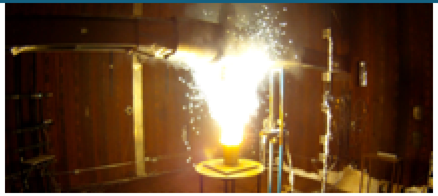
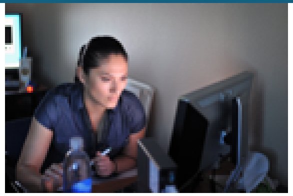
Sandia National Laboratories

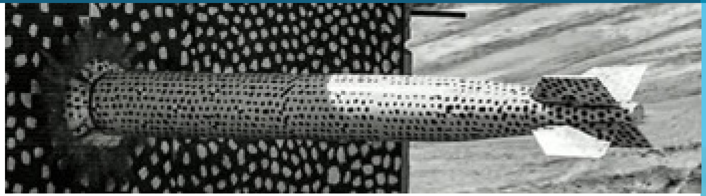
SAND2020-11992PE

Applied WEC modeling and control design

Oct. 29 2020, UMass-Amherst







Presented by

Ryan Coe, rcoe@sandia.gov

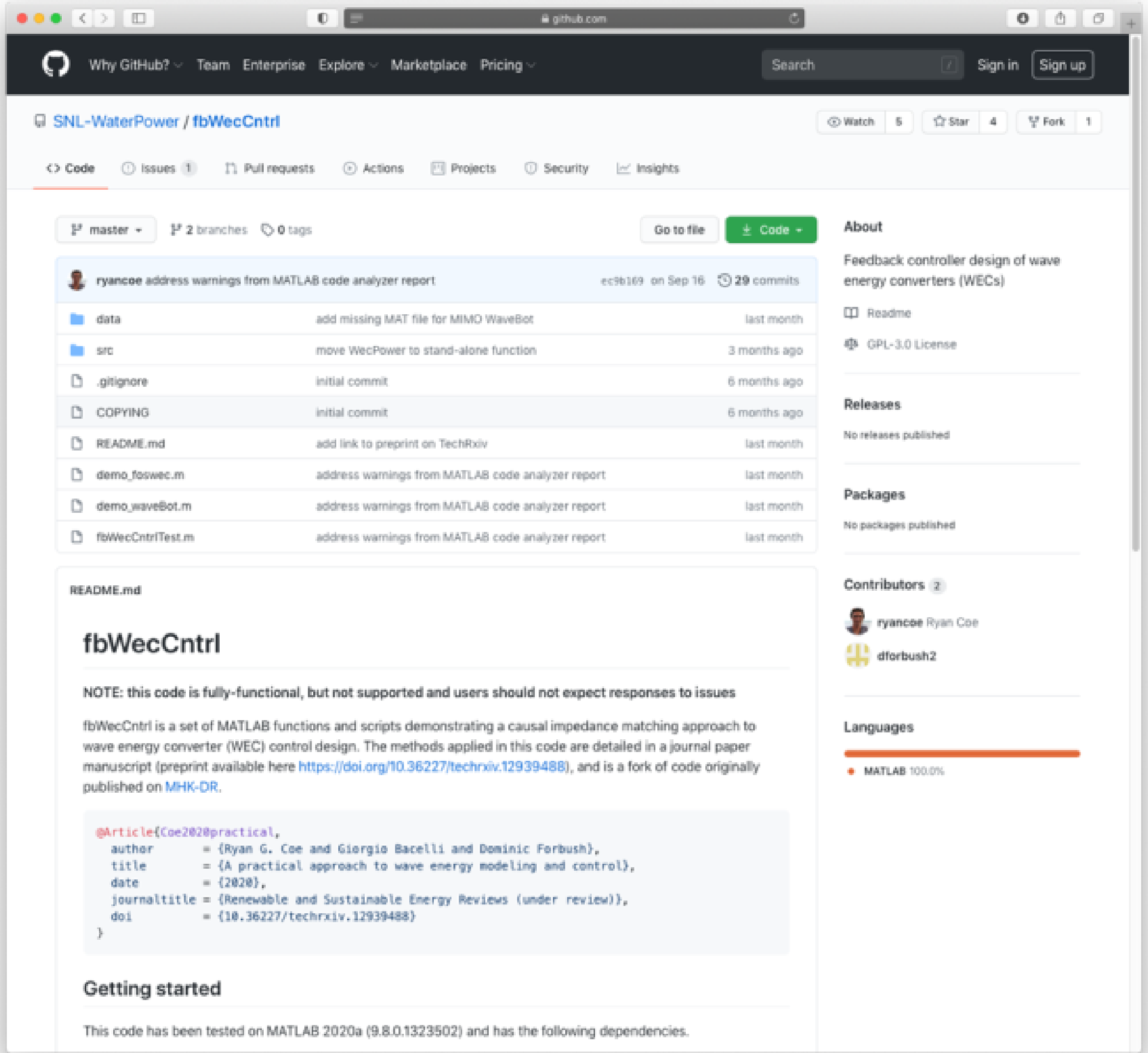
Slides based on combined work of the author, Giorgio Bacelli, Dominic Forbush, Steven Spencer, and others

