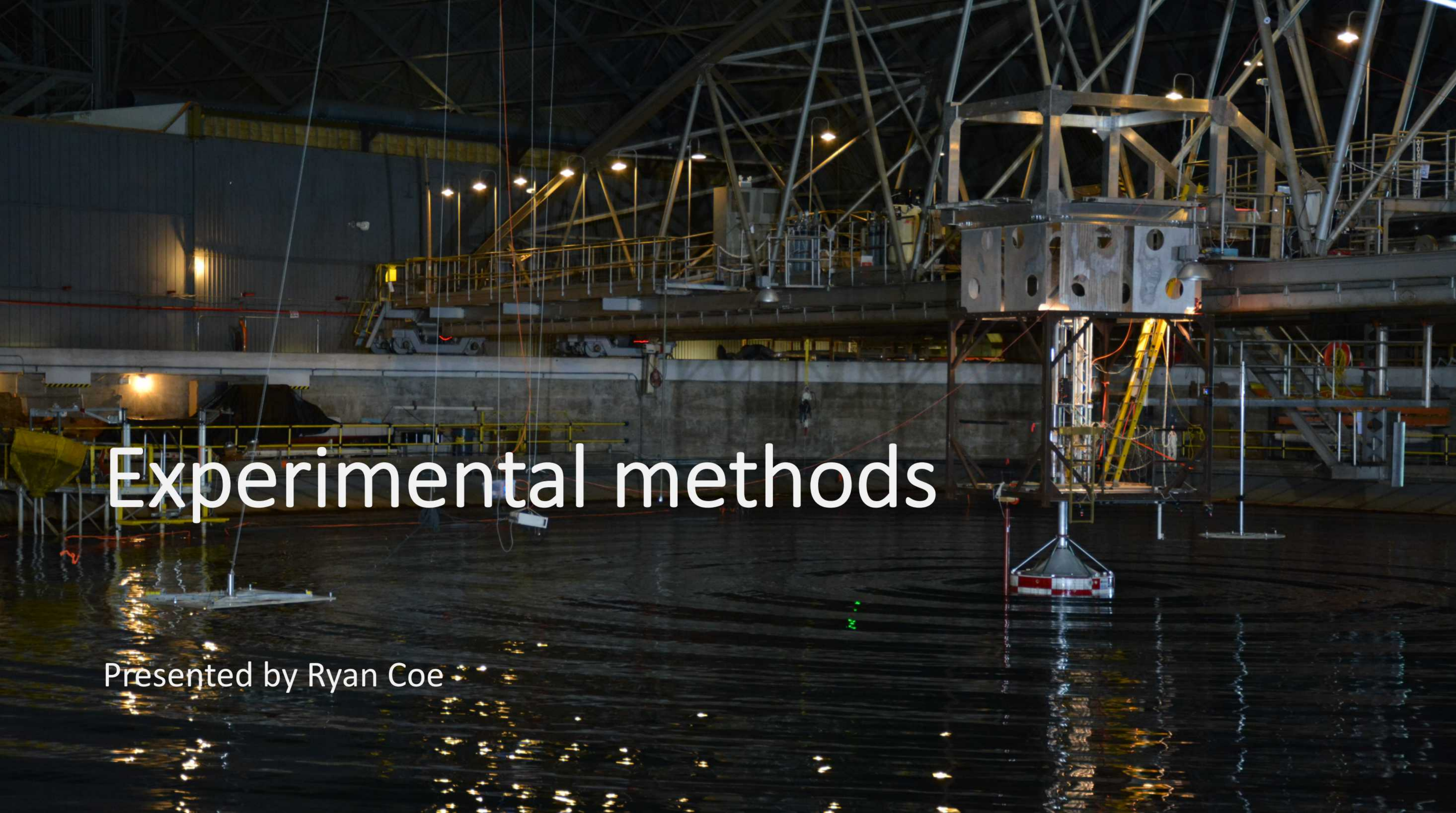
Wave Energy Prize Sea States

Wave #	Tp (s)	Hs (m)	Weighting
IWS 1	7.31	2.34	0.175
IWS 2	9.86	2.64	0.268
IWS 3	11.52	5.36	0.058
IWS 4	12.71	2.05	0.295
IWS 5	15.23	5.84	0.034
IWS 6	16.50	3.25	0.054



PTO System Modeling Challenges

- A multi-physics problem
- What level of detail do we want to resolve?
- Numerical stabilities – often required smaller time steps or use different time-step sizes for different physics.

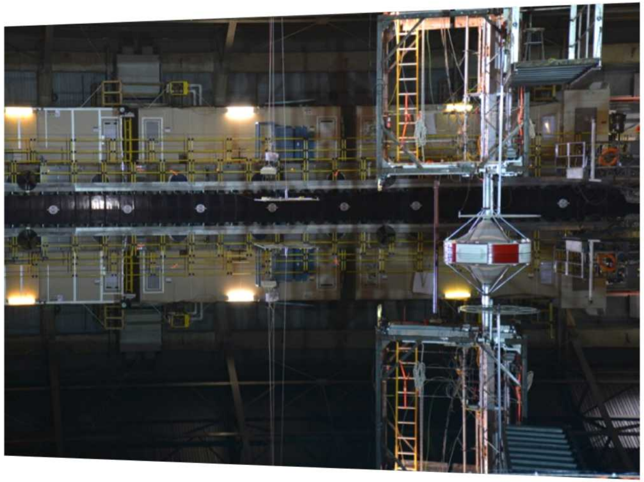


Experimental methods

Presented by Ryan Coe

Why System ID?

- Most effective control strategies are model-based
- Control effectiveness is directly dependent on model accuracy
- Numerical methods (e.g., boundary element) are imperfect
  - Linearized
  - Only tell you about part of the system



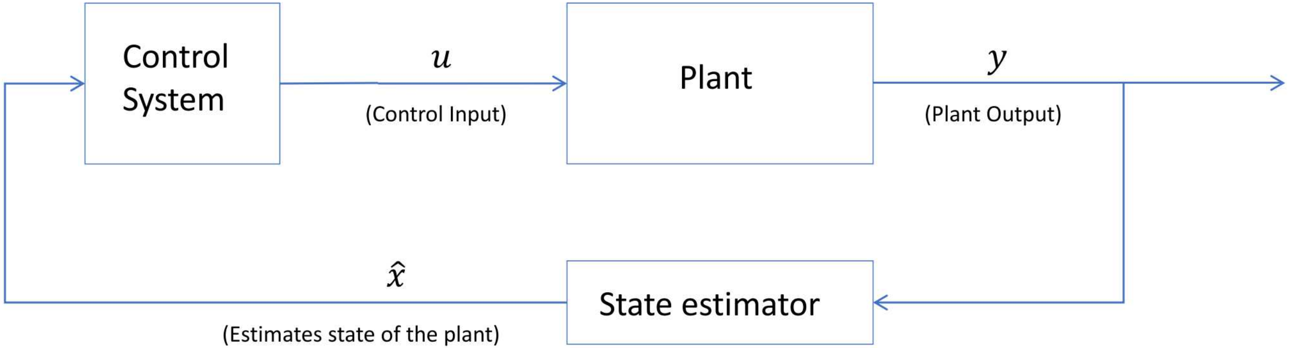
Control models

What is the objective?

Control system design

Steps

1. Identify available measurements (y)
2. Study quality of the measurements (y) (e.g. noise)
3. Design state estimator/observer
    - E.g.: Kalman filter and Luenberger observer are **model** based
4. Design control system
    - Many control algorithms require a **model** of the plant (e,g. MPC, LQ)



Control System

u

(Control Input)

Plant

y

(Plant Output)

$\hat{x}$

(Estimates state of the plant)

State estimator

G. Bacelli and R. G. Coe, "State estimation for wave energy converters," Sandia National Laboratories, Tech. Rep. SAND2017-4401, 2017.

Types of models

- Many types of models to choose from
- “Correct” model type dictated by intended application(s)

	Time domain	Frequency domain
Parametric	State-space	Transfer function
Non-parametric	Impulse response function	Frequency response function (WAMIT)

Types of models

Frequency domain models often provide useful insight in system dynamics and assist in analytic tuning

	Time domain	Frequency domain
Parametric	State-space	**Transfer function**
Non-parametric	Impulse response function	**Frequency response function (WAMIT)**

Types of models

	Time domain	Frequency domain
Parametric	State-space	Transfer function
Non-parametric	**Impulse response function**	**Frequency response function (WAMIT)**

Non-parametric models directly produced by numerical and empirical methods (no fitting necessary)

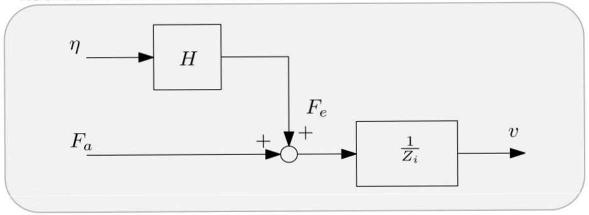
Types of models

Description of dynamics in terms of poles and zeros

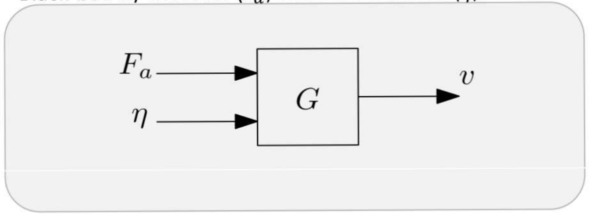
	Time domain	Frequency domain
Parametric	State-space	**Transfer function**
Non-parametric	Impulse response function	Frequency response function (WAMIT)

Types of models

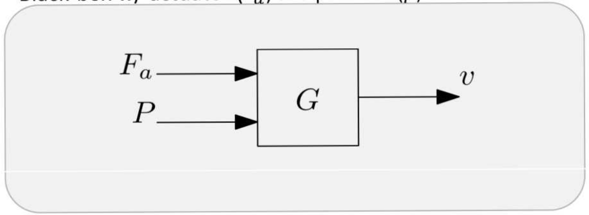
Radiation-diffraction model



Black-box w/ actuator (F_a) and wave elevation (η)

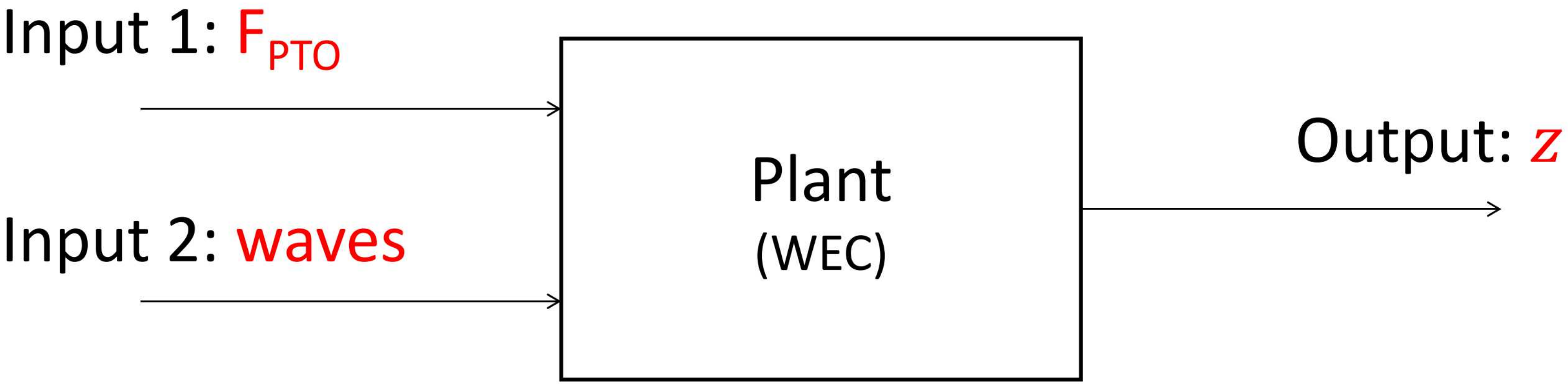


Black-box w/ actuator (F_a) and pressure (p)



	Time domain	Frequency domain
Parametric	State-space	Transfer function
Non-parametric	Impulse response function	Frequency response function (WAMIT)

Testing - System identification



Input 1: F_{PTO}

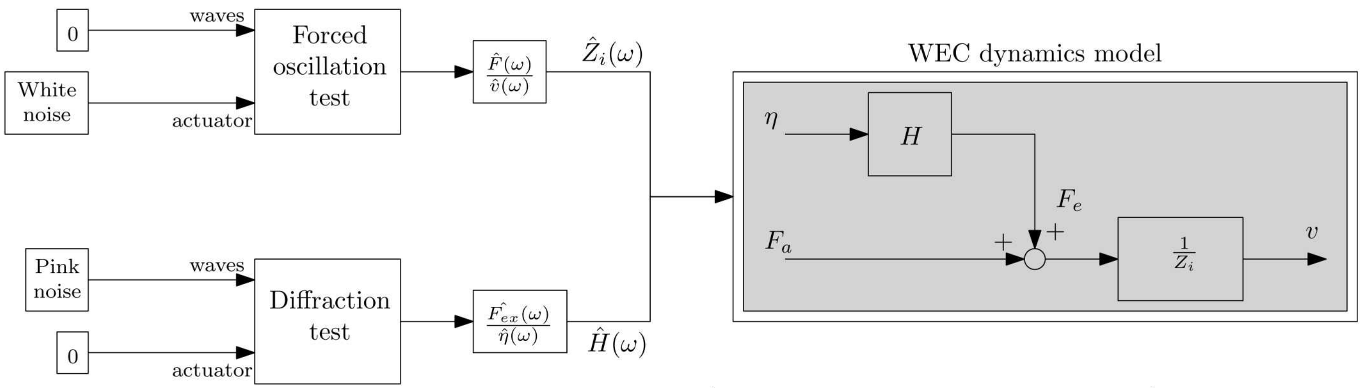
Input 2: waves

Plant
(WEC)

Output: z

Multi Input Single Output (MISO) system

WEC System Identification



- **Forced oscillation test**
  - Force control
  - Multi-sine input signal (e.g., white noise)
- **Diffraction test**
  - While idealized ocean spectra (e.g. Bretschneider) are acceptable, flatter spectra are more desirable.
  - White (flat) spectra waves have a tendency to break; pink spectra do not

$$\left(B(\omega)+B_f+i\left(\omega\left(M+A(\omega)\right)-\frac{K}{\omega}\right)\right)\hat V=\hat H(\omega)\,\hat\eta+\hat F_a$$

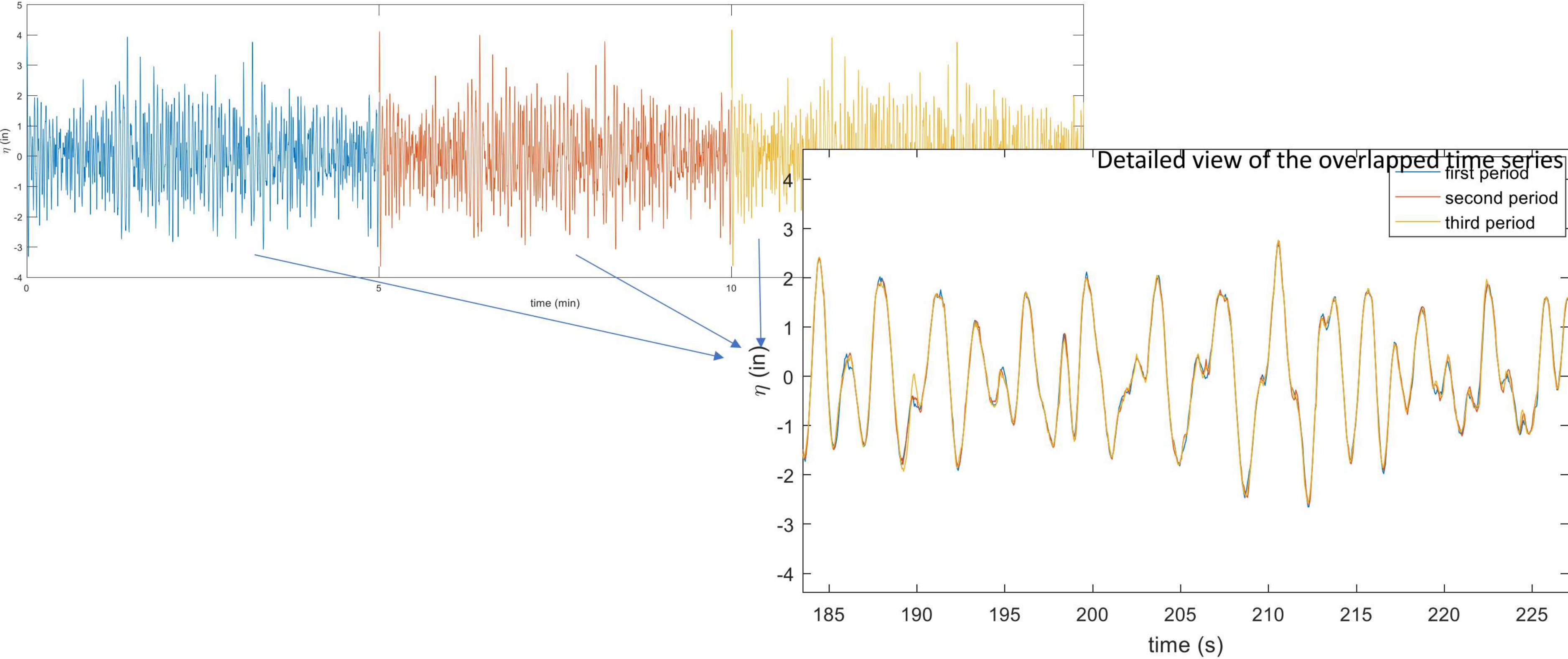
Intrinsic impedance $Z_i(\omega)=\frac{\hat F_a}{\hat V}=B(\omega)+B_f+i\big(M+A(\omega)-K/\omega\big)$

$$\hat V=\frac{H(\omega)}{Z_i(\omega)}\,\hat\eta+\frac{1}{Z_i(\omega)}\hat F_a.$$

G. Bacelli and R. G. Coe, "WEC system identification and model validation," in Marine Energy Technology Symposium (METS2017), Washington, D.C., 2017.

Testing - Repeating vs non-repeating spectra

Water surface elevation: Bretschneider spectrum, repeat period T_{rep}= 5minutes



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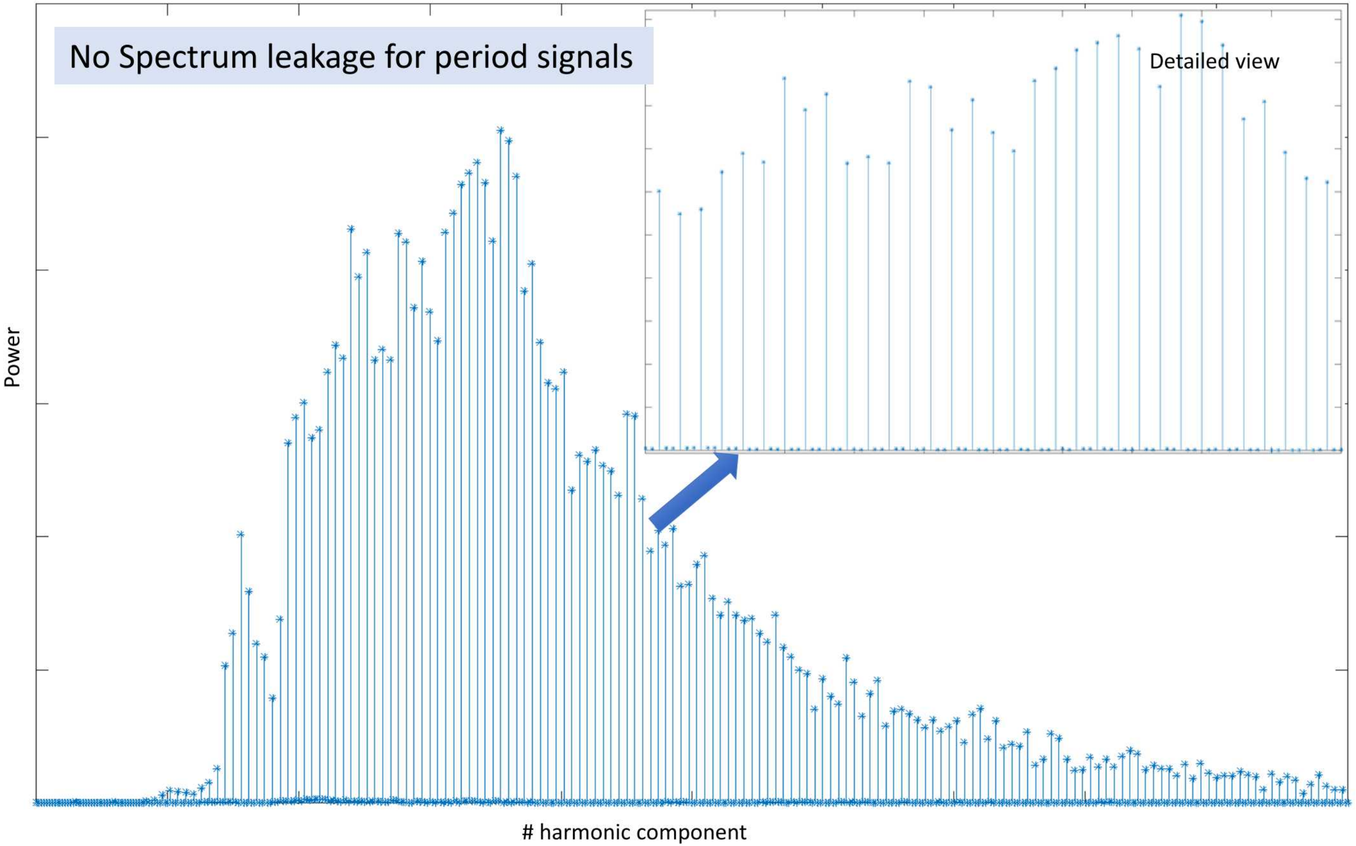
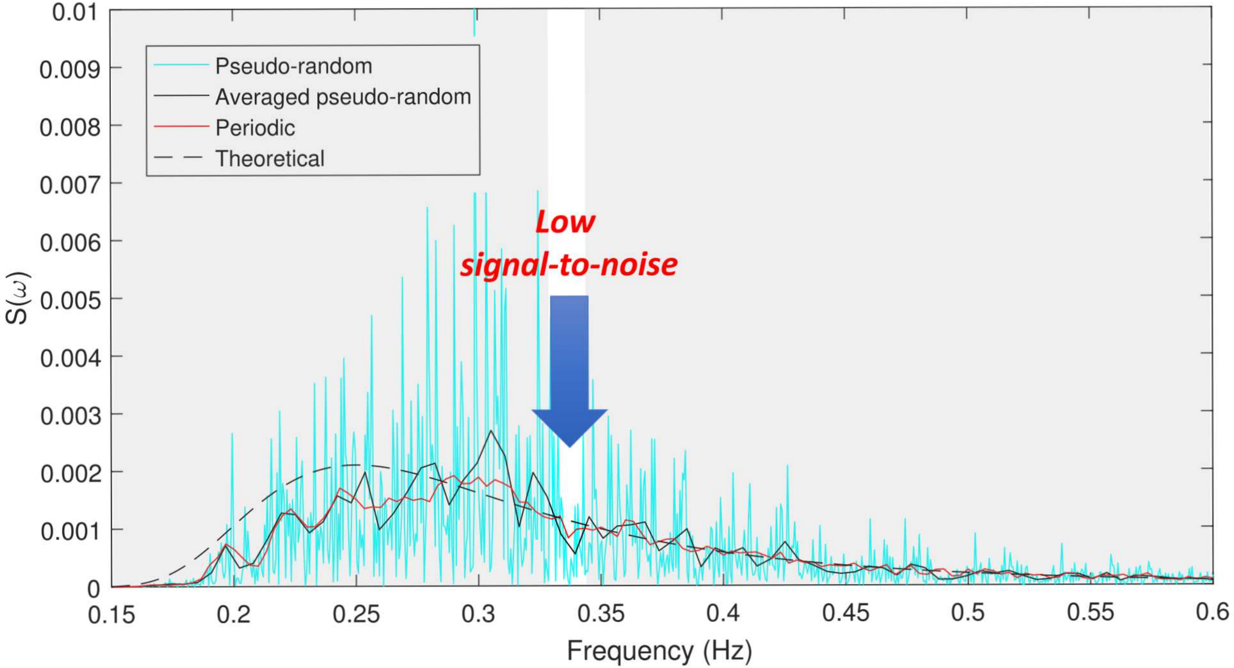


G. Bacelli and R. G. Coe, "WEC system identification and model validation," in Marine Energy Technology Symposium (METS2017), Washington, D.C., 2017.

Benefits of periodic input signals



Low signal-to-noise

$$\boxed{T_r = 2\,\mathrm{hr},\, T_{\mathrm{exp}} = 30\,\mathrm{min}} \qquad \boxed{T_r = 5\,\mathrm{min},\, T_{\mathrm{exp}} = 15\,\mathrm{min}}$$

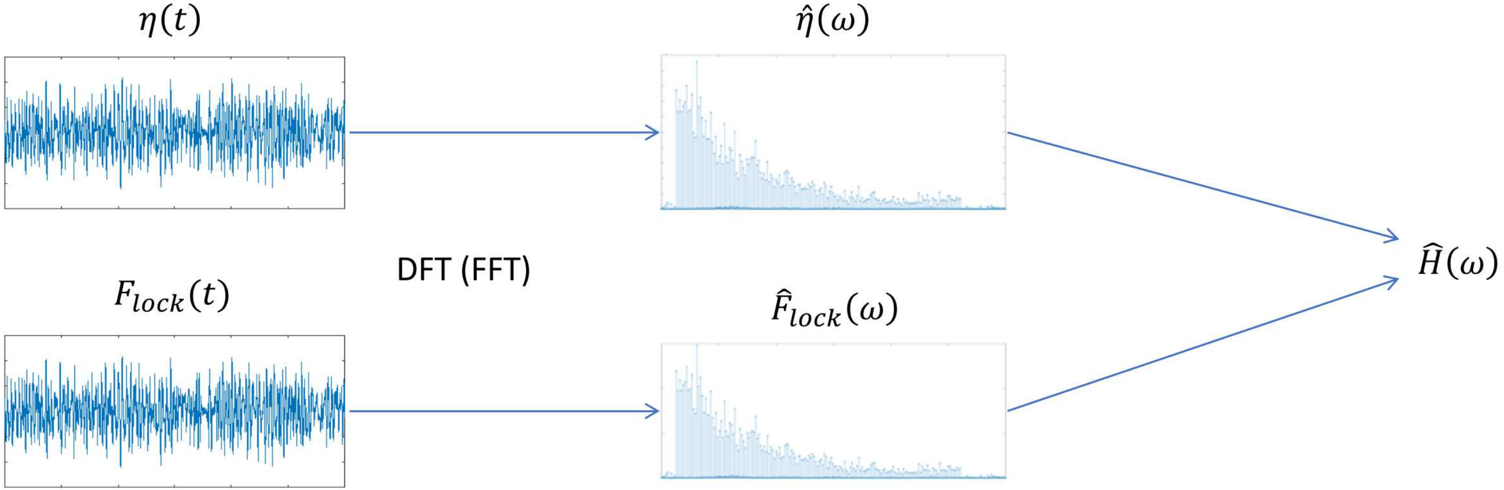
G. Bacelli and R. G. Coe, "WEC system identification and model validation," in Marine Energy Technology Symposium (METS2017), Washington, D.C., 2017.

MASK Basin Testing

https://www.youtube.com/watch?v=XCB12Het4c4

Testing - Excitation FRF

$$\widehat{H}(\omega) = \widehat{F}_{lock}(\omega)/\hat{\eta}(\omega)$$



$\eta(t)$

$\hat{\eta}(\omega)$

DFT (FFT)

$\widehat{H}(\omega)$

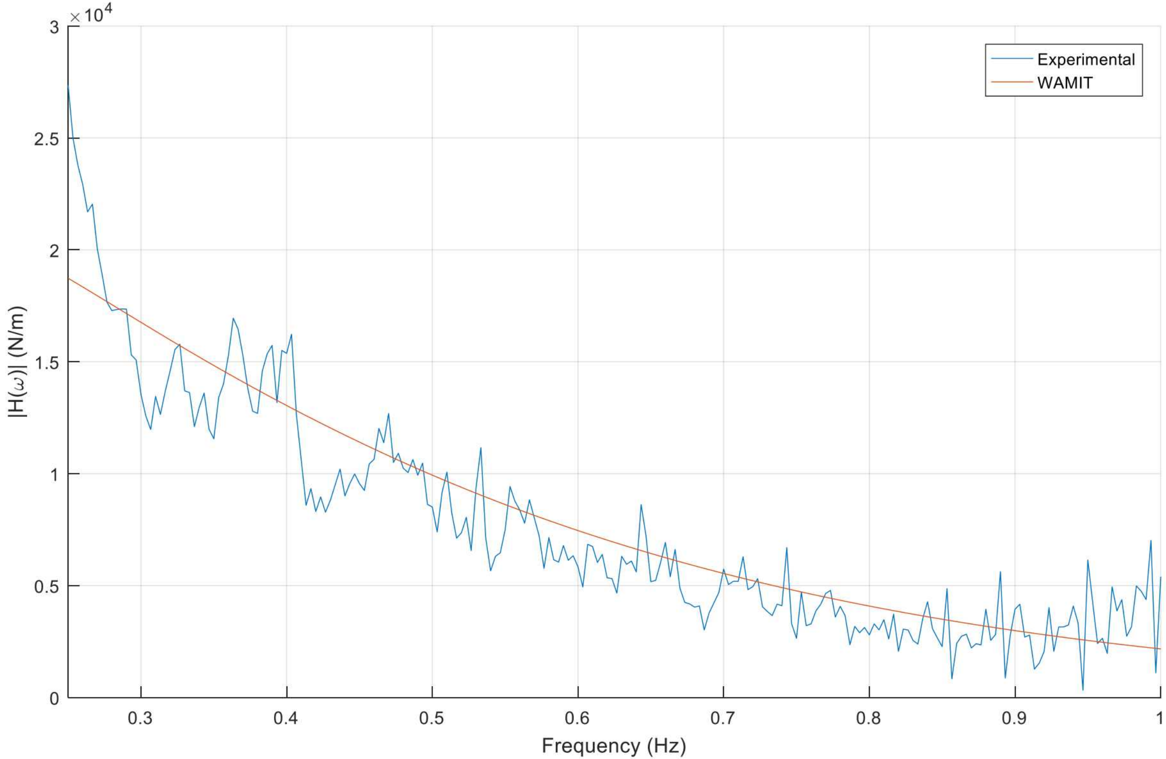
$F_{lock}(t)$

$\widehat{F}_{lock}(\omega)$

$\eta(t), F_{lock}(t)$ trimmed at integer multiple of period

Testing - Excitation FRF

$$\hat{H}(\omega) = \hat{F}_{lock}(\omega)/\hat{\eta}(\omega)$$

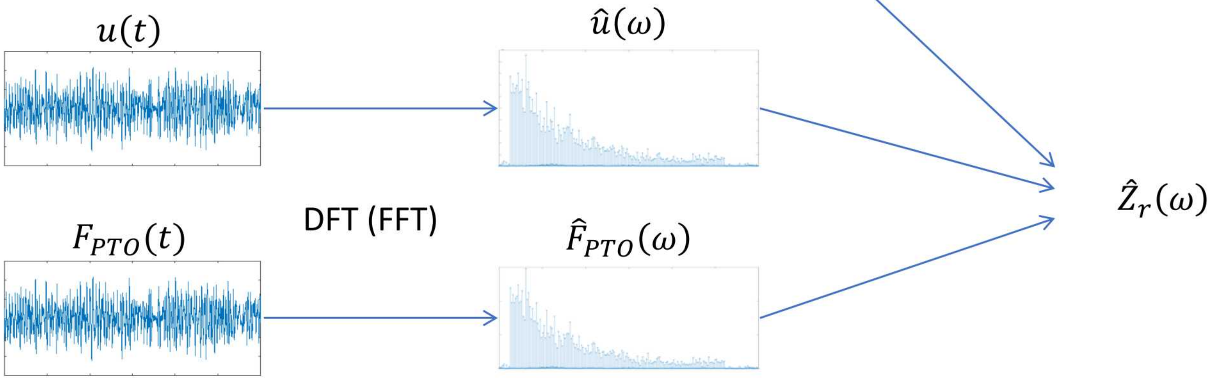


G. Bacelli, R. G. Coe, D. Patterson, and D. Wilson, "System identification of a heaving point absorber: Design of experiment and device modeling," Energies, vol. 10, no. 10, p. 472, 2017.

Testing - Radiation FRF

$$\hat{Z}_r(\omega) = \hat{R}(\omega) + i\omega\widehat{M}_a(\omega) = \frac{\widehat{F}_{PTO}(\omega)}{\hat{u}(\omega)} - B - i\left(\omega M - \frac{K}{\omega}\right)$$

$\hat{R}$ = Radiation damping
$\widehat{M}_a$ = Added mass
$\hat{u}$ = velocity
$\widehat{F}_{PTO}$ = PTO force
B = linear friction/dissipation
M= mass
K = hydrostatic restoring coeff



$u(t)$

$\hat{u}(\omega)$

DFT (FFT)

$F_{PTO}(t)$

$\widehat{F}_{PTO}(\omega)$

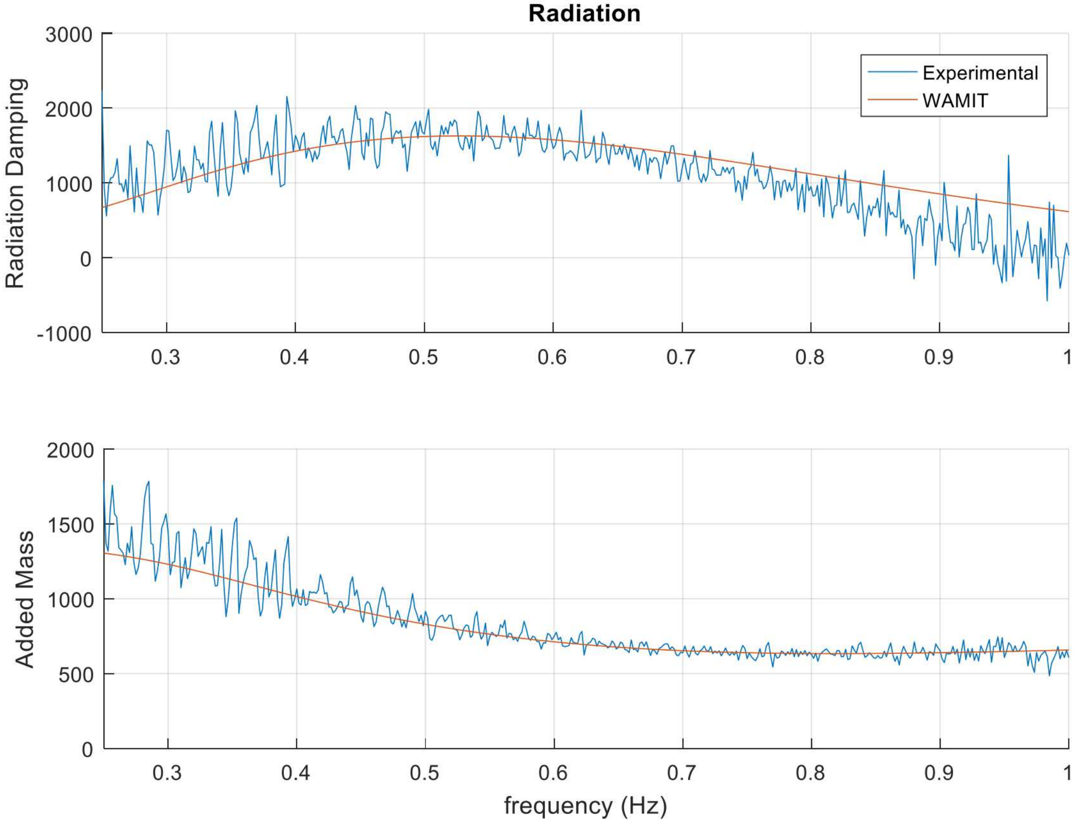
$\hat{Z}_r(\omega)$

$u(t), F_{PTO}(t)$ trimmed at integer multiple of period

G. Bacelli, R. G. Coe, D. Patterson, and D. Wilson, "System identification of a heaving point absorber: Design of experiment and device modeling," Energies, vol. 10, no. 10, p. 472, 2017.

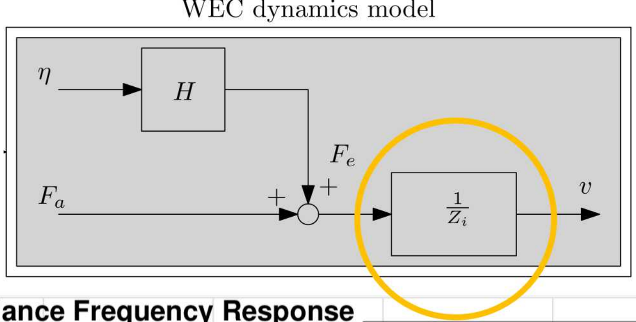
Testing - Radiation FRF

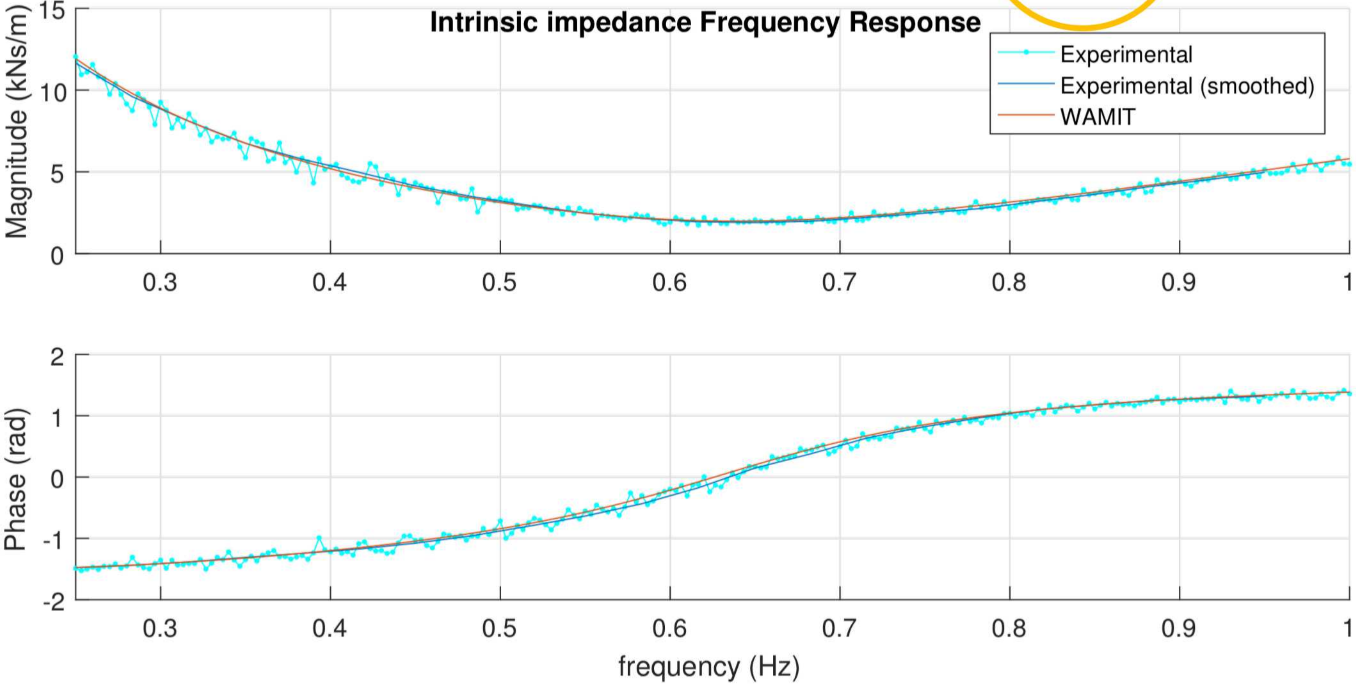
$$\hat{Z}_r(\omega) = \hat{R}(\omega) + i\omega\widehat{M}_a(\omega)$$



G. Bacelli, R. G. Coe, D. Patterson, and D. Wilson, "System identification of a heaving point absorber: Design of experiment and device modeling," Energies, vol. 10, no. 10, p. 472, 2017.

Model validation





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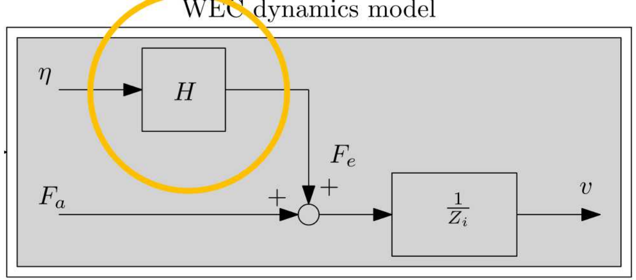
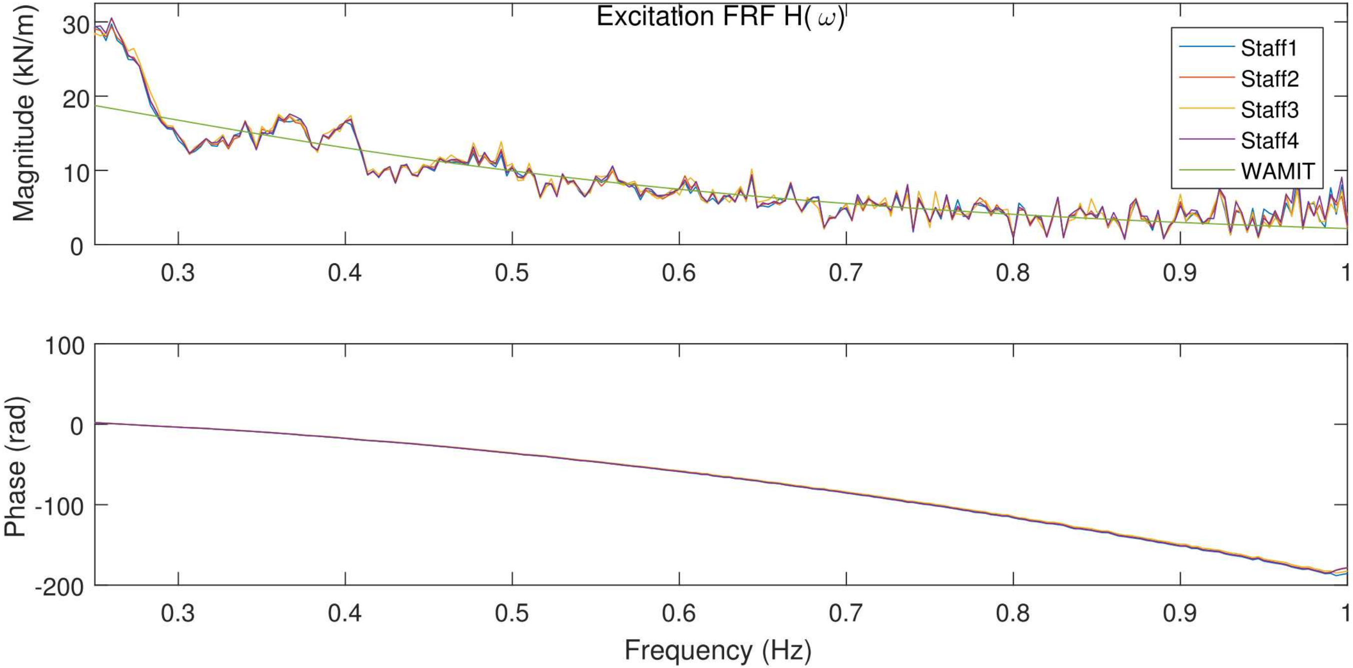
Model validation





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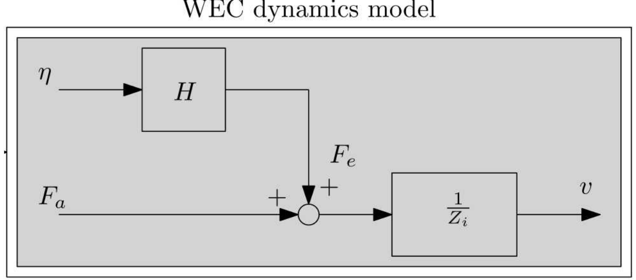
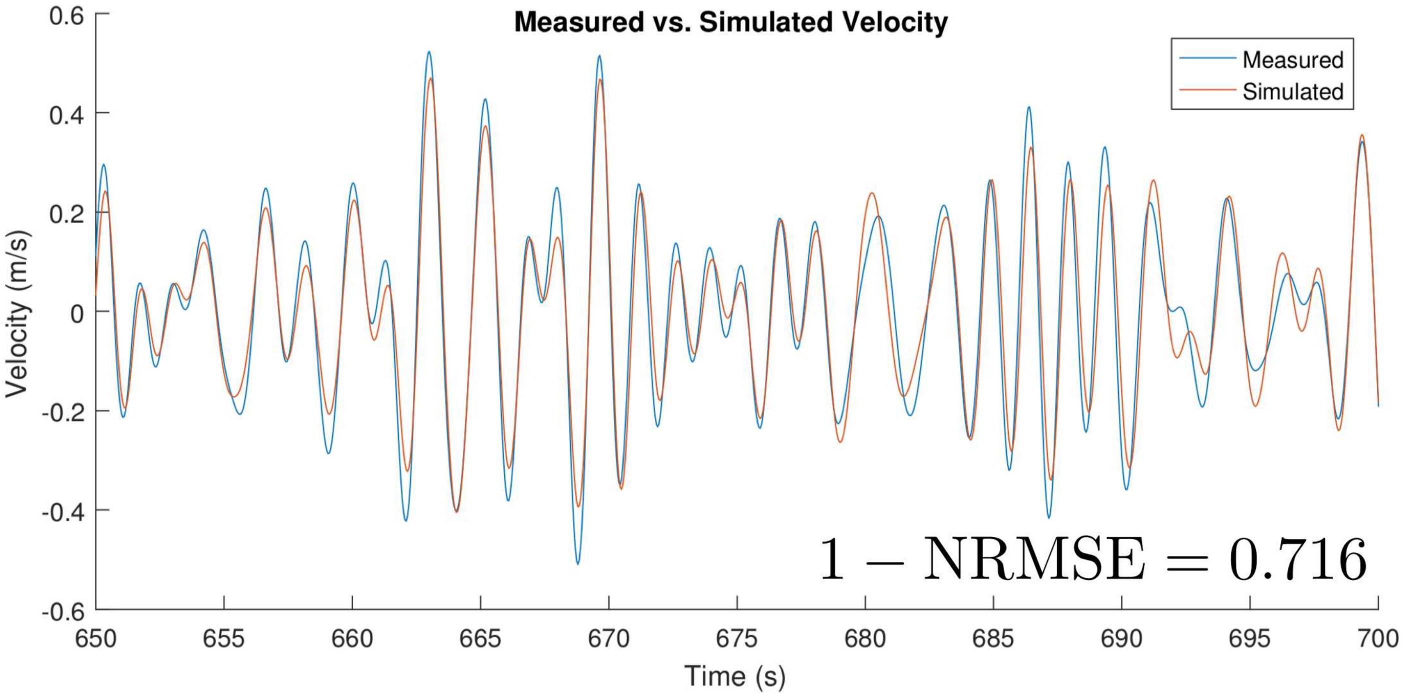
Model validation

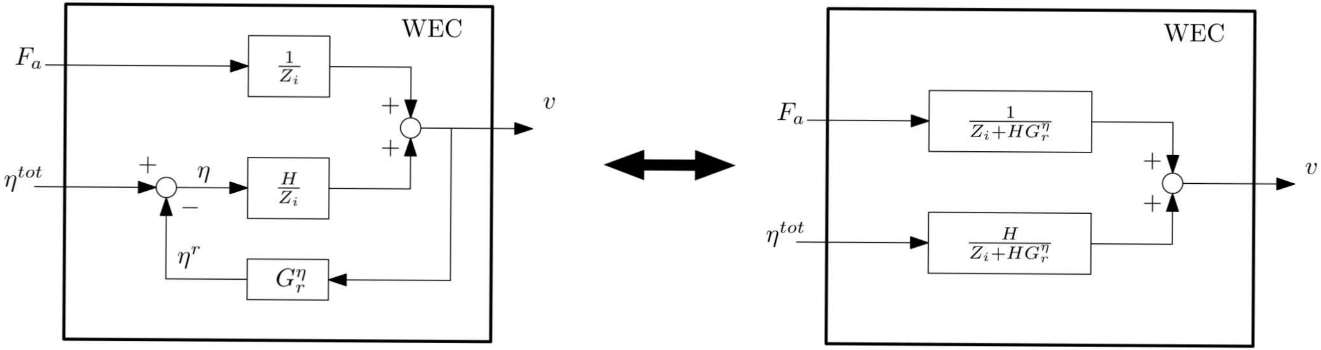




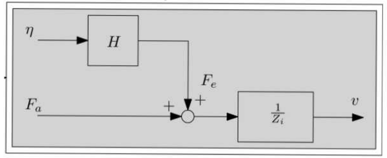
$$1 - \mathrm{NRMSE} = 0.716$$

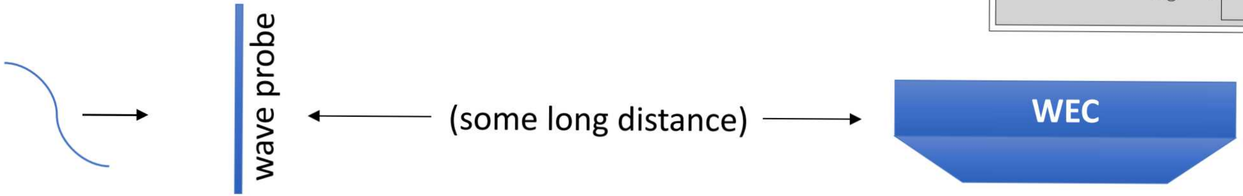
G. Bacelli, R. G. Coe, D. Patterson, and D. Wilson, "System identification of a heaving point absorber: Design of experiment and device modeling," Energies, vol. 10, no. 10, p. 472, 2017.