U.S. DEPARTMENT OF ENERGY NNSA

Class agenda

I. About me
II. Wave energy background
III. Case-study (with examples in MATLAB)
    I. Modeling a WEC
    II. Controlling a WEC

MATLAB examples



1. Go to the fbWecCntrl repository:
   https://github.com/SNL-WaterPower/fbWecCntrl

2. Download or clone the repository (clone preferred to allow for easier updates)

3. Follow instructions installing*:
   https://github.com/SNL-WaterPower/fbWecCntrl#getting-started

4. The material for the lecture is located in the seminar_examples directory

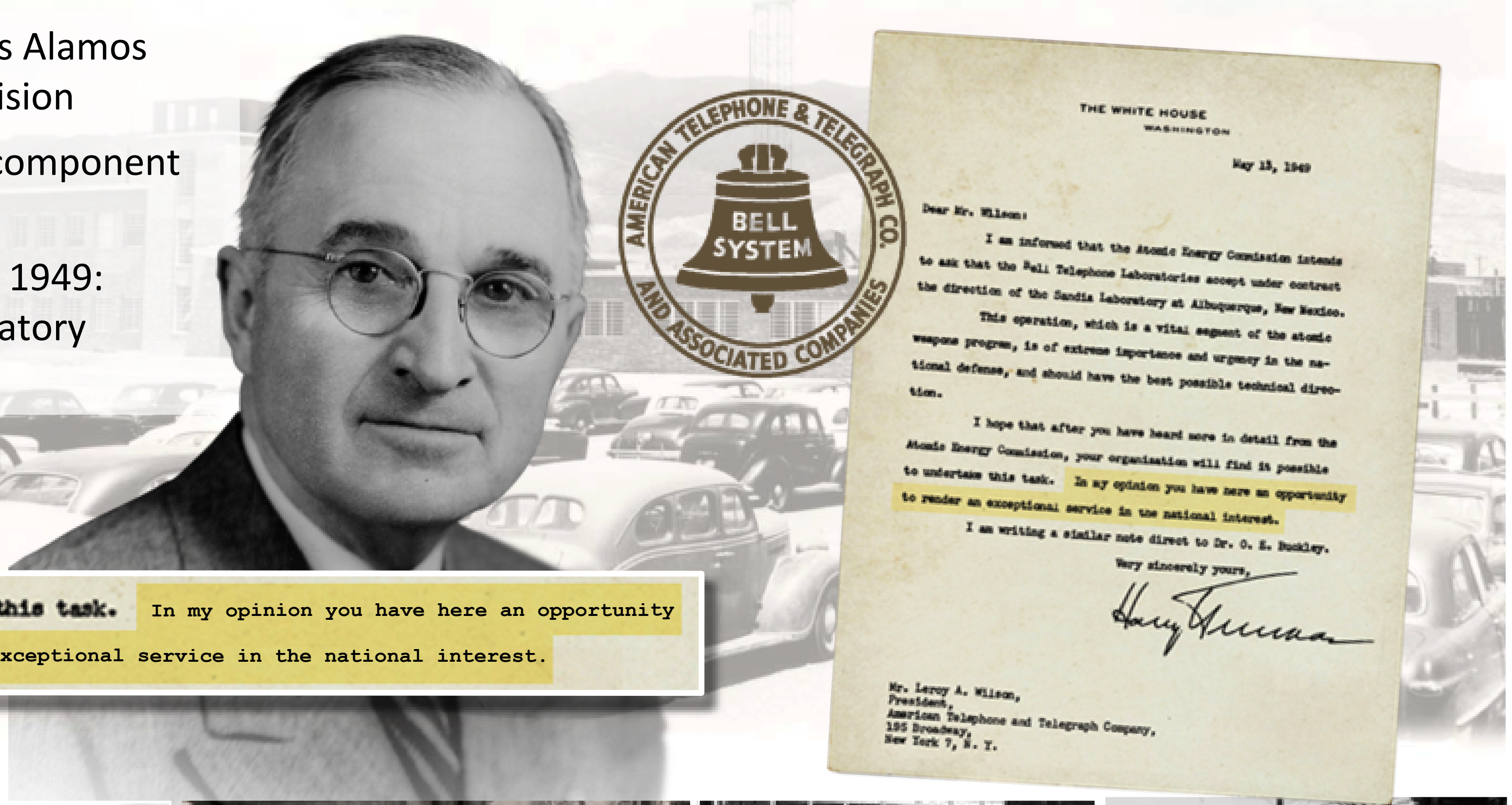
* Note that WAFO (https://github.com/wafo-project/wafo) is used to generate JONSWAP wave spectra – you will need this too to run some of the examples

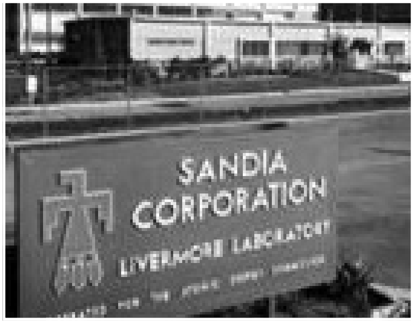
About me

Sandia National Labs

Exceptional service in the national interest

- July 1945: Los Alamos creates Z Division
- Nonnuclear component engineering
- November 1, 1949: Sandia Laboratory established





Albuquerque, NM

About Ryan

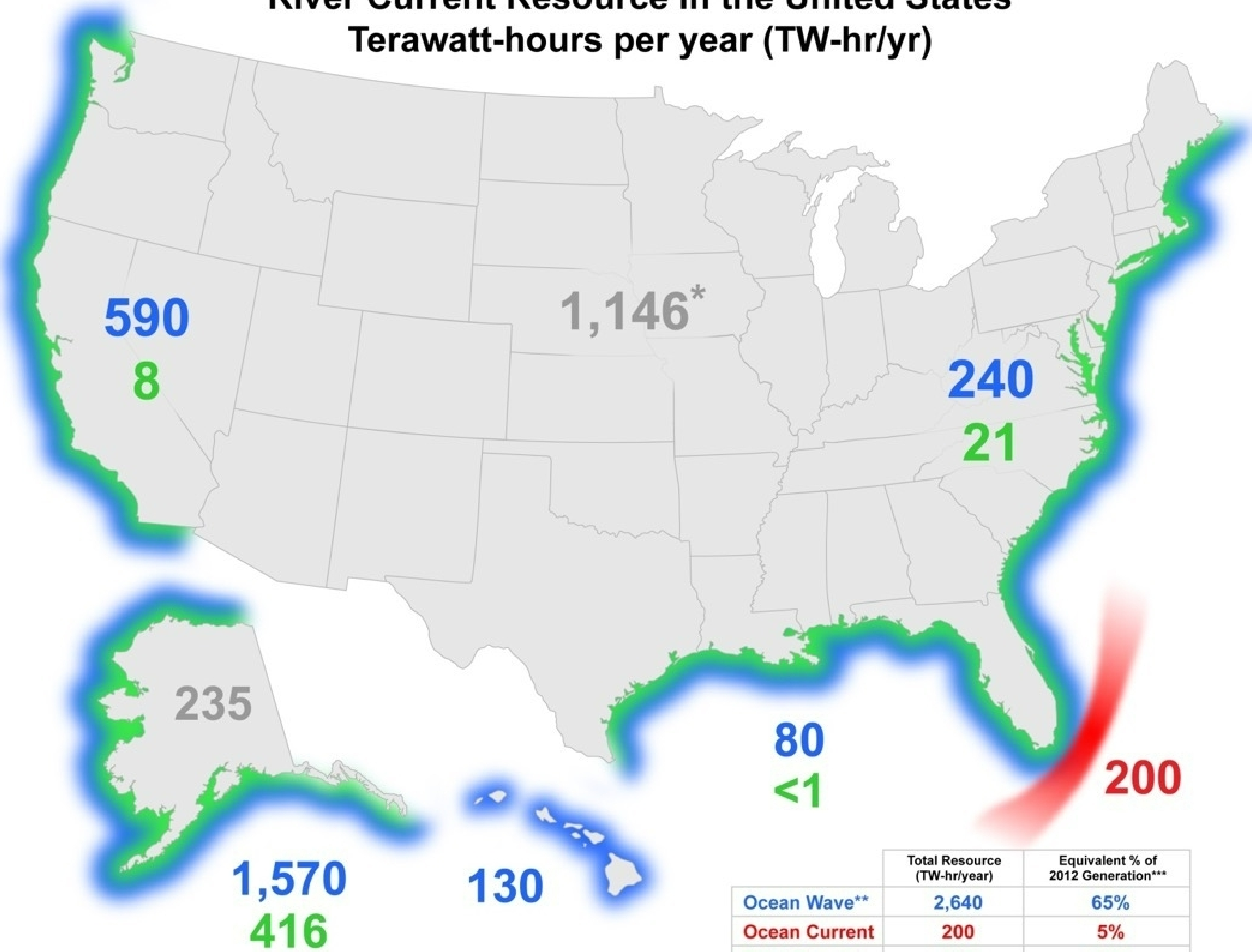
BS and PhD from Virginia Tech (Go Hokies!)