Multiple-Input Single-Output (MISO)

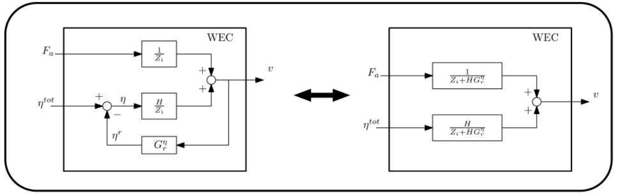


$$v = \left. \underbrace{\frac{1}{Z_i + HG_r^\eta}}_{\textit{Actuator (PTO)}} F_a + \underbrace{\frac{H}{Z_i + HG_r^\eta}}_{\textit{excitation}} \eta^{tot} \right|_{G_r^\eta \to 0} \approx \frac{1}{Z_i} F_a + \frac{H}{Z_i} \eta^{tot}$$





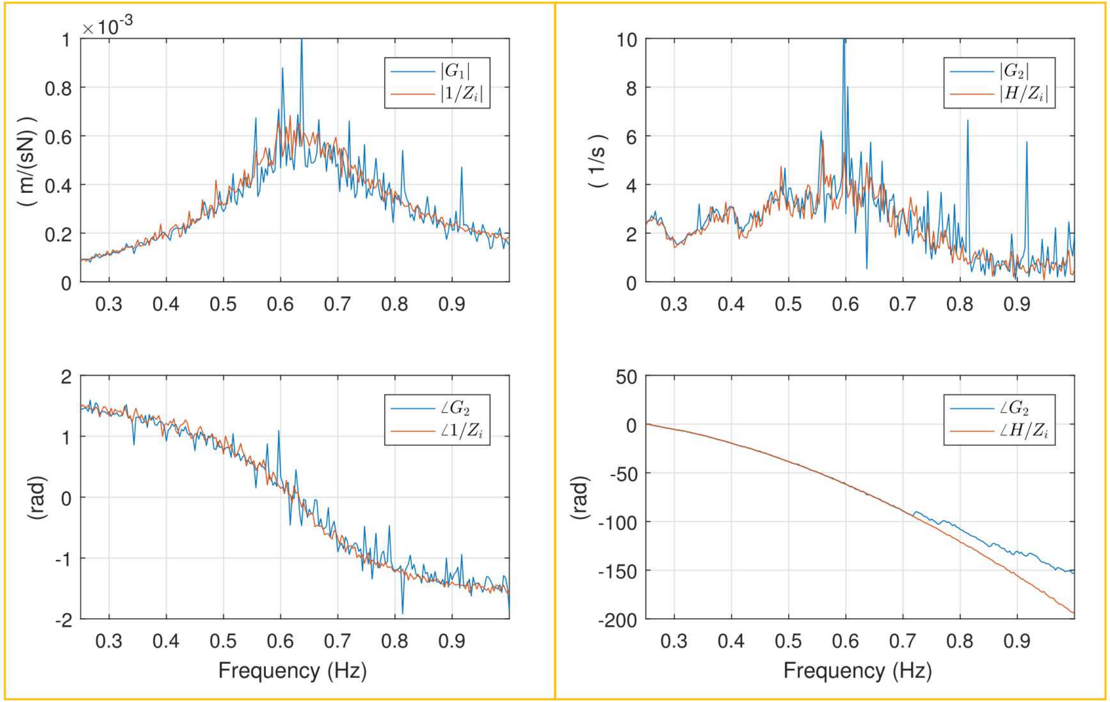
MISO model



MISO vs. **radiation/diffraction**

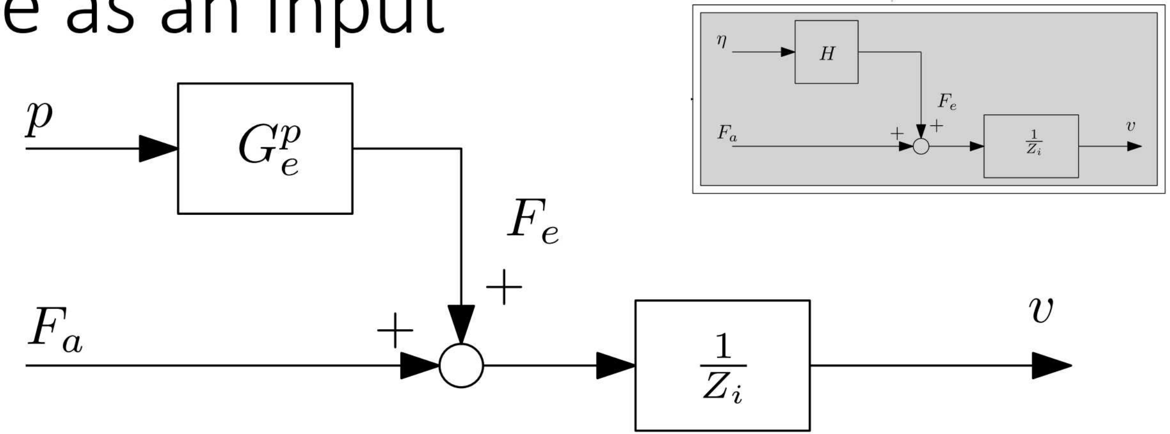
impedance/admittance

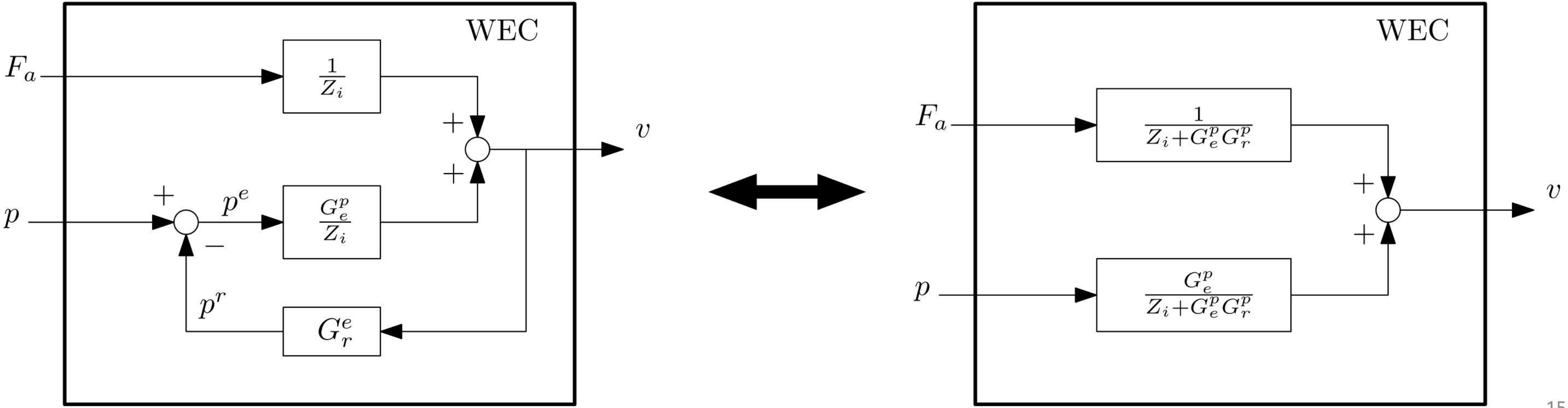
excitation



G. Bacelli, R. G. Coe, D. Patterson, and D. Wilson, "System identification of a heaving point absorber: Design of experiment and device modeling," Energies, vol. 10, no. 10, p. 472, 2017.

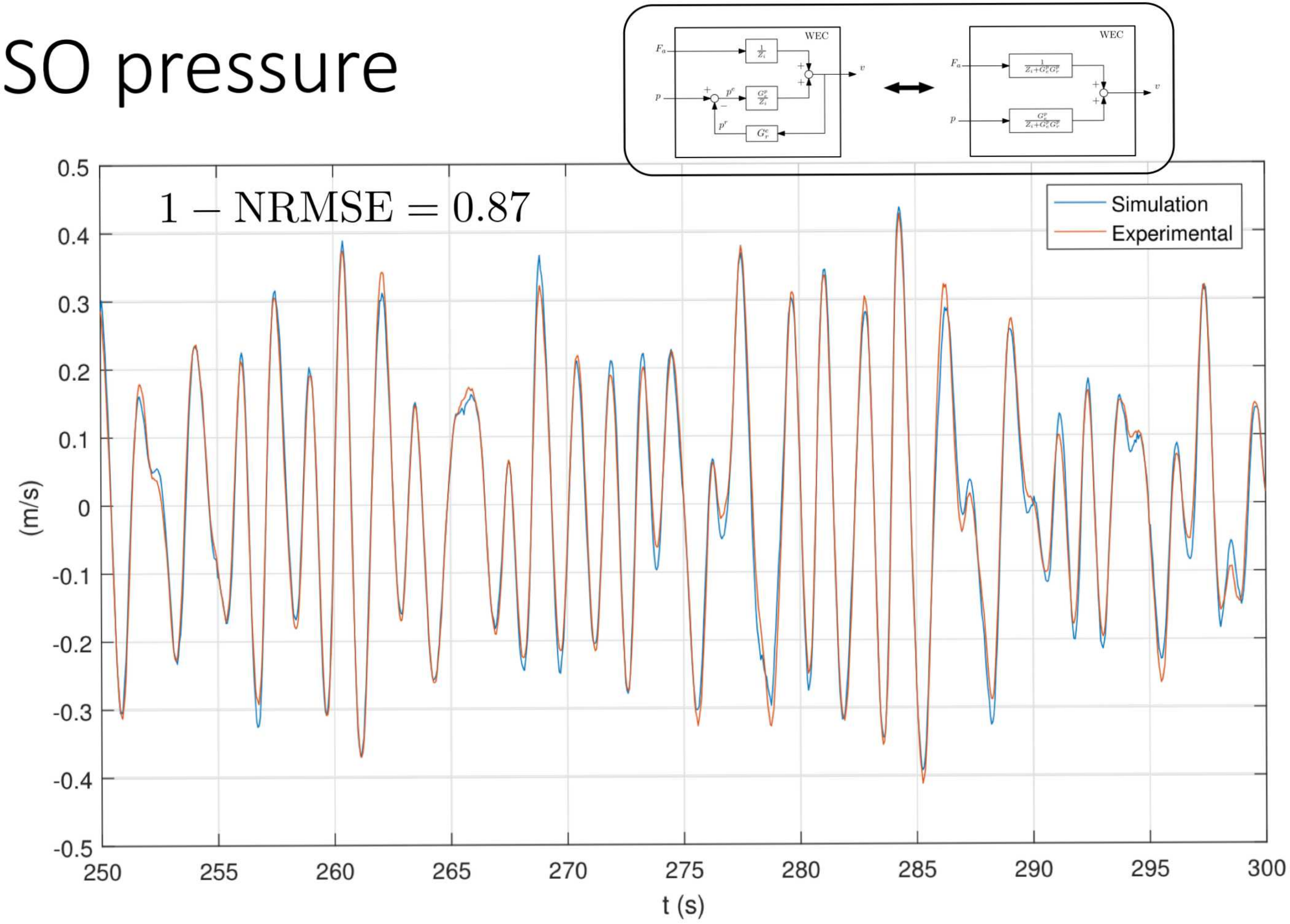
Pressure as an input





G. Bacelli, R. G. Coe, D. Patterson, and D. Wilson, "System identification of a heaving point absorber: Design of experiment and device modeling," Energies, vol. 10, no. 10, p. 472, 2017.

MISO pressure



G. Bacelli, R. G. Coe, D. Patterson, and D. Wilson, "System identification of a heaving point absorber: Design of experiment and device modeling," Energies, vol. 10, no. 10, p. 472, 2017.

Modeling: nonlinearities

NL hydrostatics

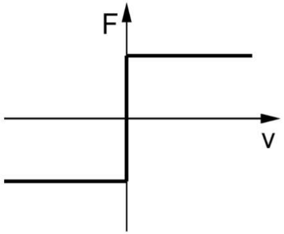
$$F_h(x) = k_1 x + k_2 x^2 + k_3 x^3 \ldots$$

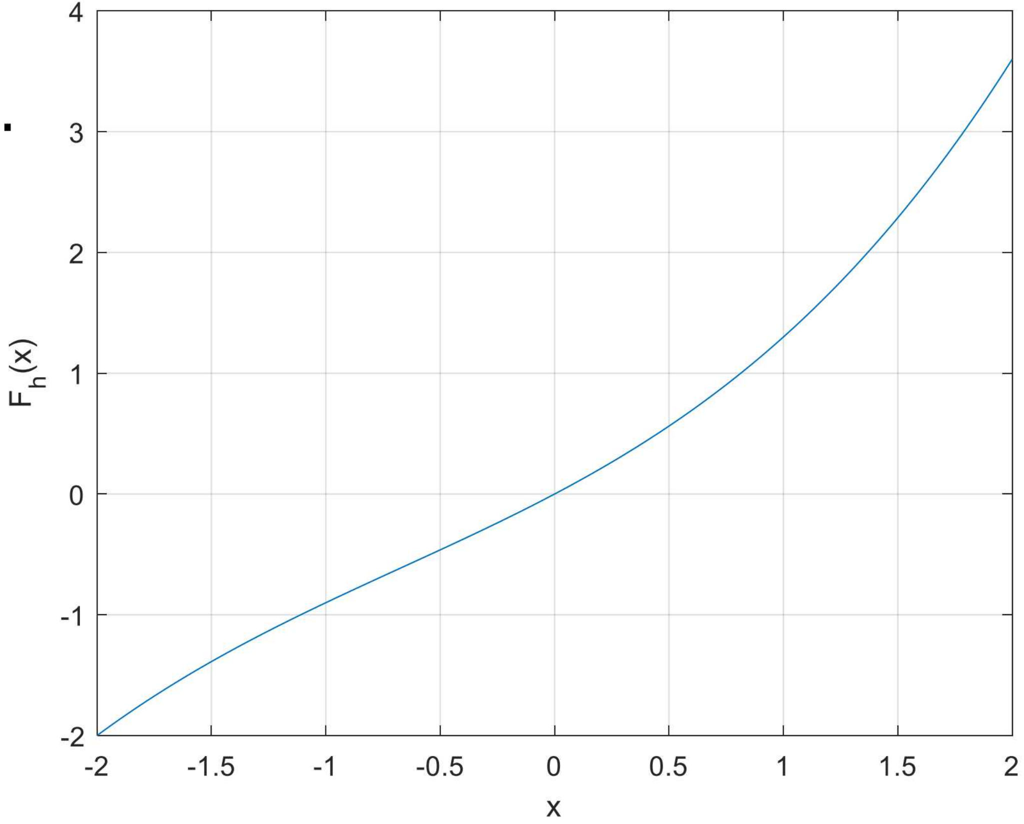
NL drag

$$F_d(v) = b_1 v + b_2 v|v| + b_3 v^3 \ldots$$

Saturations

$$F_c(v) = c_1 \mathrm{sign}(v)$$

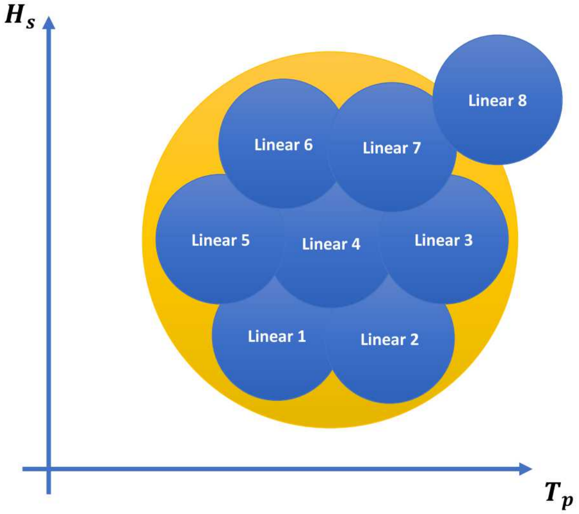




Slide originated from Giorgio Bacelli

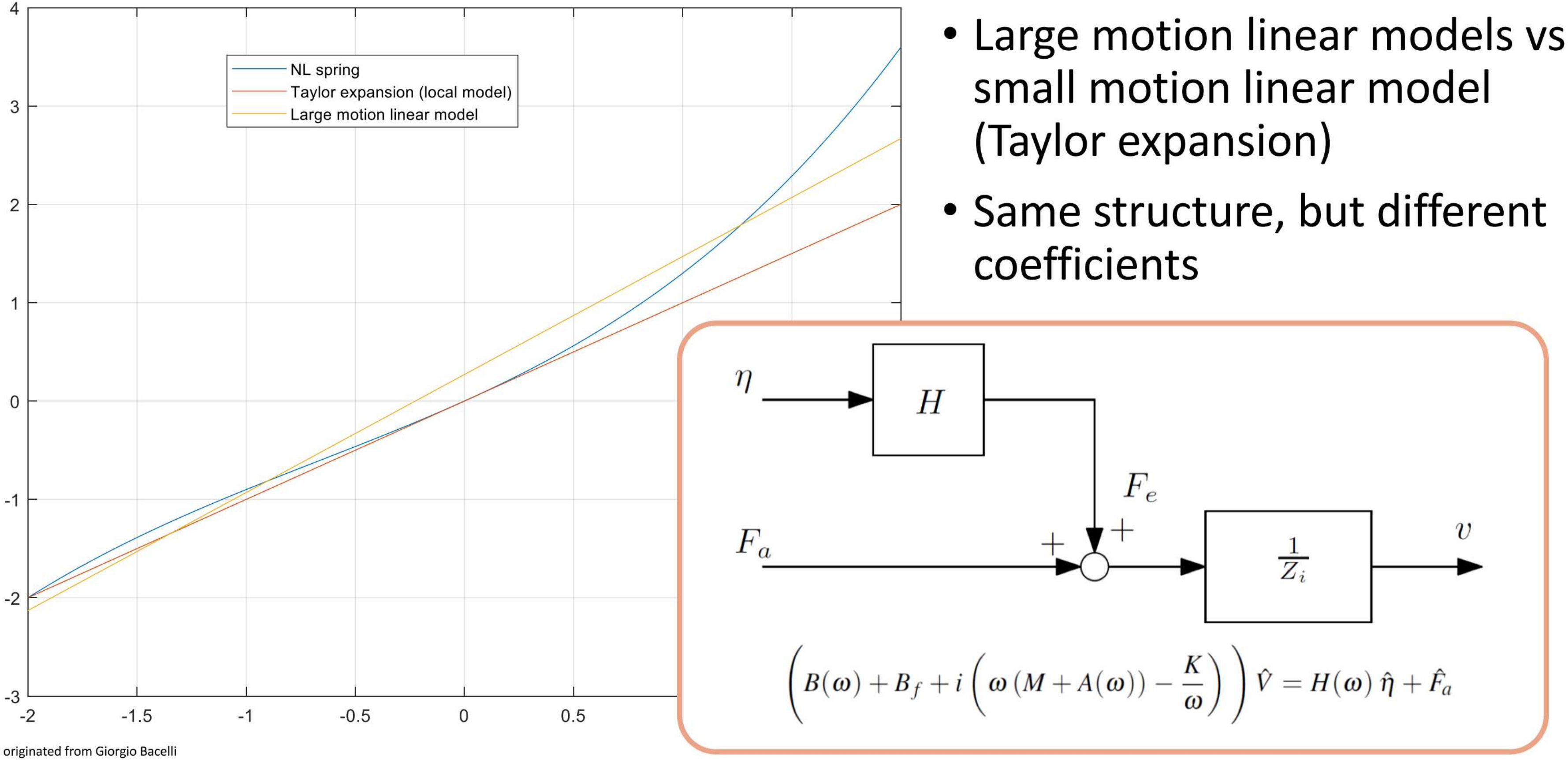
Linear vs. Nonlinear models

- Non Linear:
    - Pro
        - More accurate description of system dynamics over broader region of operation
        - Better performing control
    - Cons
        - More difficult to identify
        - More difficult for control design
        - May be less “robust” (good interpolators, but may not be good extrapolators)
- Linear
    - Pro
        - Identification is much easier (plenty of tools and theory available)
        - Control design is easier (plenty of tools and theory available)
        - Can have many “local model” and controllers (e.g. Gain scheduling)
    - Cons
        - Local approximation (models are good only around a region of operation)
        - Certain systems cannot be approximated by linear models



Linearization of non linear models

- Large motion linear models vs small motion linear model (Taylor expansion)
- Same structure, but different coefficients



$$\left(B(\omega) + B_f + i\left(\omega\,(M + A(\omega)) - \frac{K}{\omega}\right)\right)\hat{V} = H(\omega)\,\hat{\eta} + \hat{F}_a$$