Sandia researcher for ~7 years

Hobbies: fly fishing, rock climbing, linear algebra

Background

The Ocean Wave, Ocean Current, Tidal Current, and River Current Resource in the United States
Terawatt-hours per year (TW-hr/yr)

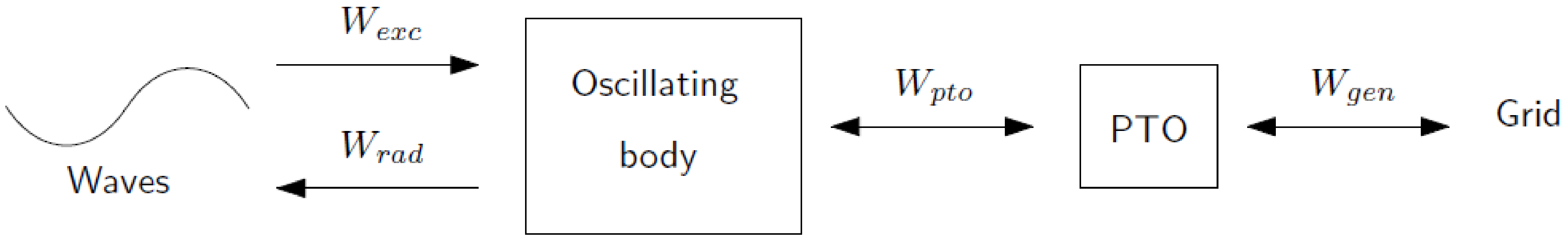


	Total Resource (TW-hr/year)	Equivalent % of 2012 Generation***
Ocean Wave**	2,640	65%
Ocean Current	200	5%
Tidal Current	445	11%
River Current	1,381	34%

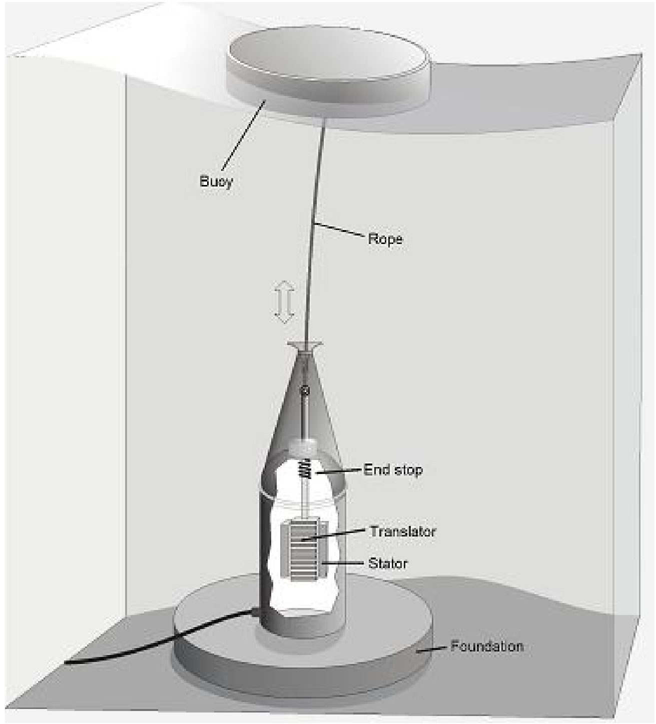
Ocean Wave: *P. Jacobson, G. Hagerman, and G. Scott, "Mapping and Assessment of the United States Ocean Wave Energy Resource," Electric Power Research Institute, Report Number 1024637, 2011.*
Ocean Current: *K. Haas, H. Fritz, S. French, and V. Neary, "Assessment of Energy Production Potential from Ocean Currents Along the United States Coastlines," Georgia Tech Research Corporation, 2013.*
Tidal Current: *K. Haas, H. Fritz, S. French, B. Smith, and V. Neary, "Assessment of Energy Production Potential from Tidal Streams in the United States," Georgia Tech Research Corporation, 2011.*
River Current: *T. Ravens, K. Cunningham, and G. Scott, "Assessment and Mapping of the Riverine Hydrokinetic Resource in the Continental United States," Electrical Power Research Institute, Report Number 1026880, 2012.*

*Resource distributed throughout the river systems in the United States.
**Resource data for the 200-m depth contour.
***The size of the resource with respect to total U.S. electricity generation in 2012, which was 4,054 TW-hr (U.S. Energy Information Administration, "Electric Power Monthly," May 2013).

What is a Wave Energy Converter?



Energy transfer through an oscillating body wave energy converter



Wave Energy Transport

Most of the energy within a wave is contained near the surface.

wave energy devices are designed to stay near the water surface to maximize the energy available for capture

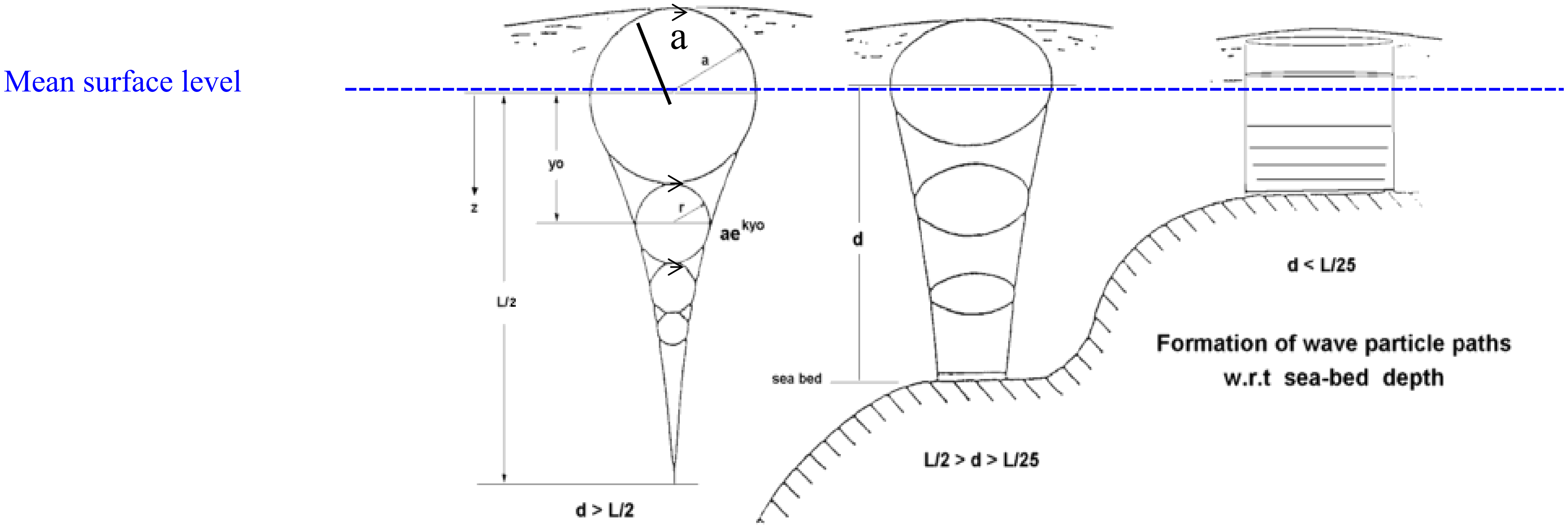
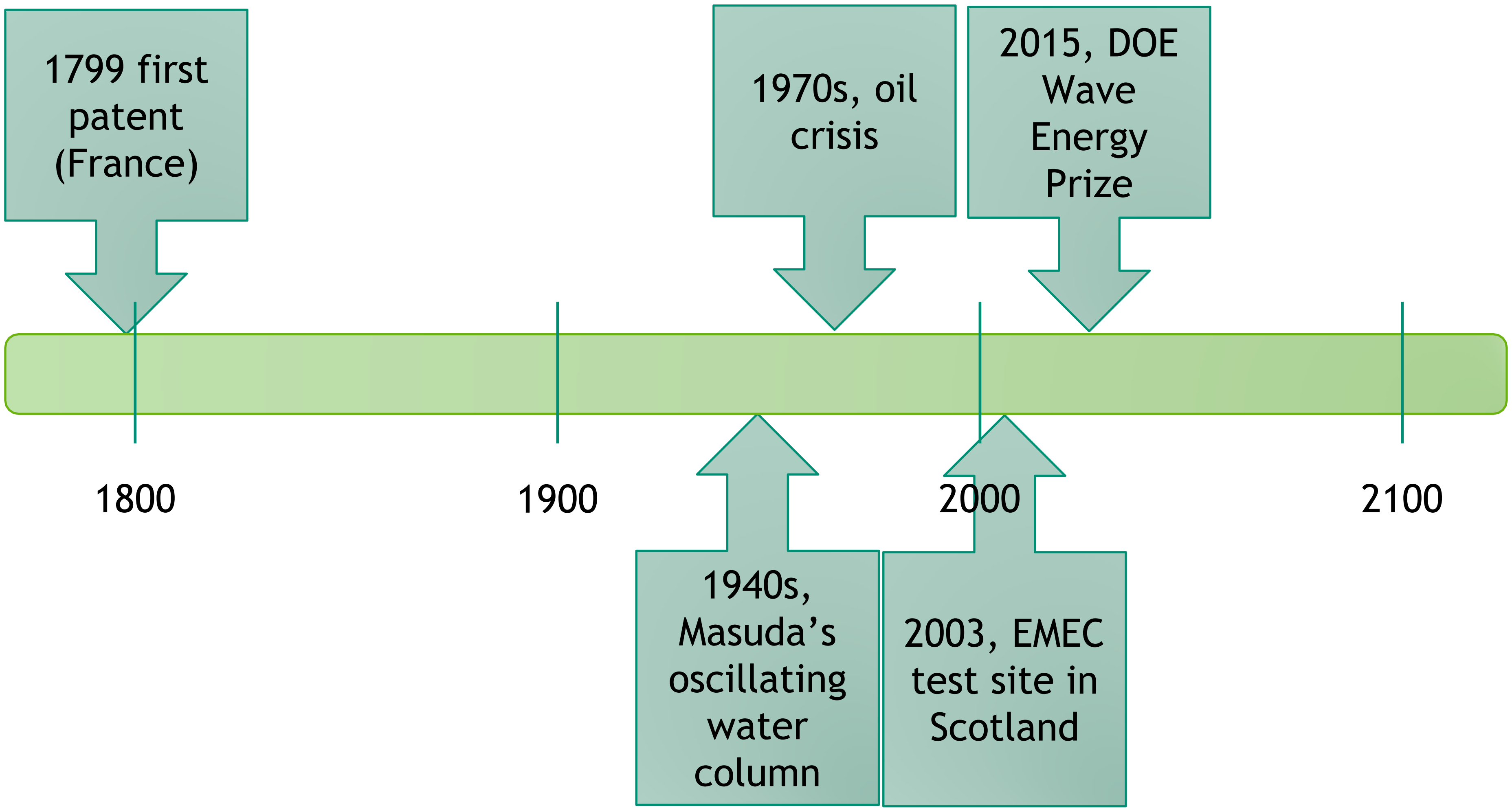
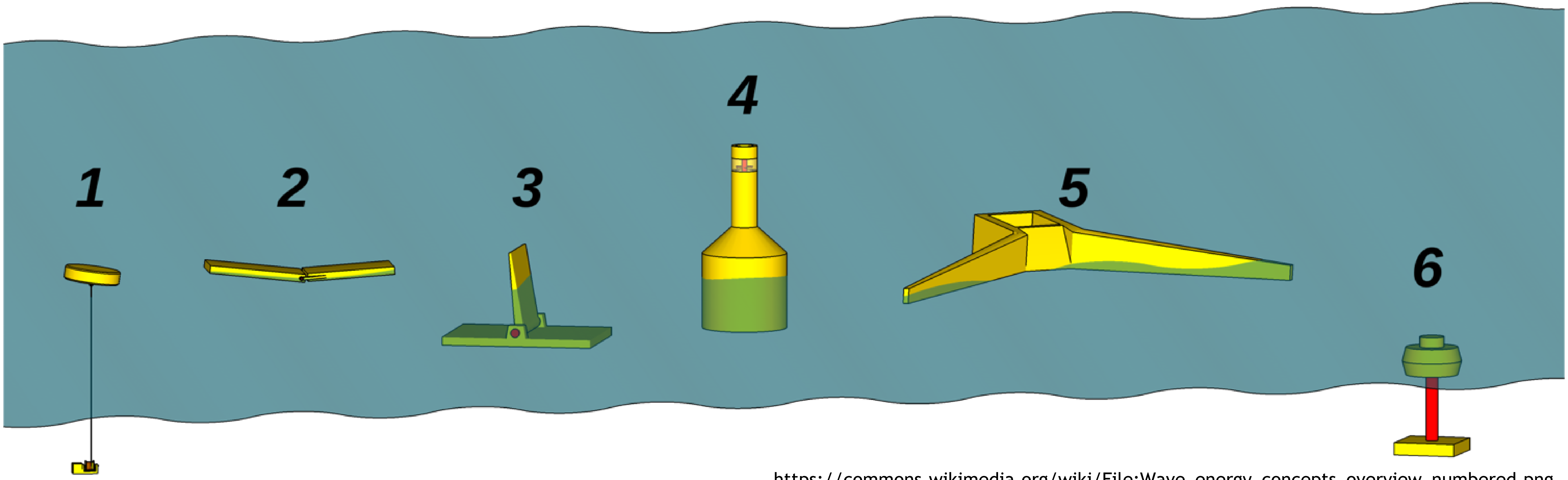