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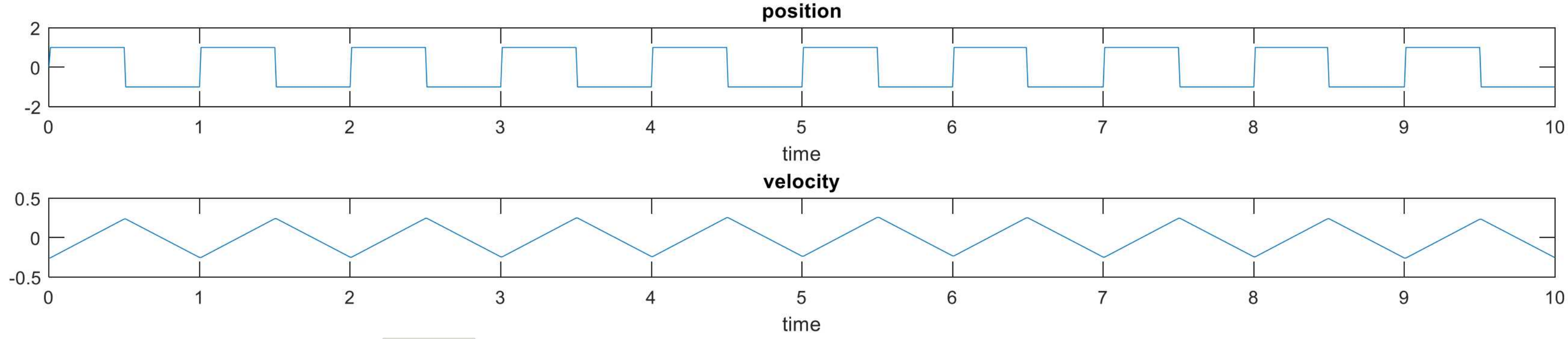
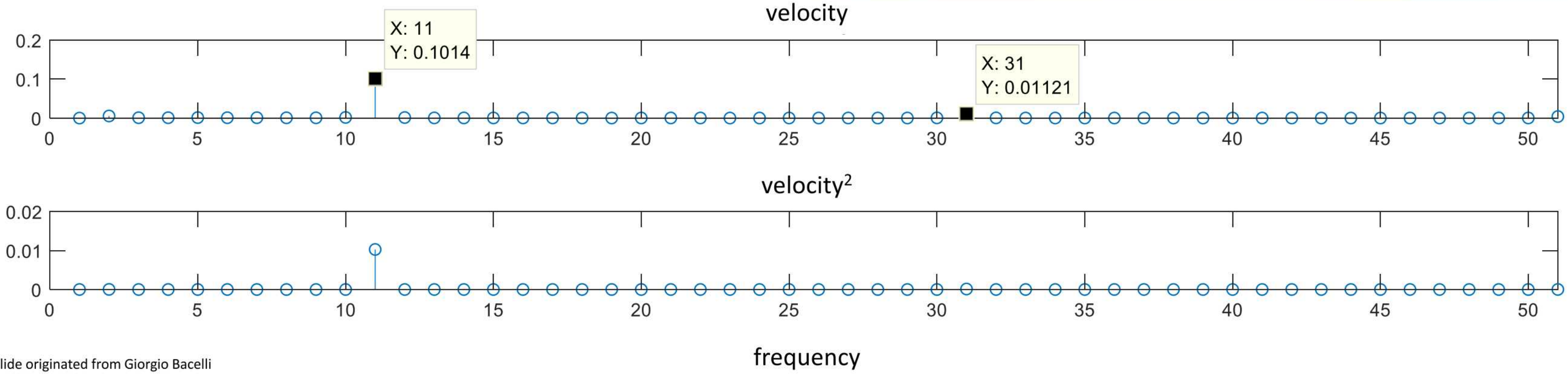
Nonlinearities

- How important is it to consider nonlinearities?
- Example: Spectral content of square wave (Parseval’s identity)





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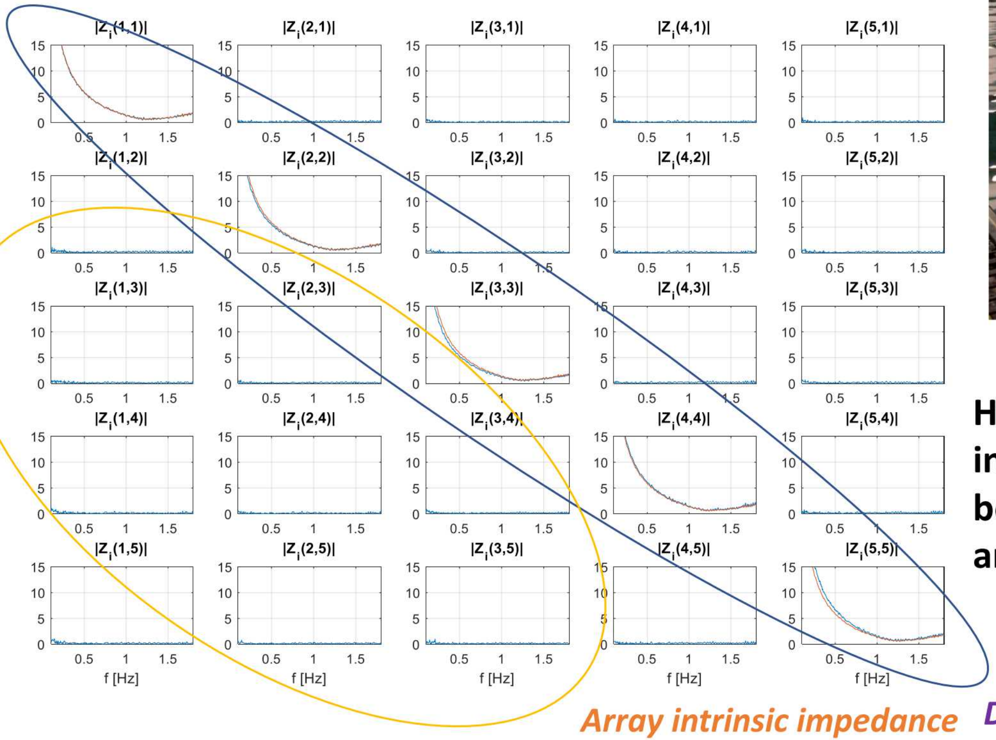
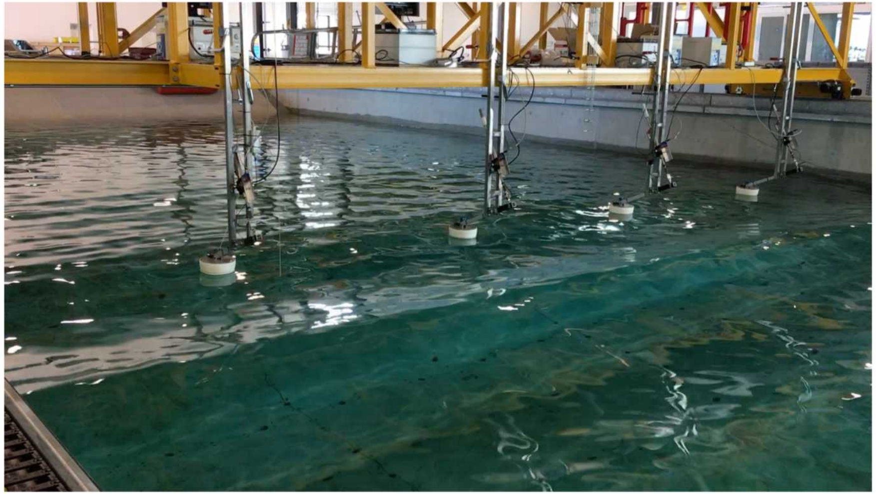
Array testing



Array intrinsic impedance

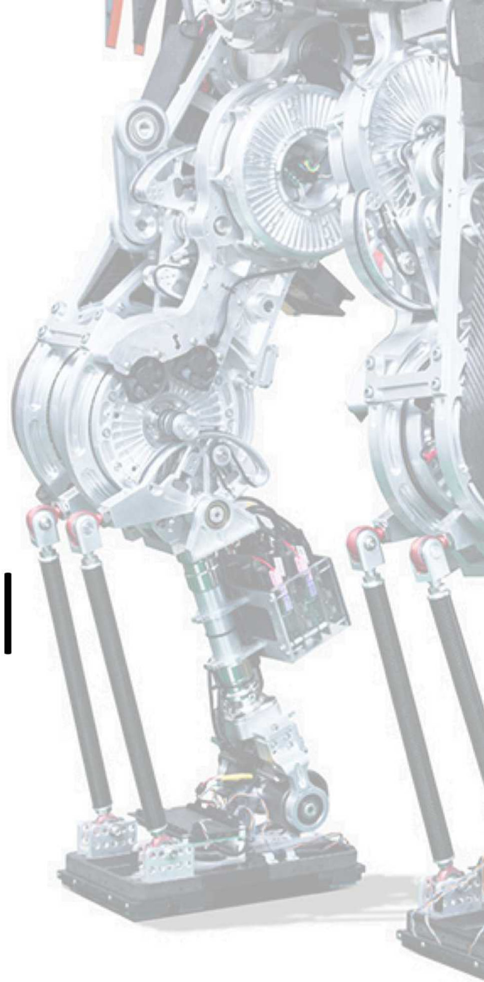
Device intrinsic impedance



Hydrodynamic interactions between devices are small (<10%)

Electrical interaction more important

Coffee Break (15 mins)



Implementing WEC control

Presented by Ryan Coe

Dynamical Systems

"particle or ensemble of particles whose state varies over time and thus obeys differential equations involving time derivatives."

If linear

Time domain:
states-pace (ODE)

$$\dot{\mathbf{x}}(t) = A\mathbf{x}(t) + B\mathbf{u}(t)$$
$$\mathbf{y}(t) = C\mathbf{x}(t) + D\mathbf{u}(t)$$

⟷

Laplace transform

Complex domain:
Transfer function

$$H(s) = \frac{Y(s)}{X(s)}$$

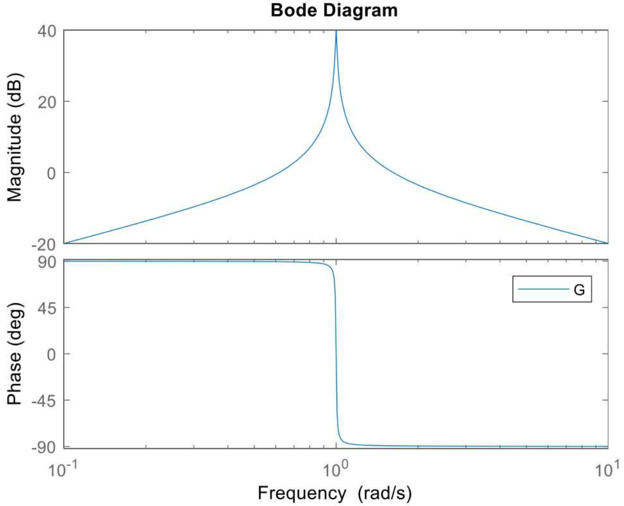
If s = jω ➡ Frequency domain

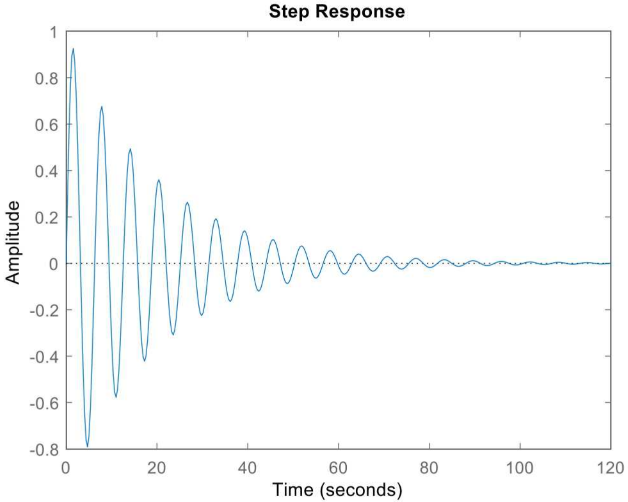
Slide originated from Giorgio Bacelli

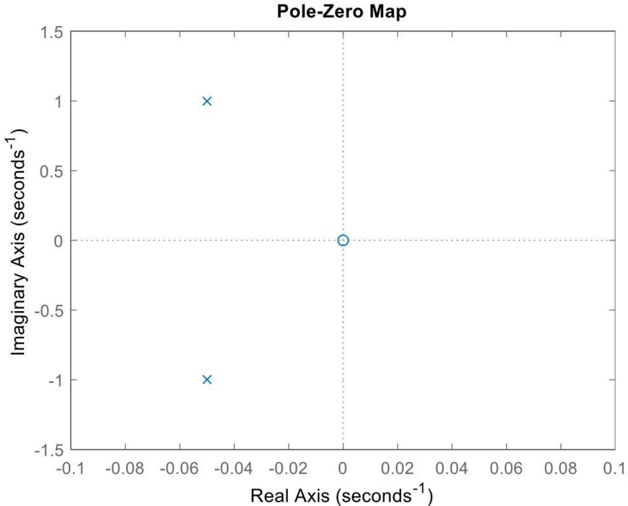
Dynamical Systems: analysis

Example: Mass-Spring-Damper

$$H(s) = \frac{v}{f} = \frac{s}{m\,s^2 + b\,s + k}$$







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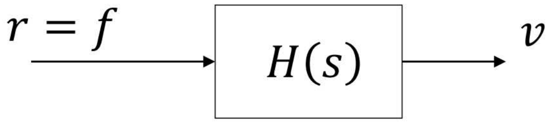
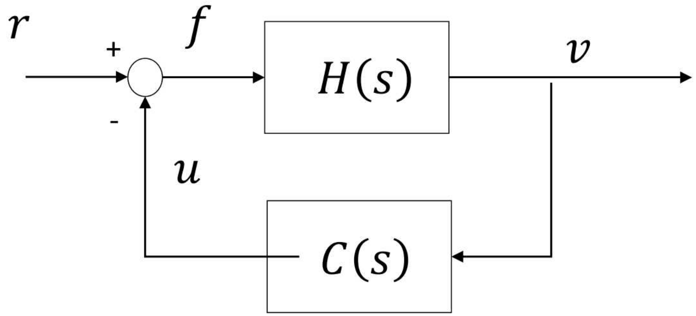
Control of dynamical system

Uncontrolled system



$$\frac{out}{in} = \frac{v}{r} = \frac{v}{f} = H(s)$$

Controlled system



$$\frac{out}{in} = \frac{v}{r} = \frac{v}{f+u} = \frac{H(s)}{1 + H(s)C(s)}$$

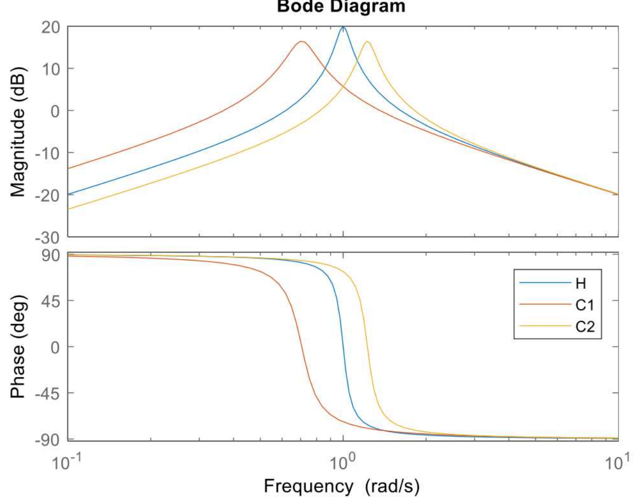
Slide originated from Giorgio Bacelli

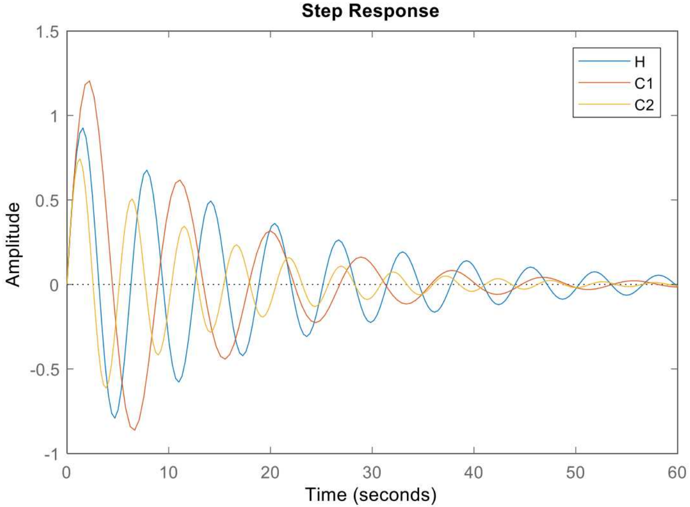
Control of dynamical system

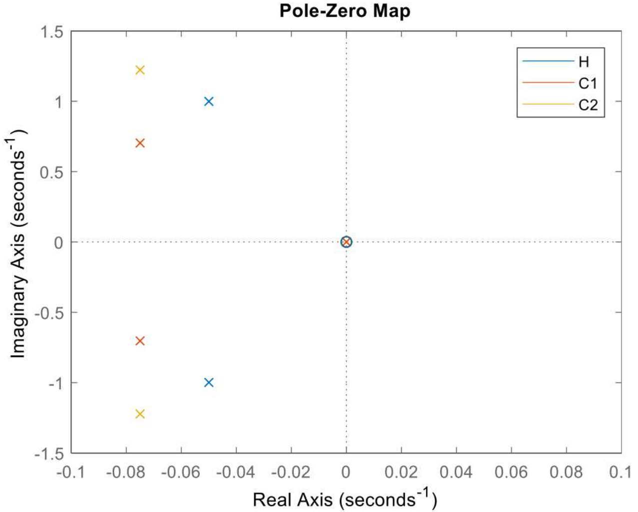
What happens to the system when it's being controlled?

$$H(s) = \frac{s}{m\,s^2 + b\,s + k} \qquad C(s) = K_p + \frac{K_i}{s}$$

$$\frac{H(s)}{1+H(s)C(s)} = \frac{s^2}{s^3+b_2s^2+b_1+b_0}$$







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Example: importance of linear analysis

Even if the system is nonlinear, linear analysis is still very important

Figure 6. *NASA X-29 forward-swept-wing aircraft (photo courtesy of NASA).*

"…You see, all of the various control design teams used modern digging machines early in the design process. As a result, we were well insulated from the fundamental difficulties imposed by the airplane's violent open-loop instability. … We discovered only at the last moment that the vehicle was almost too unstable to control with the given hardware."

G. Stein, "Respect the unstable," in *IEEE Control Systems*, vol. 23, no. 4, pp. 12-25, Aug. 2003.

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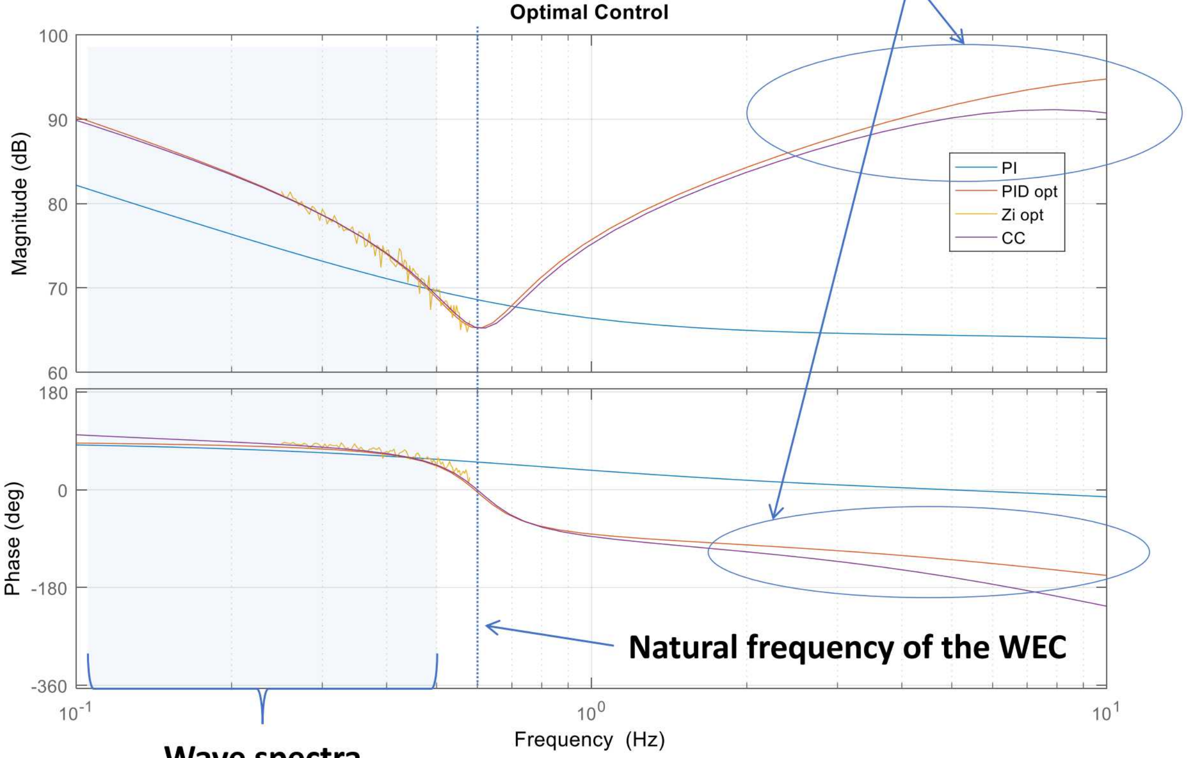
How essential is wave foreknowledge?