Fig. orbital motion of the water particles

Wave energy, a (brief) history

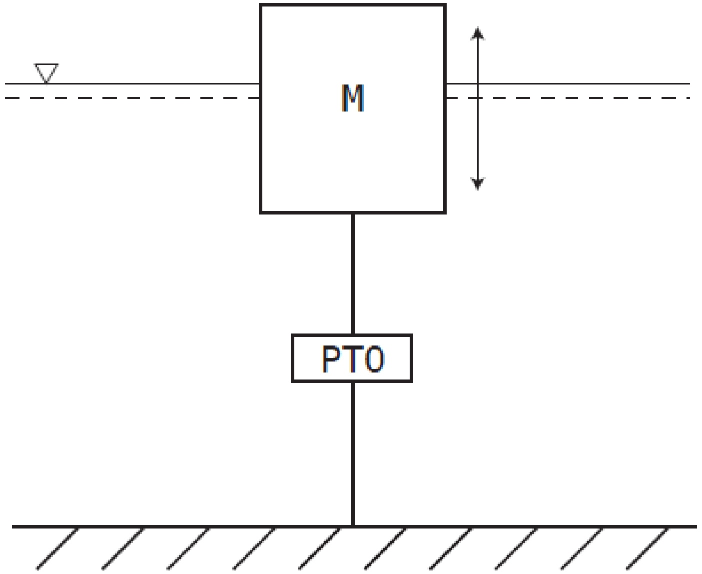


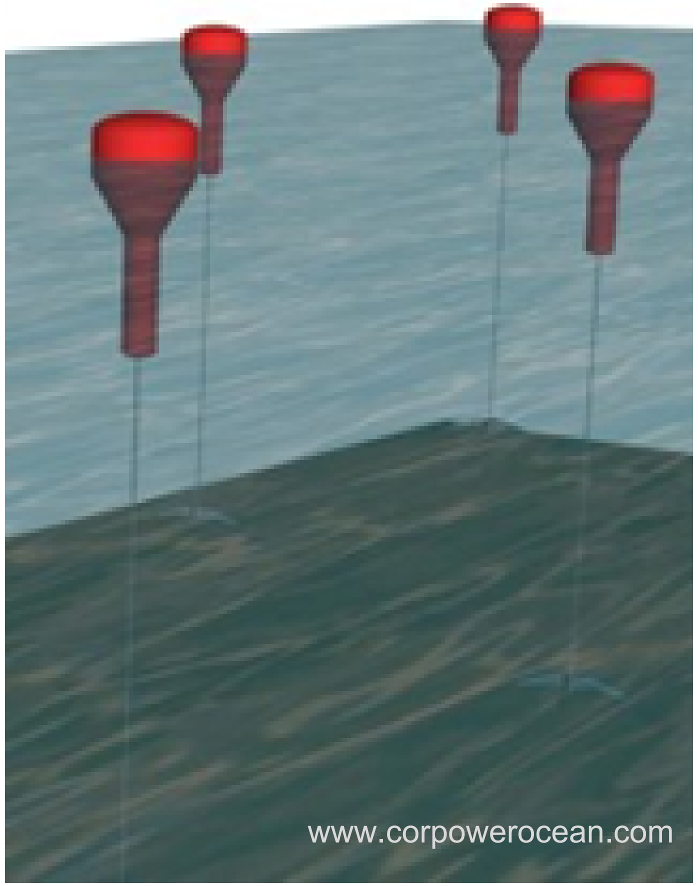
Wave energy concepts