NON-CAUSALITY shows up in the asymptotic behavior (freq →∞)

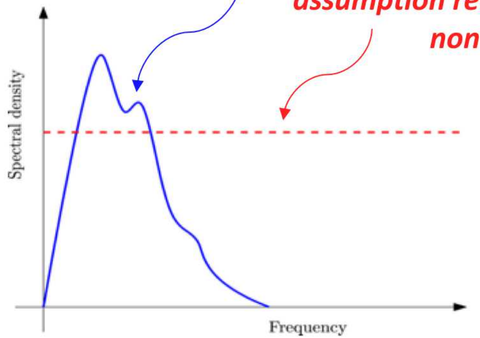


Natural frequency of the WEC

Wave spectra

real ocean waves

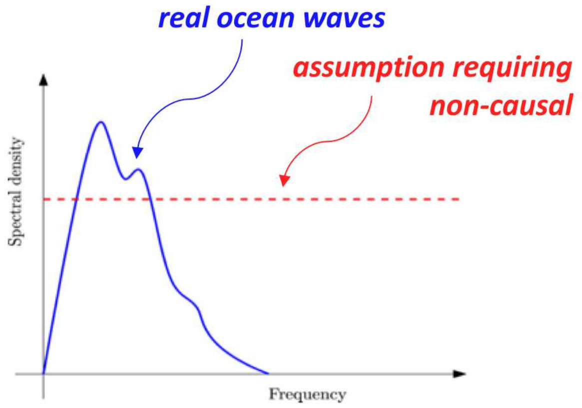
assumption requiring non-causal

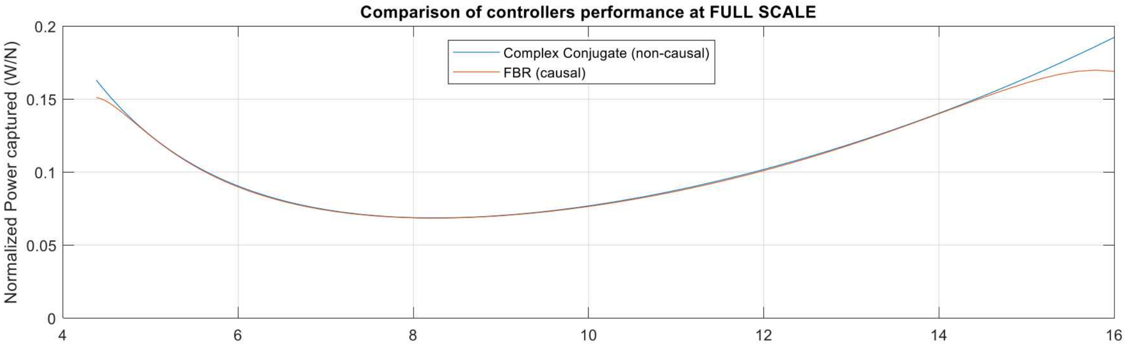


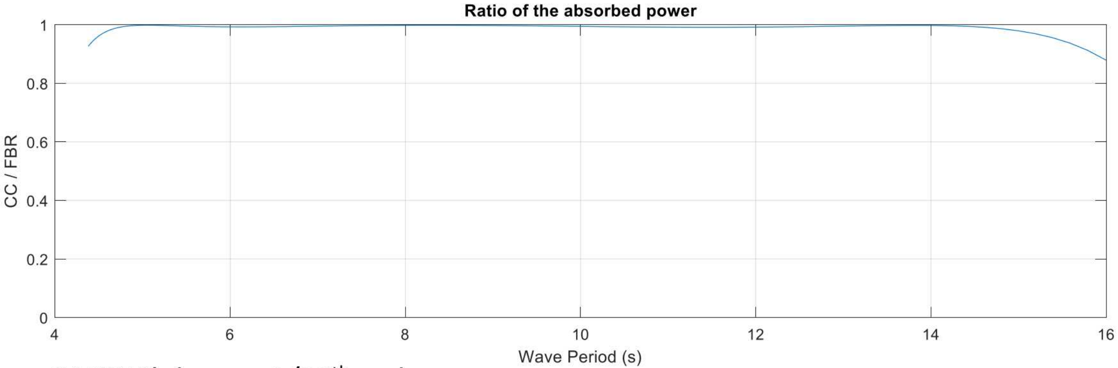
Can realize most of control improvement w/o wave foreknowledge

How essential is wave foreknowledge?

Let's make some (reasonable) assumption: band limited wave spectra




Comparison of controllers performance at FULL SCALE


Ratio of the absorbed power

SANDIA's buoy: ~1/16th scale

Real ocean waves are band-limited

Causal FBR Controller is almost as efficient as Non causal CC controller in a limited frequency band (95%-100%)

Can be tuned to different Frequency bands for different scales

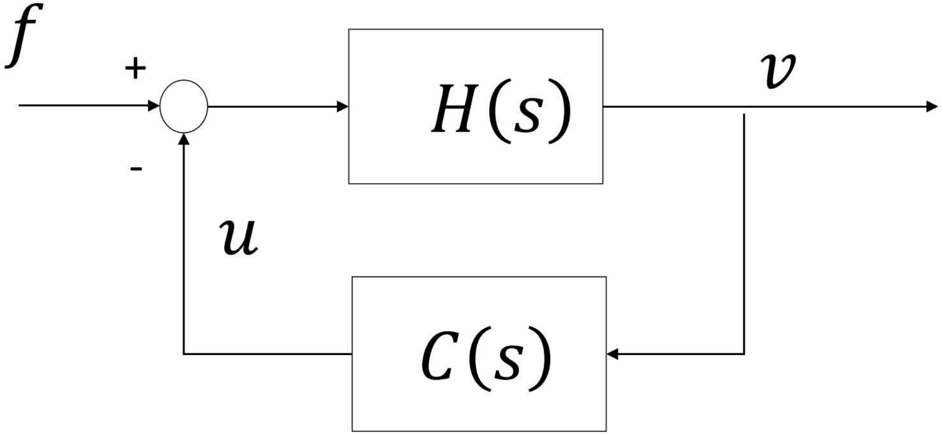
Control design

Modeling → $H(s)$

Measurement and Estimation → v

Controller → $C(s)$

(Iterate on design)



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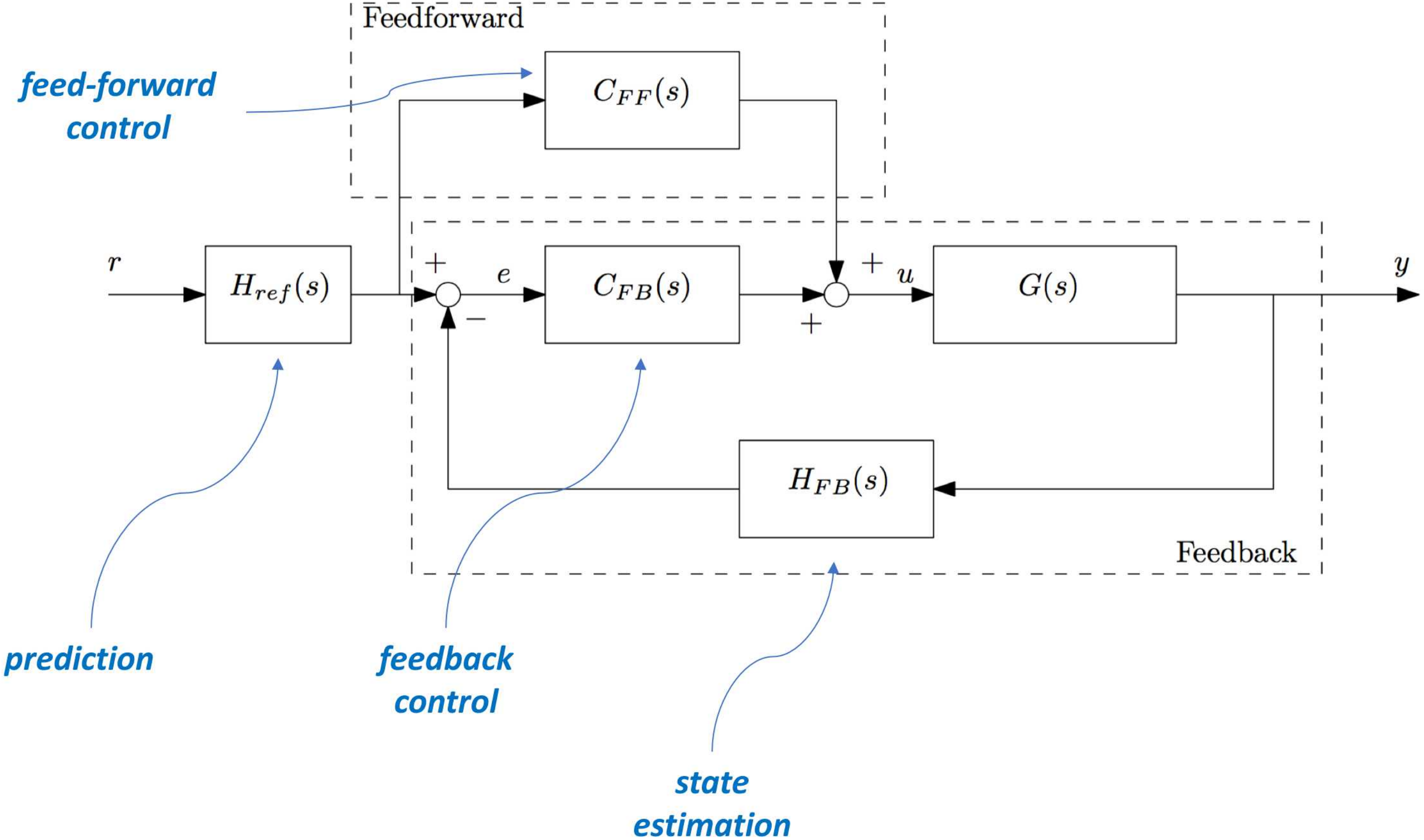
Implementation of control on a numerical model



feed-forward control

prediction

feedback control

state estimation

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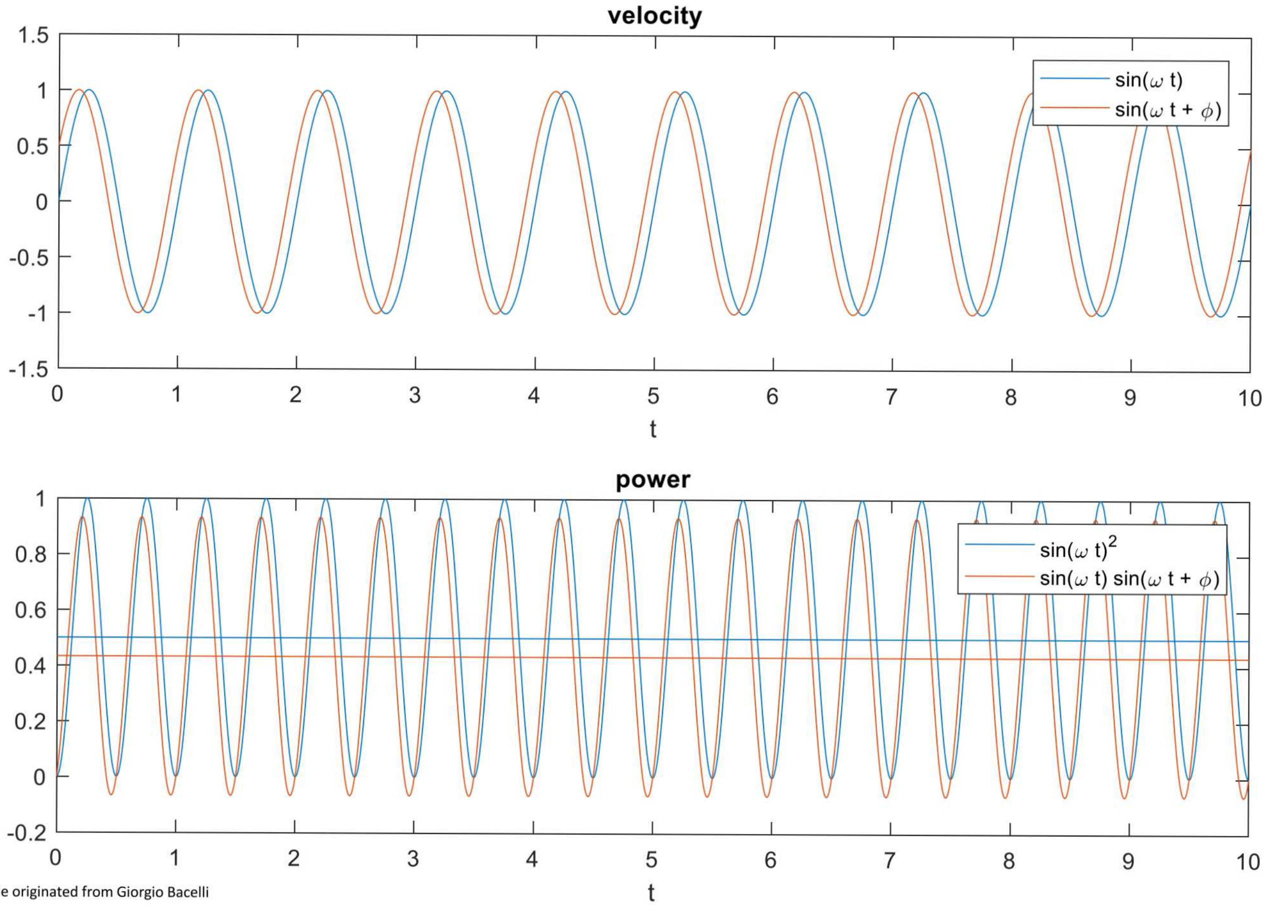
Implementation of control on hardware

- Key considerations for sensor selection
  - Saturation limits
  - ***Frequency response***
  - Signal type (minimize noise)

Implementation of control on hardware



Oscillating system, phase is important

Slide originated from Giorgio Bacelli

Practical aspects – Real-time systems

- What is a real-time (RT) system
  - Hard RT
  - Soft RT
- Very basic example: Calculate velocity from position
  - $v = dx/dt$
  - In RT systems, *dt* is constant
  - In Non-RT systems *dt* may not be constant -> velocity not calculated accurately

Slide originated from Giorgio Bacelli

Practical aspects – Real-time systems

Ethernet is fast, right?

All of the packets go to all of the nodes, and collisions between data packets are a serious problem

Data can take variable paths and therefore variable times to travel from the sending node to the receiving node

➡ Rate of communication is fast, but the time span (the determinism) in which a response is expected is unpredictable

Practical aspects – DAQ/RT

- Discretization
  - sampling time
- Quantization
  - amplification/signal conditioning
- Filtering
- Communication
  - Bandwidth
  - Synchronization
  - Determinism
- Software
  - Research vs. production

RT-LAB

MATLAB® & SIMULINK®

NATIONAL INSTRUMENTS LabVIEW™

Typhoon HIL

Slide originated from Giorgio Bacelli

Practical aspects - PTO design, modeling and control

Small Scale

Torque tracking for full scale PTO emulation and control

Large scale

Torque tracking no longer highest priority
Objective is maximize power, and satisfy constraints, therefore we need very good model for control design.
Good model also necessary for device (WEC+PTO+control) optimization

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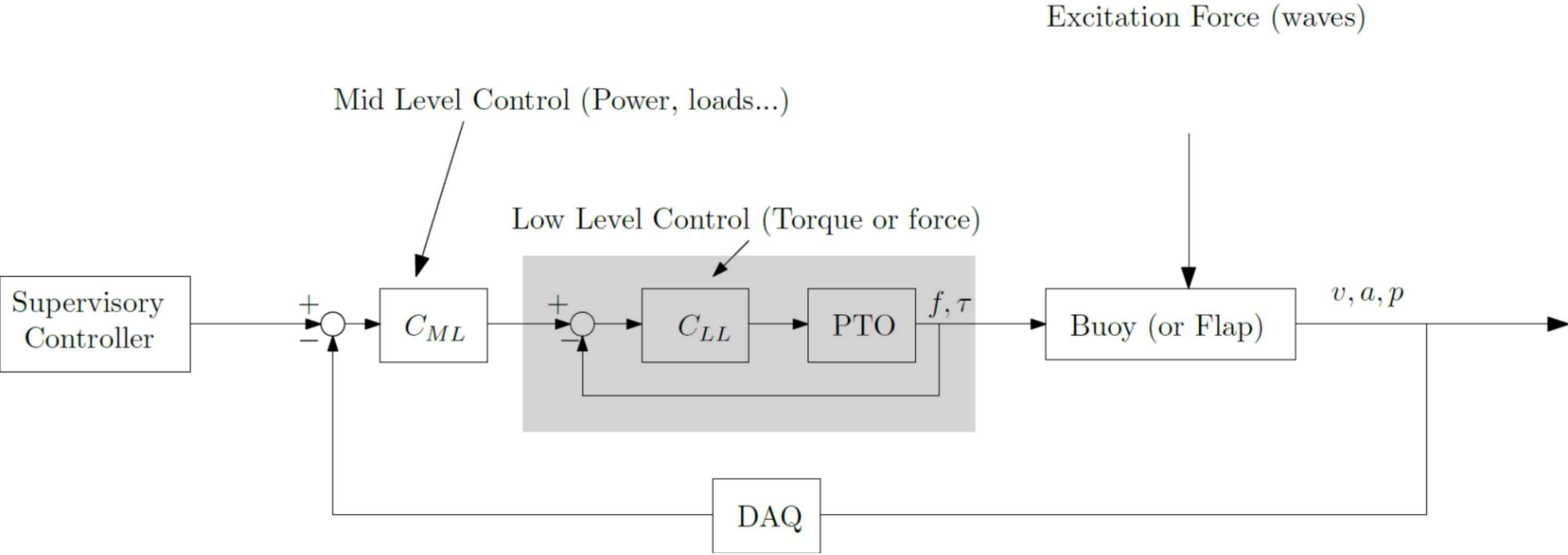
Design

Need to look a the dynamic of the whole system for design



The system needs to be designed as ONE block

(at least until we have accumulated enough experience to develop good practice)

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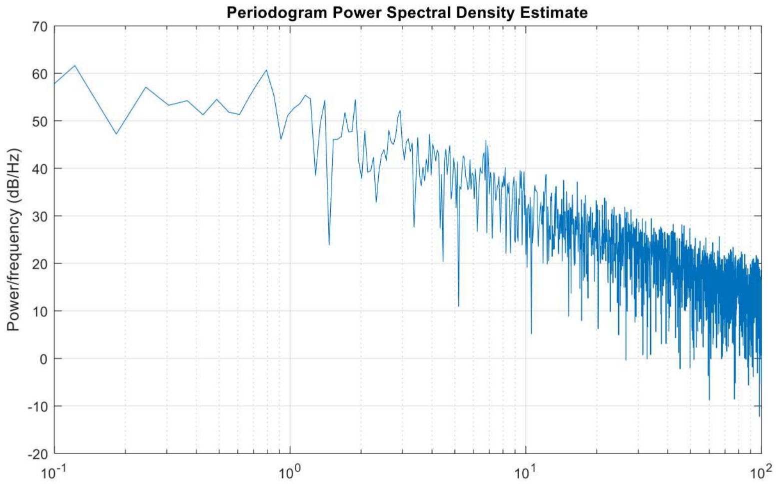
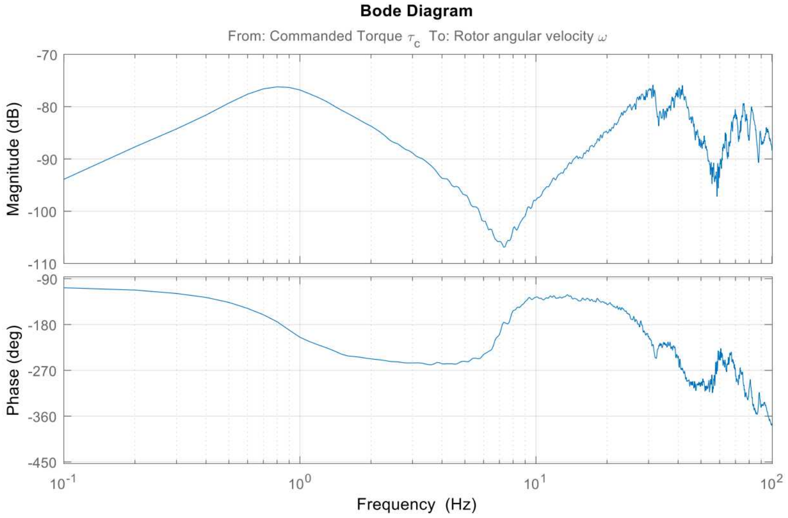
Drivetrain model – SID

Input signal: LPF white noise

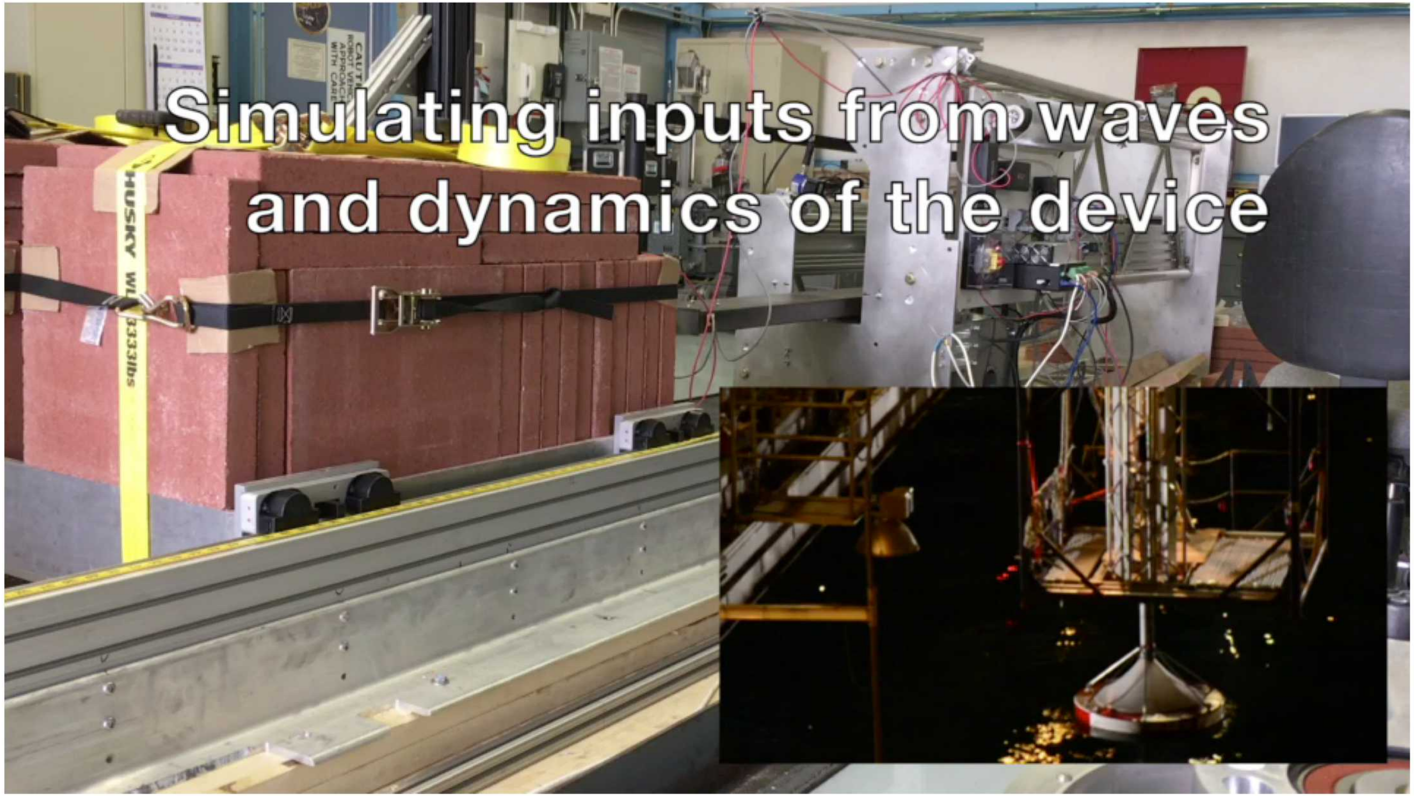


Response: torque to velocity



G. Bacelli, S. J. Spencer, R. G. Coe, A. Mazumdar, D. Patterson, and K. Dullea, “Design and bench testing of a model-scale WEC for advanced PTO control research,” in European Wave and Tidal Energy Conference (EWTEC), Cork, Ireland, 2017.

Drivetrain model – SID



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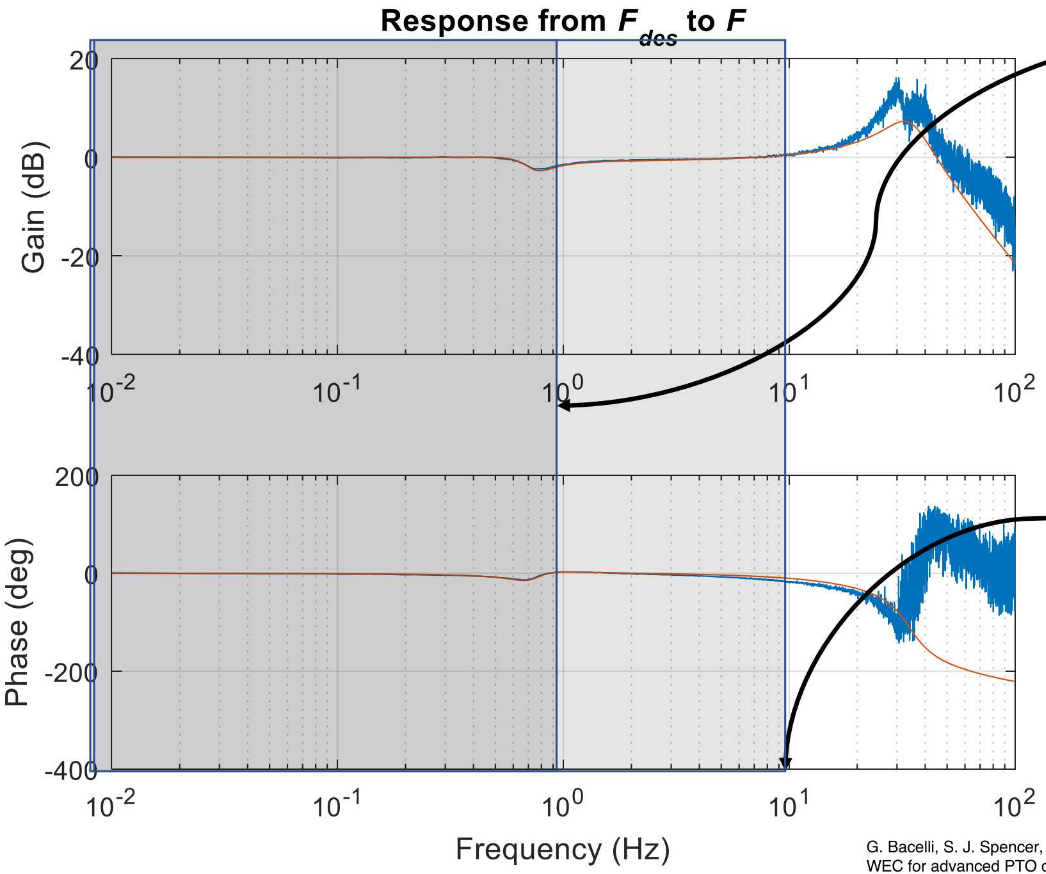
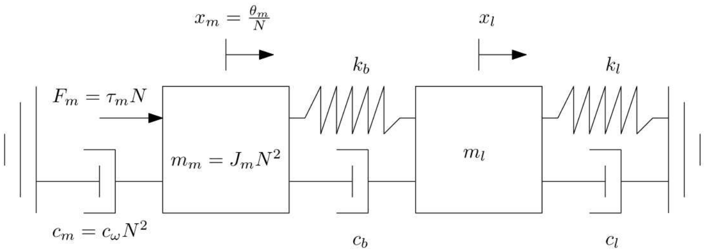
Drivetrain model – parametric



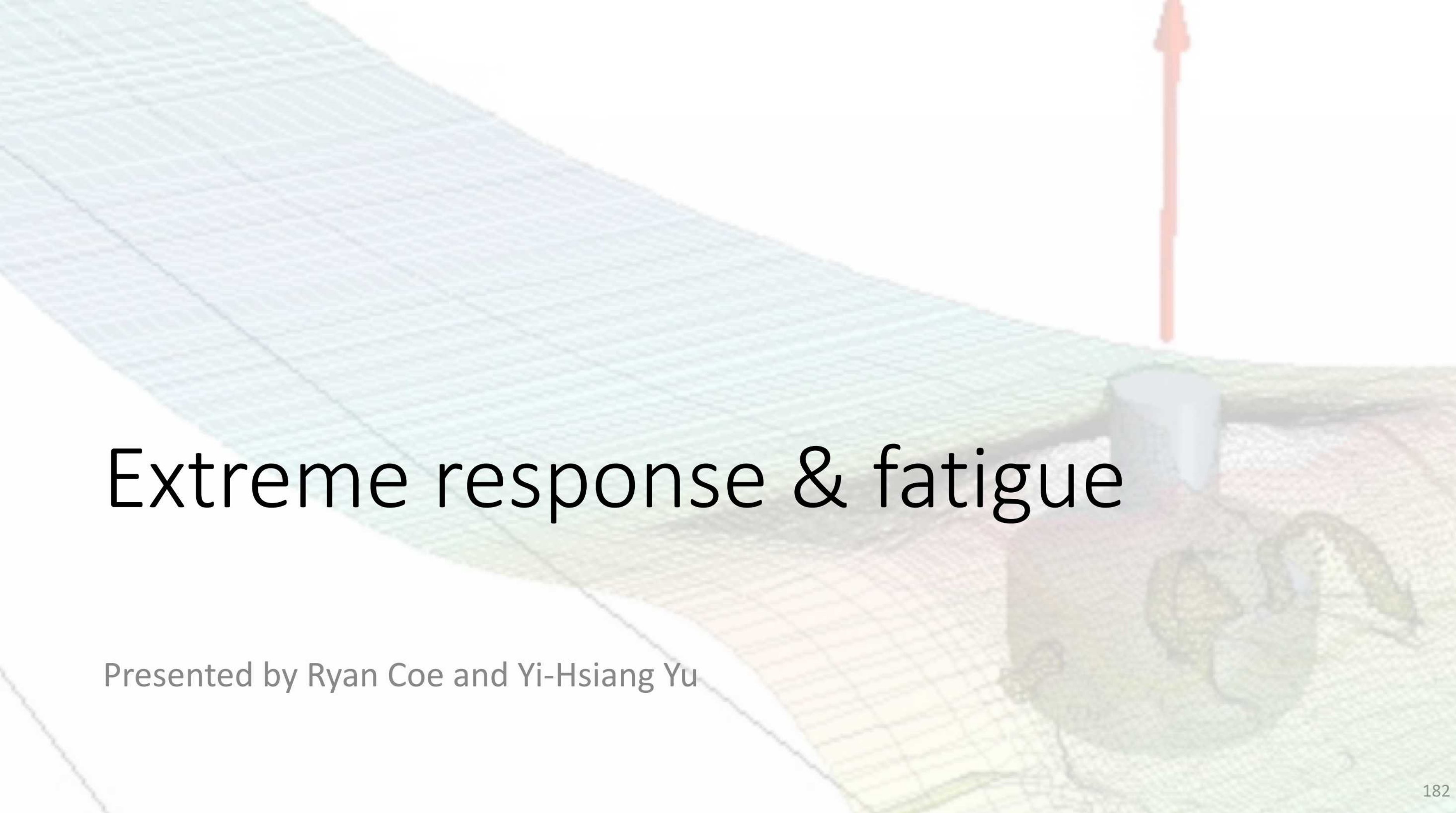
Relevant device dynamics

Accurate force tracking up to 10 Hz

Equivalent parametric model



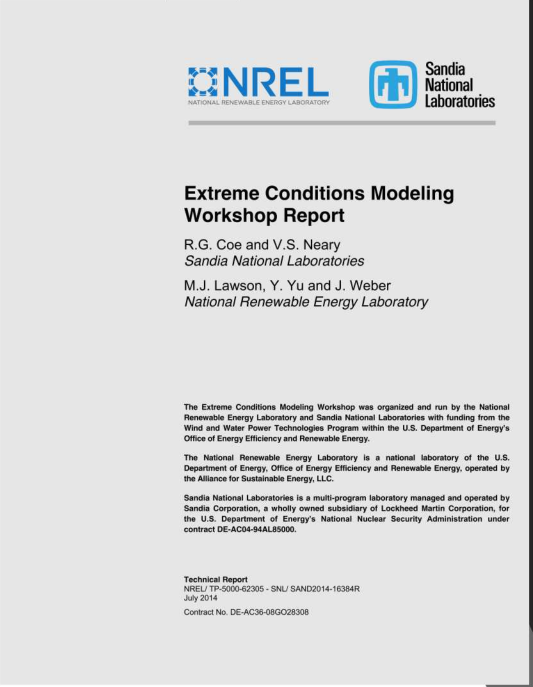
G. Bacelli, S. J. Spencer, R. G. Coe, A. Mazumdar, D. Patterson, and K. Dullea, “Design and bench testing of a model-scale WEC for advanced PTO control research,” in European Wave and Tidal Energy Conference (EWTEC), Cork, Ireland, 2017.



Extreme response & fatigue

Presented by Ryan Coe and Yi-Hsiang Yu

Extreme Condition Modeling Workshop (May13-14, 2014)



NATIONAL RENEWABLE ENERGY LABORATORY

Extreme Conditions Modeling Workshop Report

R.G. Coe and V.S. Neary
Sandia National Laboratories

M.J. Lawson, Y. Yu and J. Weber
National Renewable Energy Laboratory

The Extreme Conditions Modeling Workshop was organized and run by the National Renewable Energy Laboratory and Sandia National Laboratories with funding from the Wind and Water Power Technologies Program within the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy.

The National Renewable Energy Laboratory is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

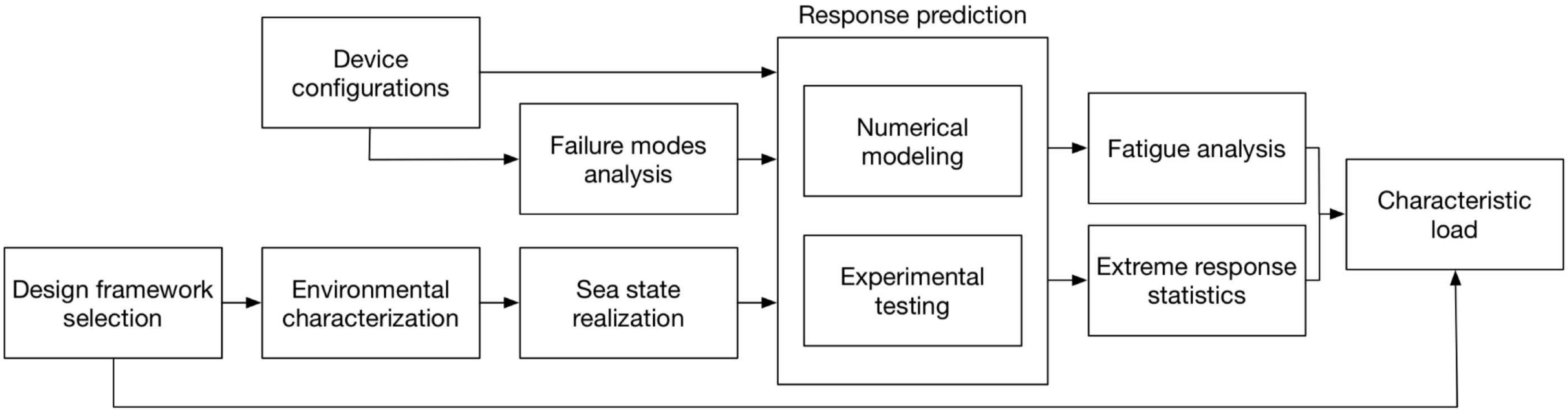
Technical Report
NREL/ TP-5000-62305 - SNL/ SAND2014-16384R
July 2014

Contract No. DE-AC36-08GO28308

Coe R. G., Neary V. S., Lawson M. J., Yu Y., and Weber J., 2014, Extreme Conditions Modeling Workshop Report, National Renewable Energy Laboratory (NREL), Golden, CO.

- More than 30 U.S. and European WEC experts from industry, academia, and national research institutes attended the workshop.
- WEC Device is designed to maximize its motion and wave-induced load at the dominant sea states, and offshore oil and gas platforms and ships are not.
- Not always the largest wave that causes extreme loads and more often it is a specific wave train (can be at a rated operational sea state).
- Nature of the irregular sea states makes extreme sea state characterization challenging and the prediction of the conditions that cause extreme loads is difficult.
- Move towards a risk-based design methodology

Generalized design analysis process

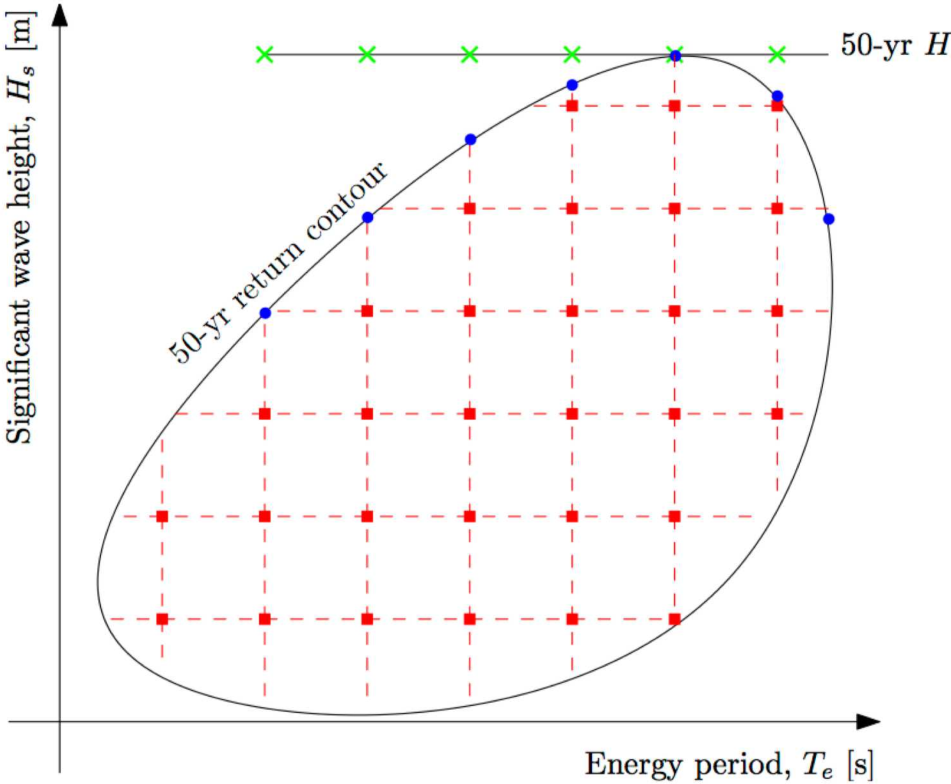


R.G. Coe, Y.-H. Yu, J. van Rij, "A survey of WEC reliability, survival, and design practices," *Energies,* vol. 11, no. 1, p. 4, 2018.

Survival analysis frameworks

Which conditions will we analyze?

- One-Dimensional
- Contour
- All-Sea-State

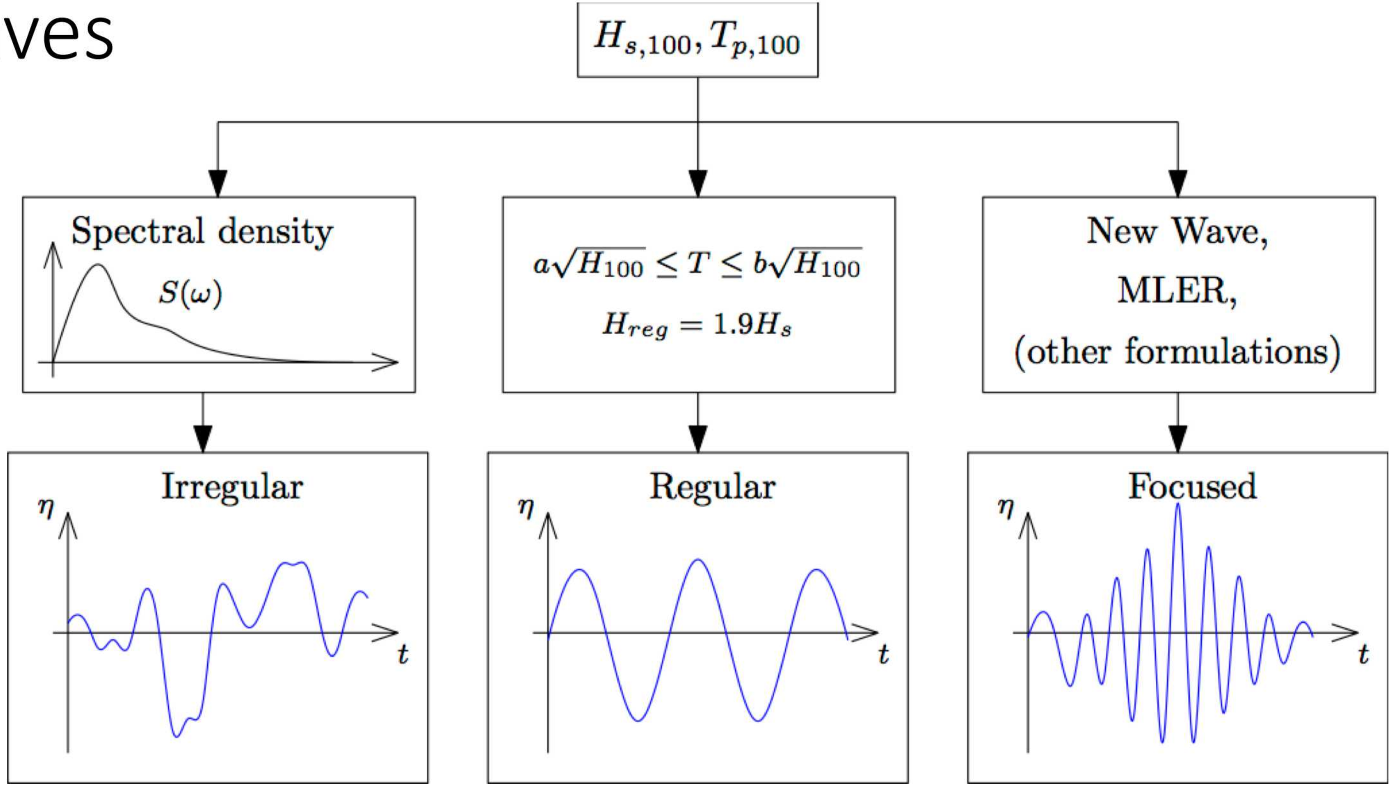


R.G. Coe, Y.-H. Yu, J. van Rij, "A survey of WEC reliability, survival, and design practices," *Energies,* vol. 11, no. 1, p. 4, 2018.

Design waves

Need to represent real ocean waves…

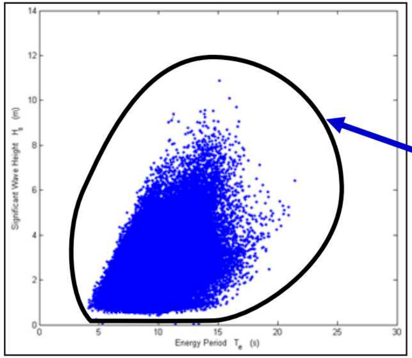
Irregular sea states are often too long, or cannot be realized by hardware



R.G. Coe, Y.-H. Yu, J. van Rij, "A survey of WEC reliability, survival, and design practices," *Energies,* vol. 11, no. 1, p. 4, 2018.

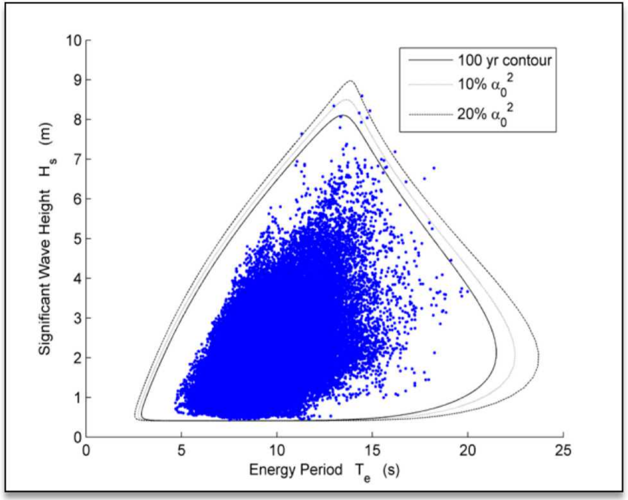
Using Environmental Contours

- **Sea state contours** seek to determine (1) the characteristics of extreme events and (2) the probability of these events by using short term data (~10 years) to find a contour of variables that describes extreme events related to a given likelihood



Contour defines pairs of variables whose combination is related to an extreme event.

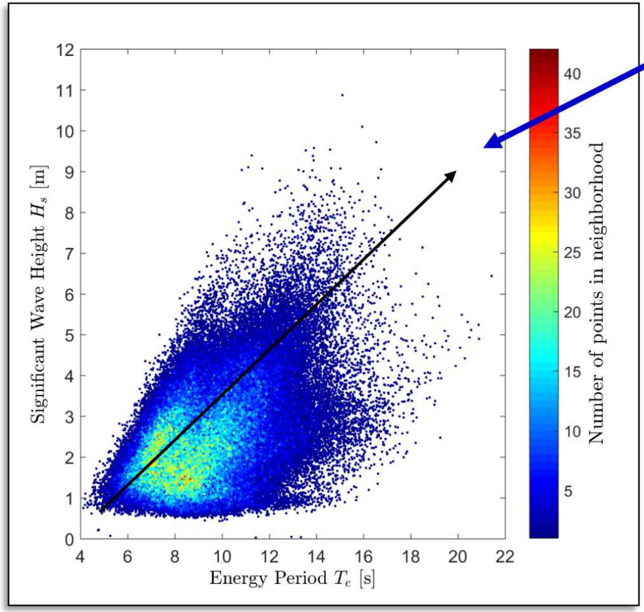
Contour from Standard of Practice



- Environmental contours derived from methodology presented in key papers that are widely cited (Haver and Winterstein, 2008) using **I-FORM** and applied in **design standards** for offshore structures

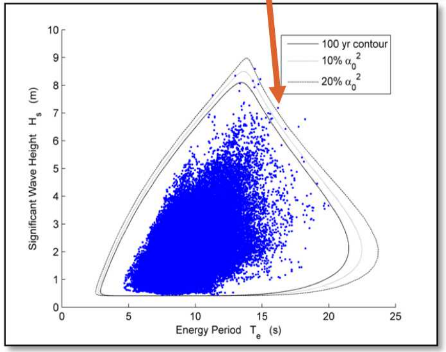
Representing Data Density

- **Data trends** in **empirically calculated density** show that contour shape should include additional regions that parametric joint probabilities do not always capture

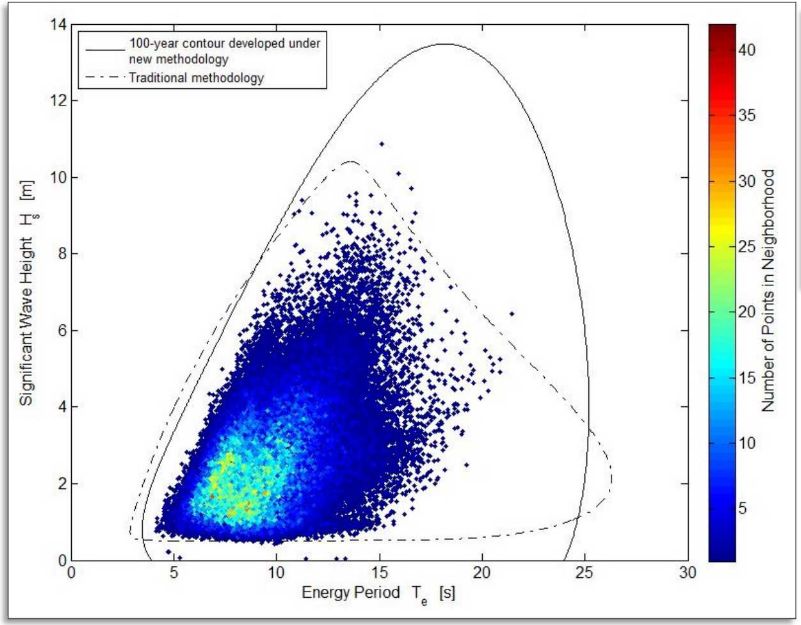


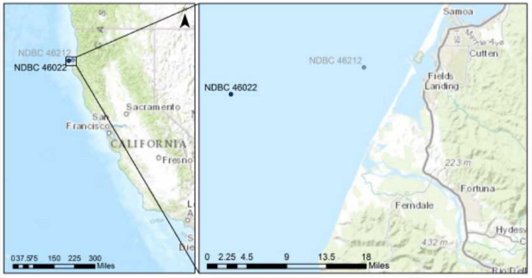
Density developing towards region of high T_e, high H_s

Too many points are outside of traditional contour



PCA Contour Results



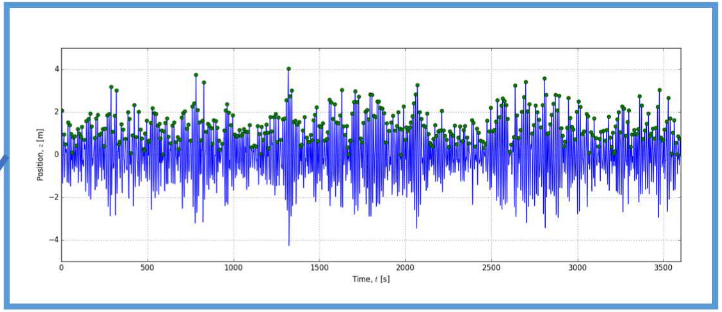


NDBC 46022 – Northern California site location.

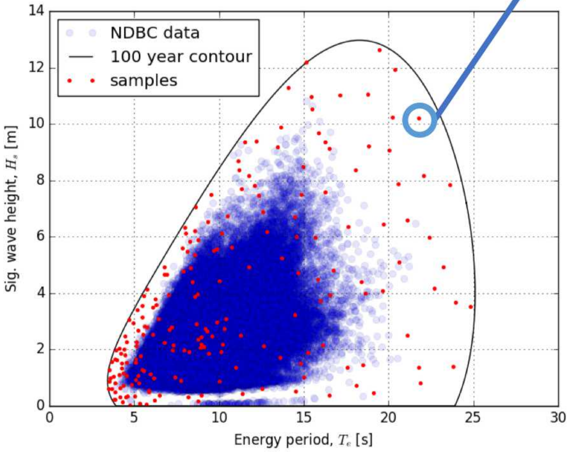
NDBC 46022 – Northern California

A. Eckert-Gallup, C. Sallaberry, A. Dallman and V. Neary. "Application of principal component analysis (PCA) and improved joint probability distributions to the inverse first-order reliability method (I-FORM) for predicting extreme sea states," *Ocean Envineering*, vol. 112, pp. 307-319, Dec. 2015.

Design Response Statistics

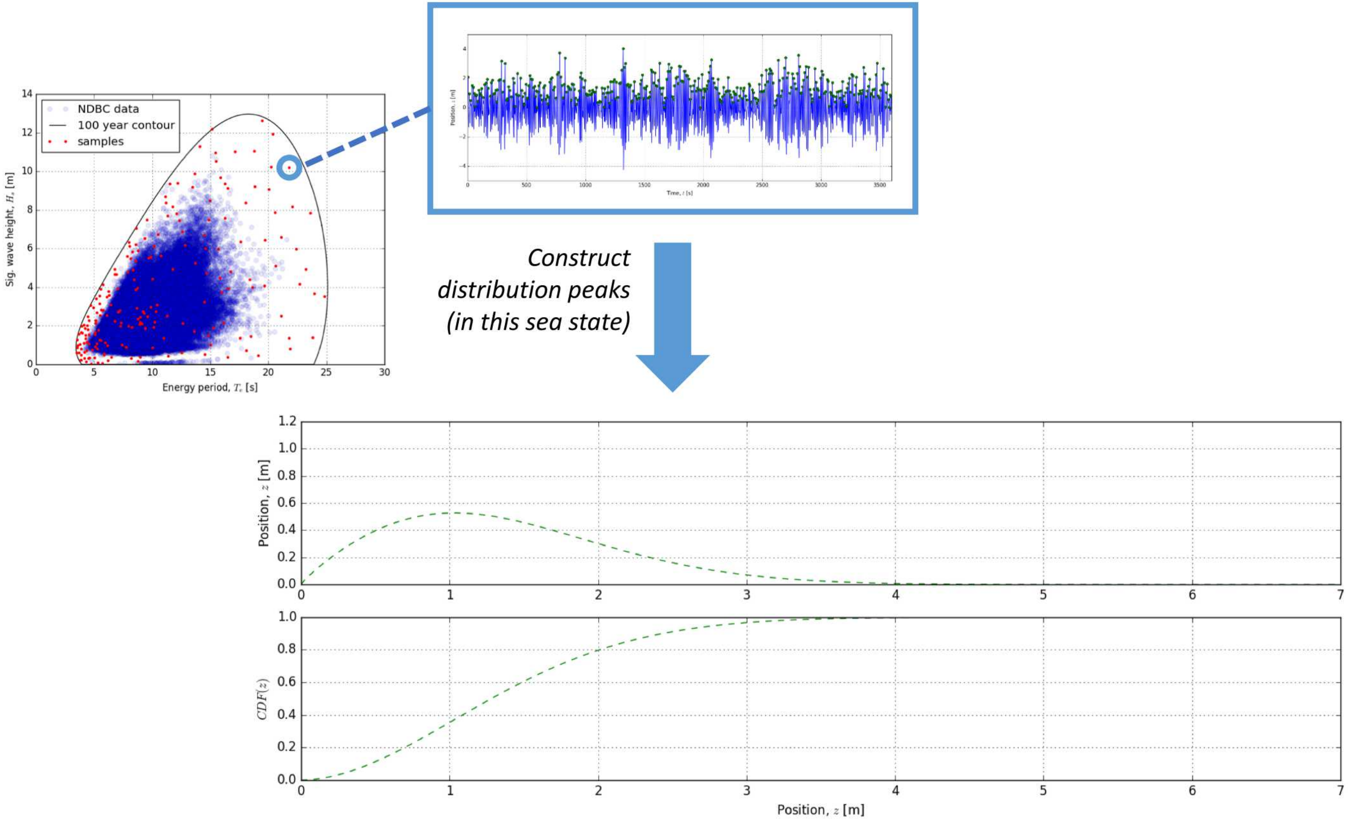


Need to observe enough peaks in the response of interest to construct a stochastic description



Coe, Ryan G., et al. "Full long-term design response analysis of a wave energy converter." *Renewable Energy* 116 (2018): 356-366.

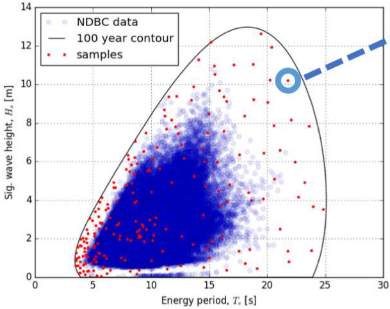
Design Response Statistics

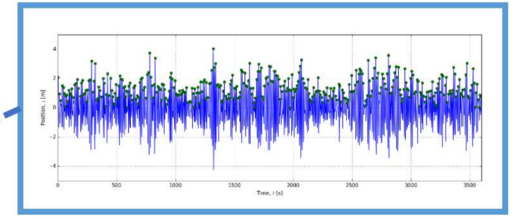


Construct distribution peaks (in this sea state)

Coe, Ryan G., et al. "Full long-term design response analysis of a wave energy converter." *Renewable Energy* 116 (2018): 356-366.

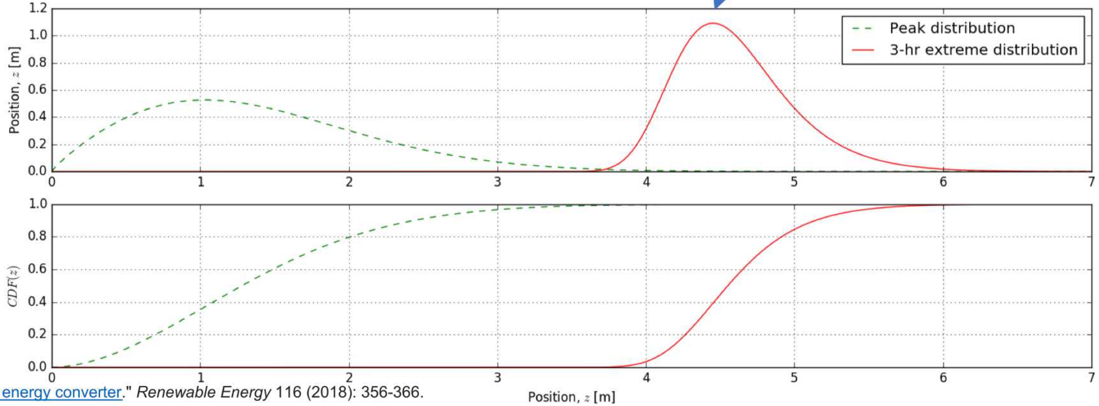
Design Response Statistics





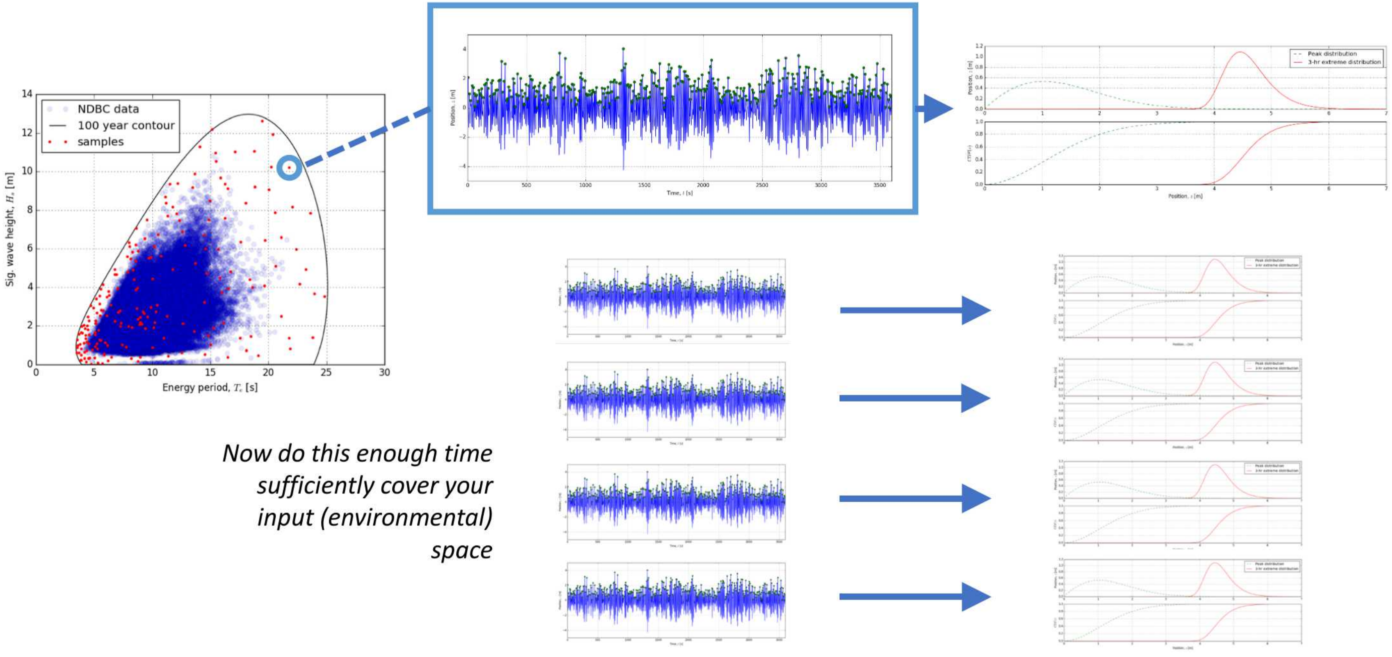
Construct distribution peaks (in this sea state)

Most probable extreme position in a 3-hour storm (with this sea state)



Coe, Ryan G., et al. "Full long-term design response analysis of a wave energy converter." *Renewable Energy* 116 (2018): 356-366.

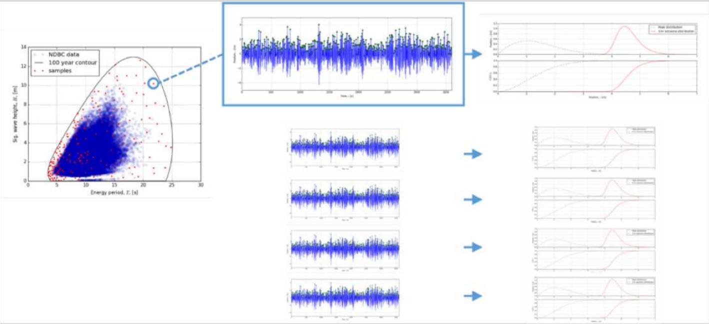
Design Response Statistics

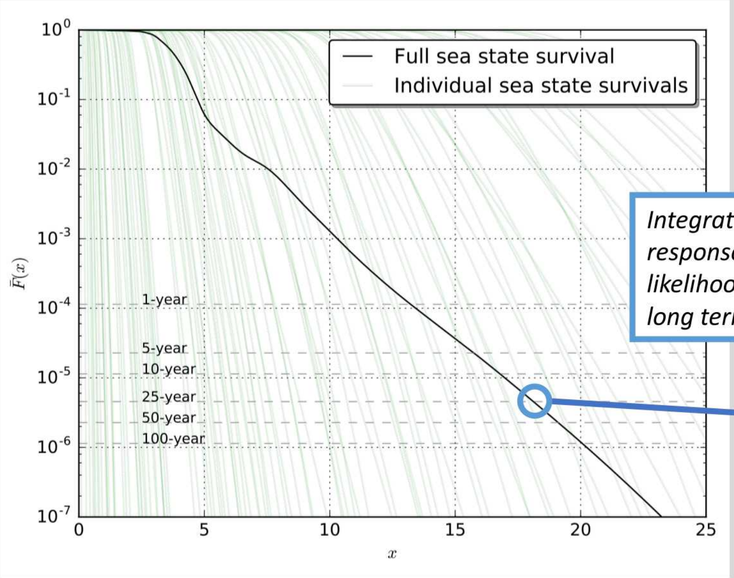


Now do this enough time sufficiently cover your input (environmental) space

Coe, Ryan G., et al. "Full long-term design response analysis of a wave energy converter." *Renewable Energy* 116 (2018): 356-366.

Design Response Statistics
All-Sea-State Approach



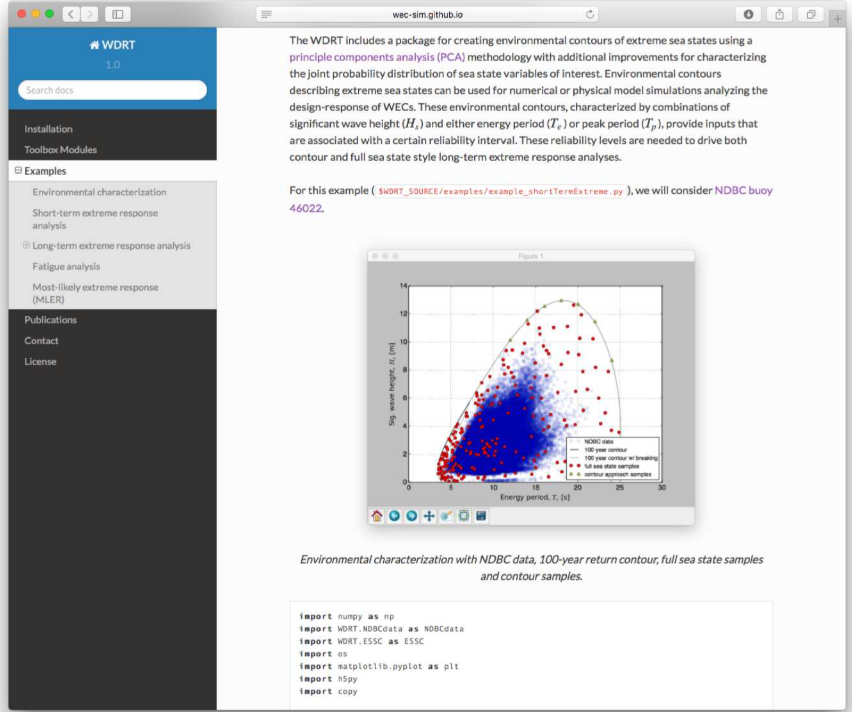


Integrating the short-term extreme responses (and weighting based on the likelihood of each sea state) gives the long term response

In a 25-year deployment at this location, we expect this device to see a max displacement of ~18 m

Coe, Ryan G., et al. "Full long-term design response analysis of a wave energy converter." *Renewable Energy* 116 (2018): 356-366.

WEC Design Response Toolbox (WDRT)



The WDRT includes a package for creating environmental contours of extreme sea states using a principle components analysis (PCA) methodology with additional improvements for characterizing the joint probability distribution of sea state variables of interest. Environmental contours describing extreme sea states can be used for numerical or physical model simulations analyzing the design-response of WECs. These environmental contours, characterized by combinations of significant wave height (H_s) and either energy period (T_e) or peak period (T_p), provide inputs that are associated with a certain reliability interval. These reliability levels are needed to drive both contour and full sea state style long-term extreme response analyses.

For this example (`$WDRT_SOURCE/examples/example_shortTermExtreme.py`), we will consider NDBC buoy 46022.

Environmental characterization with NDBC data, 100-year return contour, full sea state samples and contour samples.

```
import numpy as np
import WDRT.NDBCdata as NDBCdata
import WDRT.ESSC as ESSC
import os
import matplotlib.pyplot as plt
import h5py
import copy
```

http://wec-sim.github.io/WDRT

- Environmental Characterization
- Short-term Extreme Response
- Long-term Extreme Response
- Most-likely Extreme Response (MLER)
- Fatigue Loads
- Structural Loads

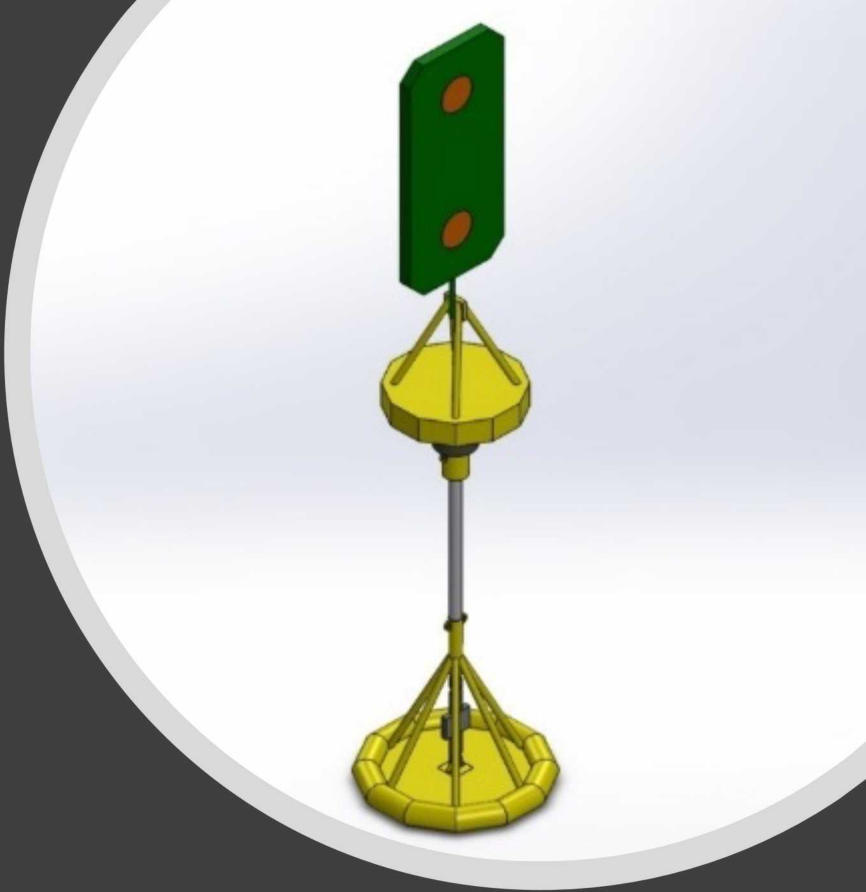
R. G. Coe, C. Michelen, A. Eckert-Gallup, Y. Yu and J. van Rij, WDRT: A toolbox for design-response analysis of wave energy converters, in Proceedings of the 4th Marine Energy Technology Symposium (METS), Washington, DC, 2016.

Design Response Statistics

Case Study: All-Sea-State Approach

- Reference Model 3 (Gen 1)
  - 1:100 scale version
  - H = 3, 9, 15 m

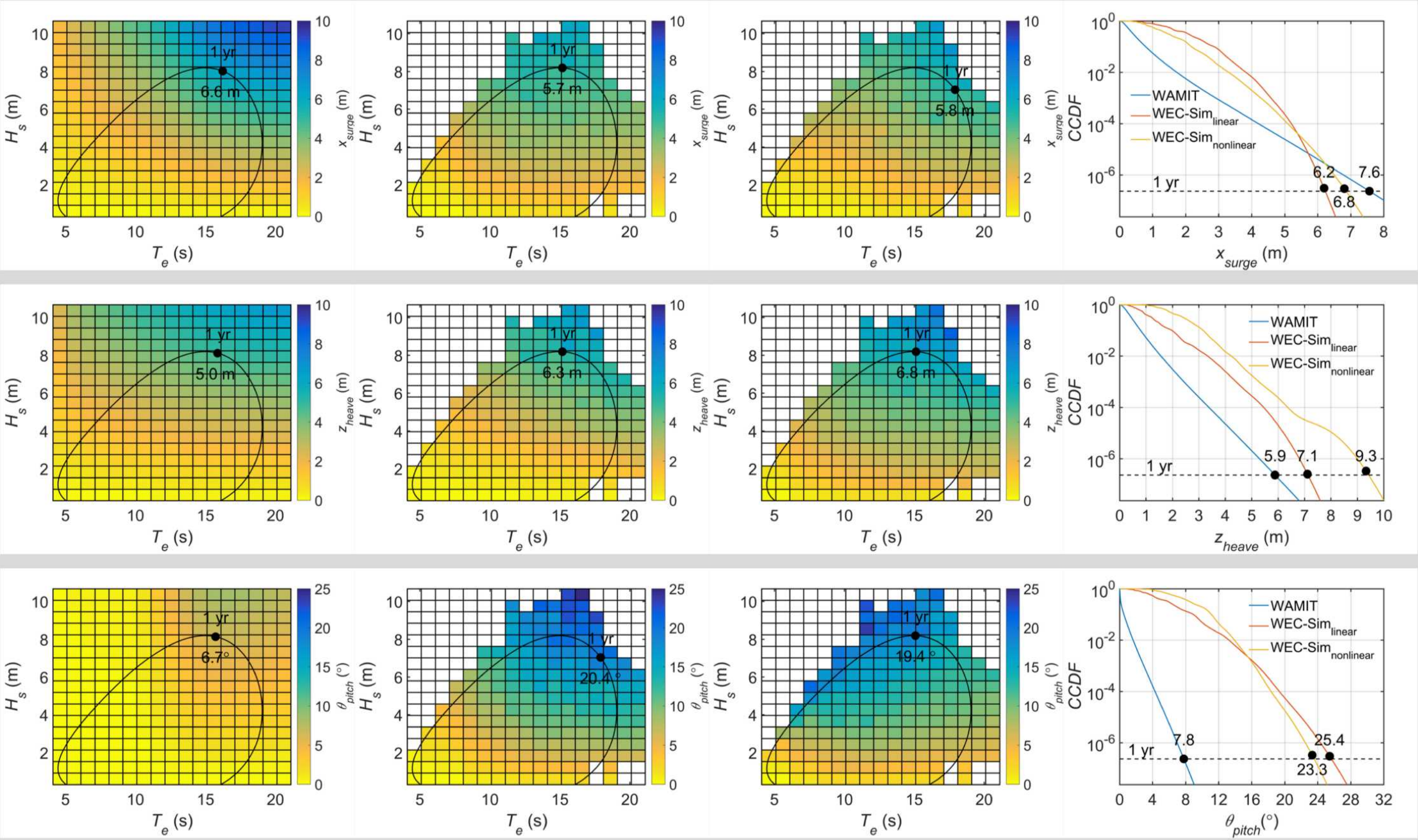
Property	Value	Units
m	0.313	kg
I_x	8.89×10^{-3}	$kg\cdot m^2$
I_y	8.89×10^{-3}	$kg\cdot m^2$
z_{cg}	-0.214	m
$z_{mooring,top}$	-0.051	m
$z_{mooring,bottom}$	-0.213	m
$k_{mooring}/8$	0.7	N/m



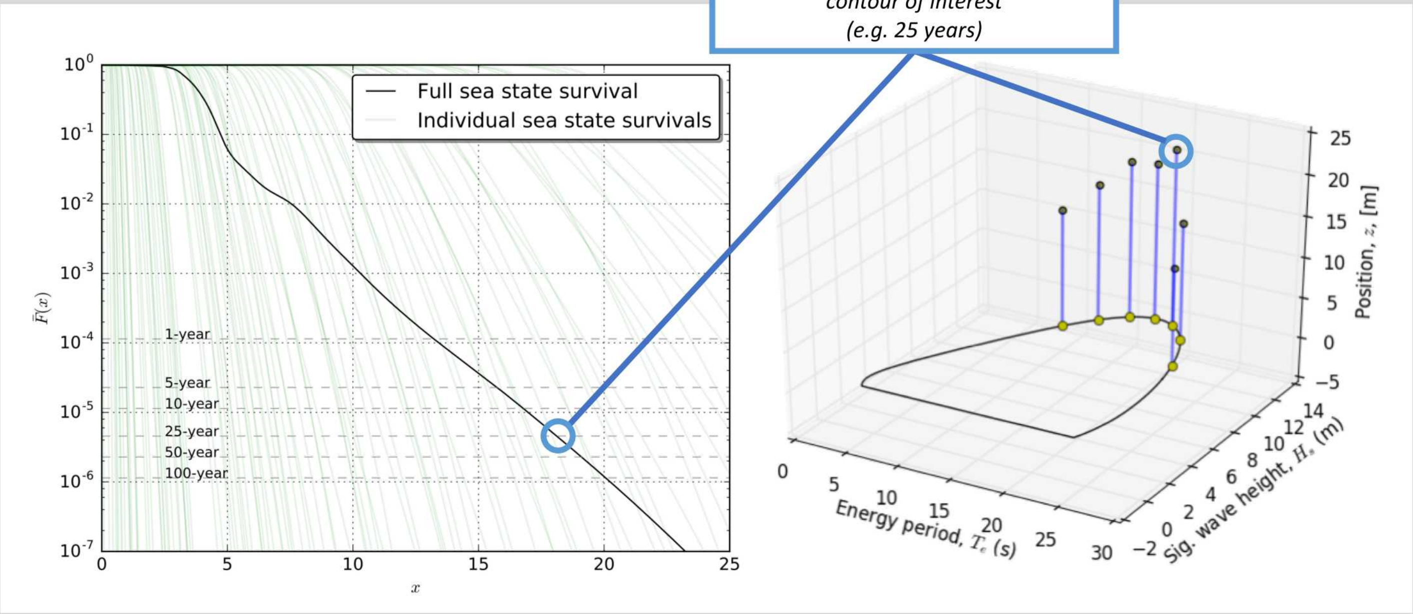
Yu, Y.-H., Lawson, M., Li, Y., Previsic, M., Epler, J., and Lou, J., 2015, Experimental Wave Tank Test for Reference Model 3 Floating-Point Absorber Wave Energy Converter Project, NREL/TP-5000-62951.

Results and Discussion

van Rij J., Yu Y.-H., and Coe R. G., 2018, “Design Load Analysis for Wave Energy Converters,” 37th International Conference on Ocean, Offshore and Arctic Engineering, OMAE, Madrid, Span.

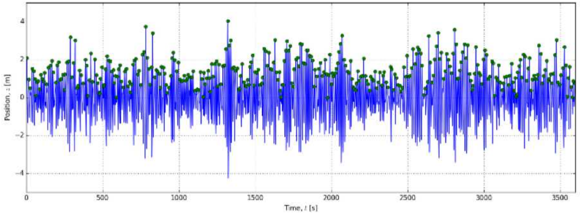


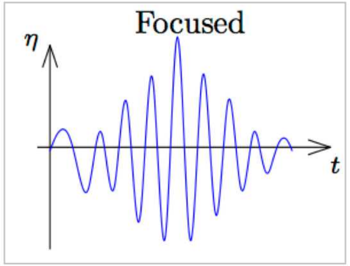
Design Response Statistics
Contour Approach

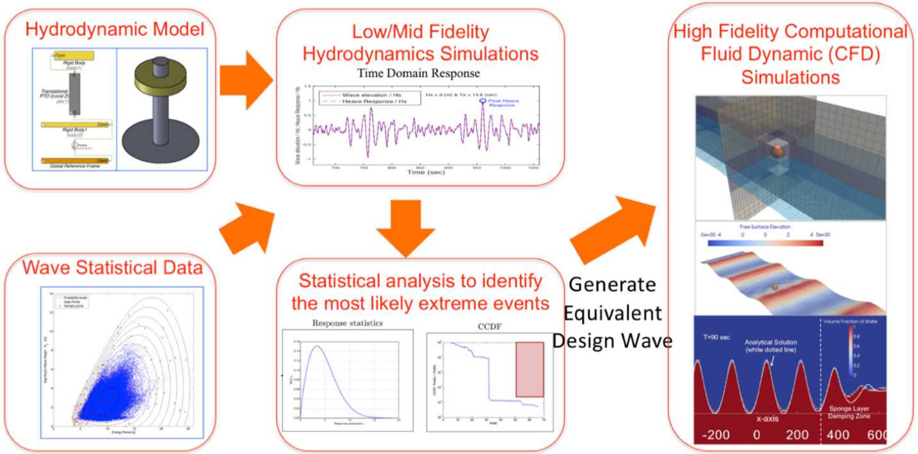


Can also model response only on the contour of interest
(e.g. 25 years)

Most-Likely Extreme Response







Hydrodynamic Model

Low/Mid Fidelity Hydrodynamics Simulations

High Fidelity Computational Fluid Dynamic (CFD) Simulations

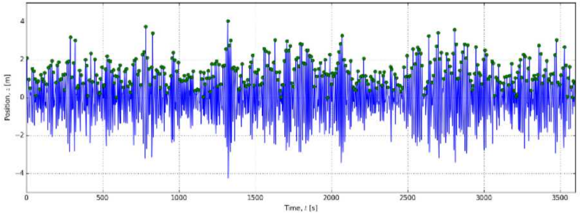
Wave Statistical Data

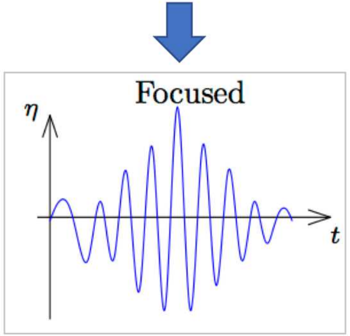
Statistical analysis to identify the most likely extreme events

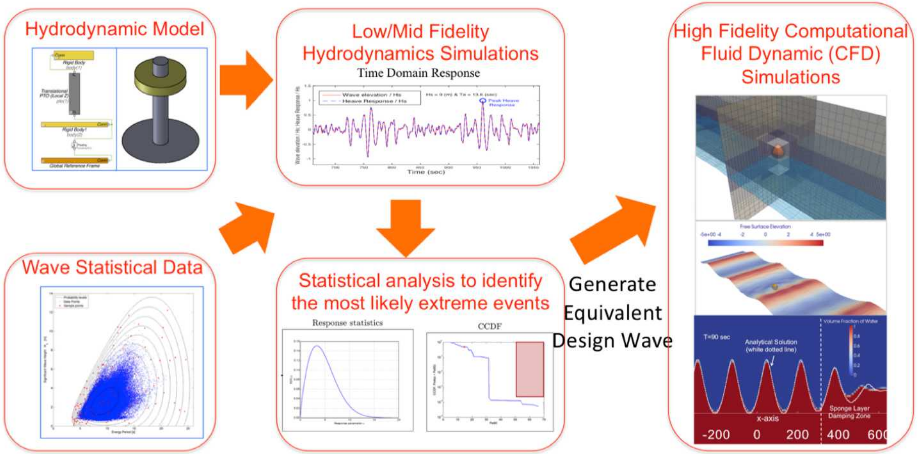
Generate Equivalent Design Wave

- The extreme load is often a matter of chance created by the instantaneous position of the device and a series of random waves.
- The occurrence of an extreme load should be studied as a stochastic event because of the nature of the irregular sea states.

Most-Likely Extreme Response







Hydrodynamic Model

Low/Mid Fidelity Hydrodynamics Simulations

High Fidelity Computational Fluid Dynamic (CFD) Simulations

Wave Statistical Data

Statistical analysis to identify the most likely extreme events

Generate Equivalent Design Wave

- The MLER method were developed to generate a **focused wave** profile that gives the largest response with the consideration of wave statistics based on spectral analysis and the response amplitude operators (RAOs) of the device.
- Often used for experimental wave tank tests or CFD simulations

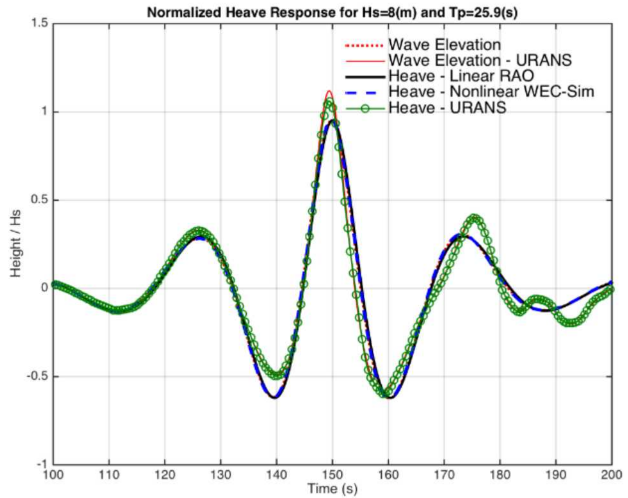
Most-Likely Extreme Response

Construct an ensemble of design wave profiles

$$\eta = \sum_{n=1}^{N} A_n[V_n cos(\omega_n t) - W_n sin(\omega_n t)],$$

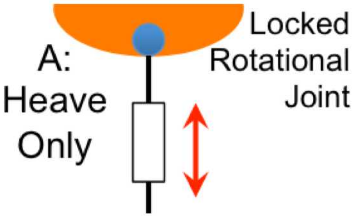
A_n: Wave spectrum

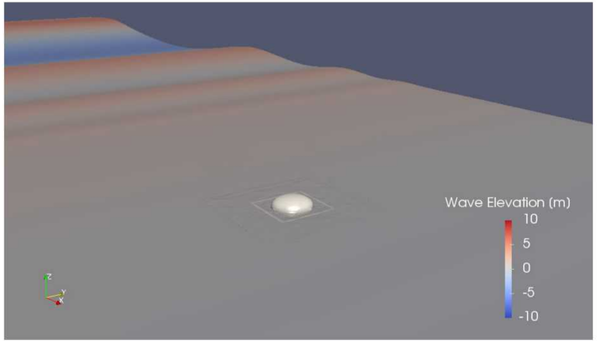
V_n and W_n: Independent standard normal random variables

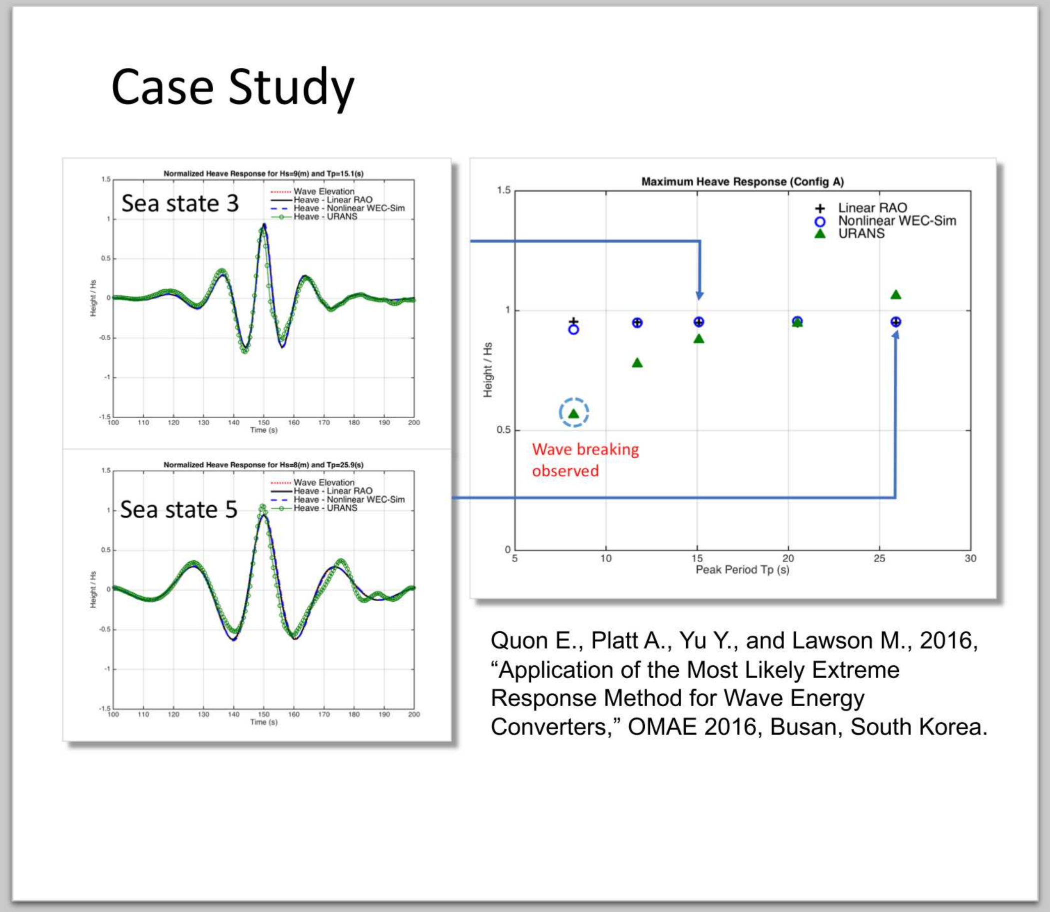


- Dietz, J. S., 2004. “Application of Conditional Waves as Critical Wave Episodes for Extreme Loads on Marine Structures”. PhD thesis, Technical University of Denmark.
- Drummen, I., Wu, M., and Moan, T., 2009. “Numerical and experimental investigations into the application of response conditioned waves for long-term nonlinear analyses,” Ma- rine Structures, 22(3), jul, pp. 576–593.
- Quon E., Platt A., Yu Y., and Lawson M., 2016, “Application of the Most Likely Extreme Response Method for Wave Energy Converters,” OMAE 2016, Busan, South Korea.

Most-Likely Extreme Response



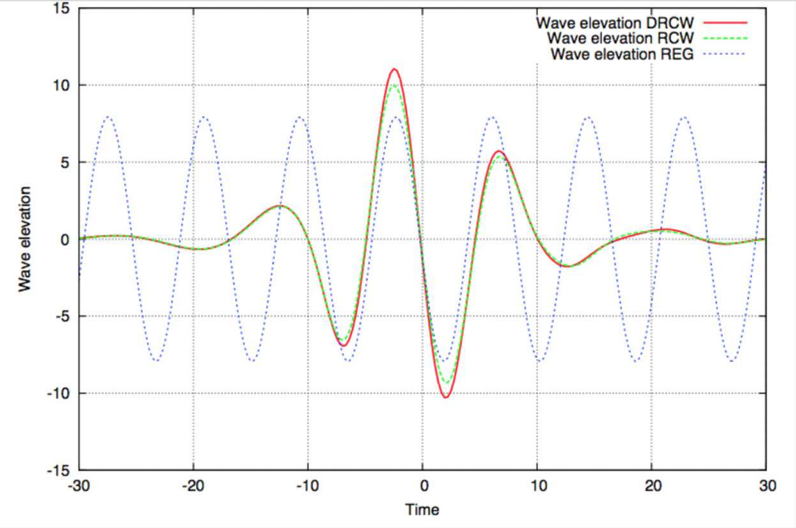




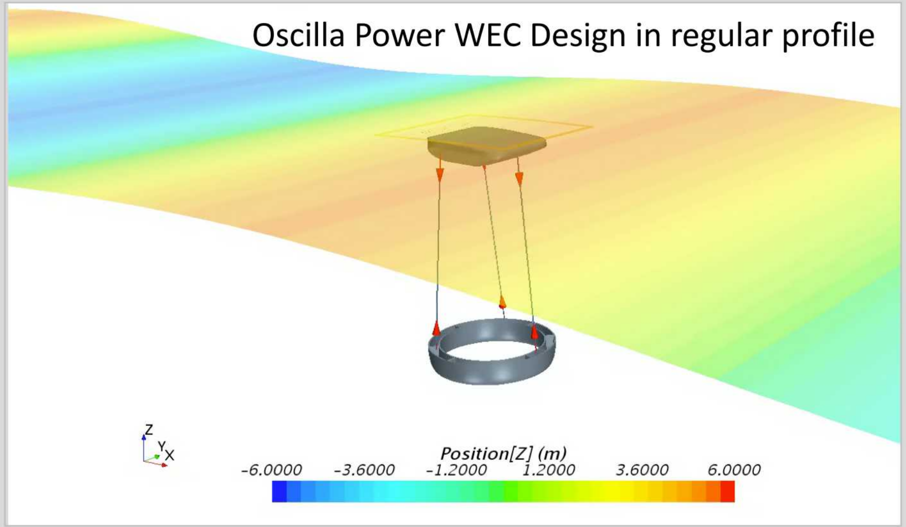
Case Study

Quon E., Platt A., Yu Y., and Lawson M., 2016, “Application of the Most Likely Extreme Response Method for Wave Energy Converters,” OMAE 2016, Busan, South Korea.

Other Response conditioned wave profiles



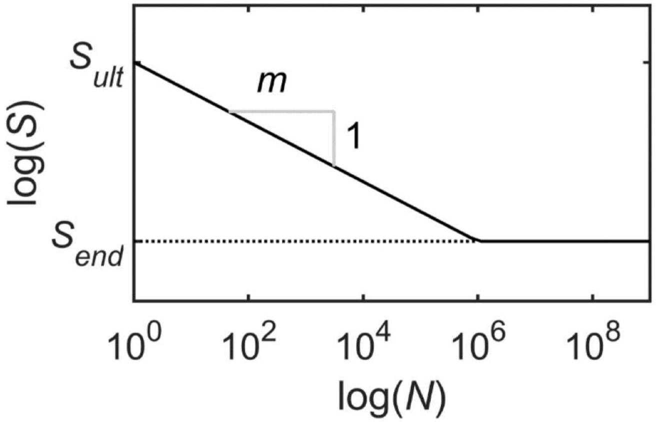
de Hauteclocque G., Derbanne Q., and El-gharbaoui A., 2012, “Comparison of Different Equivalent Design Waves with Spectral Analysis,” 31st International Conference on Ocean, Offshore and Arctic Engineering, OMAE, ed., OMAE, Rio de Janeiro, Brazil.



Ryan G. Coe, Chris C. Chartrand, Eliot W. Quon, Brian J. Rosenberg, Yi-Hsiang Yu, Jennifer van Rij, Tim R. Mundon, 2012, “CFD survival analysis of a two-body wave energy converter” (in preparation).

Fatigue Analysis

- In addition to extreme loads, a WEC must also be able to structurally withstand fatigue loading for its design life.
- Fatigue loads are time varying loads which cause cumulative damage to structural components and eventually lead to structural failure.
- Usually, a component's fatigue strength/life is reported in terms of an S-N curve. The S-N curve, which is typically obtained empirically, gives the number of load cycles N to failure at constant load amplitude S.



Fatigue Analysis

- WEC loads, however, are highly variable and by no means of constant amplitude. The most common method used to predict the cumulative damage of variable loading is the Palmgren-Miner rule.

- The total damage equivalent load, S_N, is obtained with a linear summation of the distributed load ranges, obtained via the rainflow counting method.

$$S_N = \left(\sum \frac{S_i^m n_i}{N} \right)^{\frac{1}{m}}$$

Fatigue Analysis

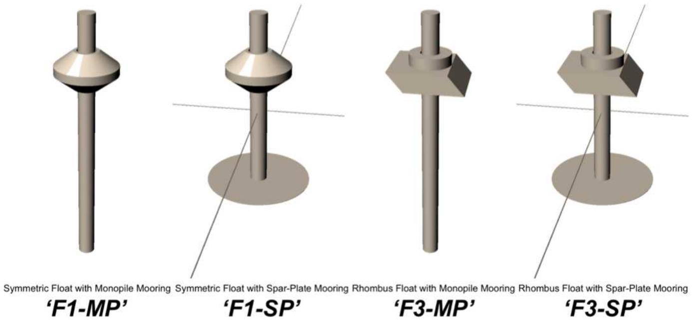
The intended use of the fatigue analysis here is as an early design stage WEC fatigue load estimator. The required inputs are:

$$S_N = \left(\sum \frac{S_i^m n_i}{N}\right)^{\frac{1}{m}}$$

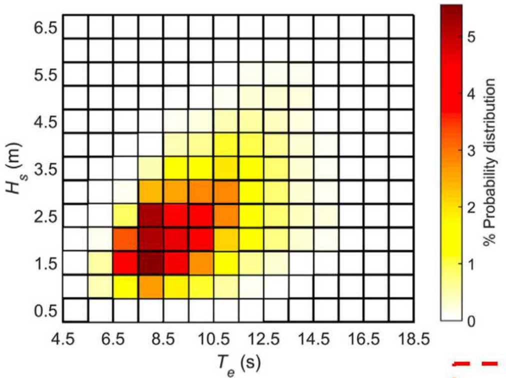
- A force or stress history, which may be obtained either experimentally or via simulation. Pertinent loads may include, power-take-off (PTO) loads, mooring loads, bending moments, etc.
- The S_N curve slope, m, which is likely unknown with any accuracy in the early stages of design, but as an initial estimate, the following ranges may be used: $m\approx3-4m\approx3-4$ for welded steel, $m\approx6-8m\approx6-8$ for cast iron, and $m\approx9-12m\approx9-12$ for composites.
- And, N, the number of cycles expected in the WEC's design life, which is up to the user to ascertain given a specified design life and environmental characterization.

Fatigue Analysis: Case Study

- Innovative buoy design for OPT



J. van Rij and Y-H. Yu, NREL and K. A. Edwards and M. Mekhiche, METS 2016. Submitted for IJOME in March 2017.



Joint probability distribution of Humboldt Bay, California, from 2004 to 2012

	$\frac{P_{avg}^{1yr}}{W_{disp}}$	$\frac{P_{avg}^{1yr}}{F_{eq}^{1yr}}$	$\frac{P_{avg}^{1yr}}{F_{float}}$
	$\frac{kW}{MN}$	$\frac{kW}{MN}$	$\frac{kW}{MN}$
F1-MP (0°)	8.23	161.65	40.21
F3-MP (0°)	7.80	169.52	31.76
F3-MP (30°)	7.51	164.64	30.09
F1-SP (0°)	9.13	137.15	44.23
F3-SP (0°)	7.12	147.81	36.47
F3-SP (30°)	7.03	141.71	39.21

Power to fatigue load ratio

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