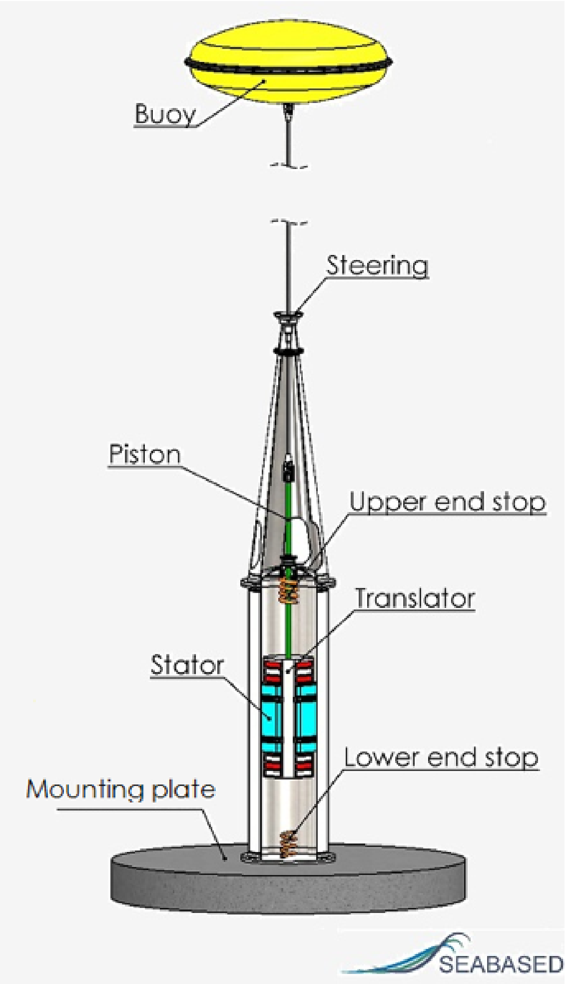


https://commons.wikimedia.org/wiki/File:Wave_energy_concepts_overview_numbered.png

Wave energy concepts – heaving point absorber

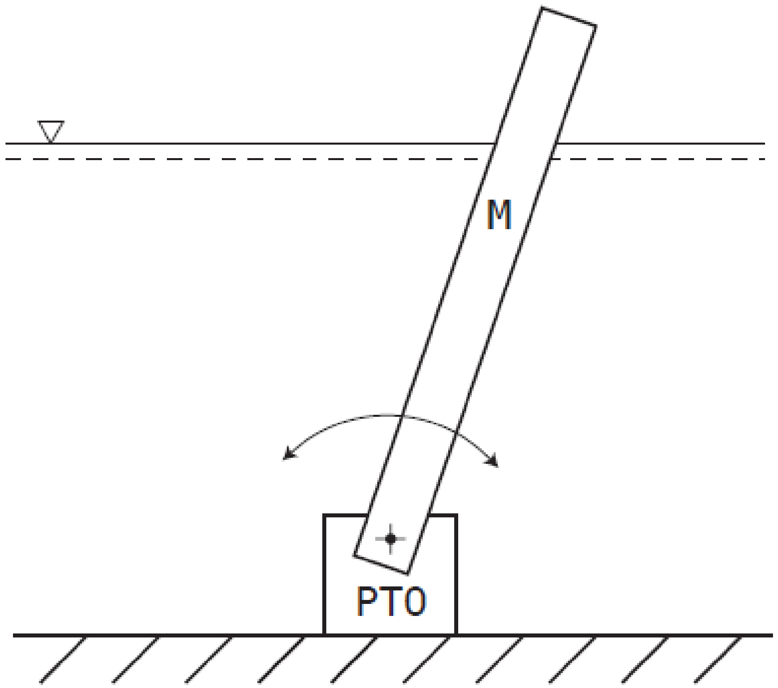




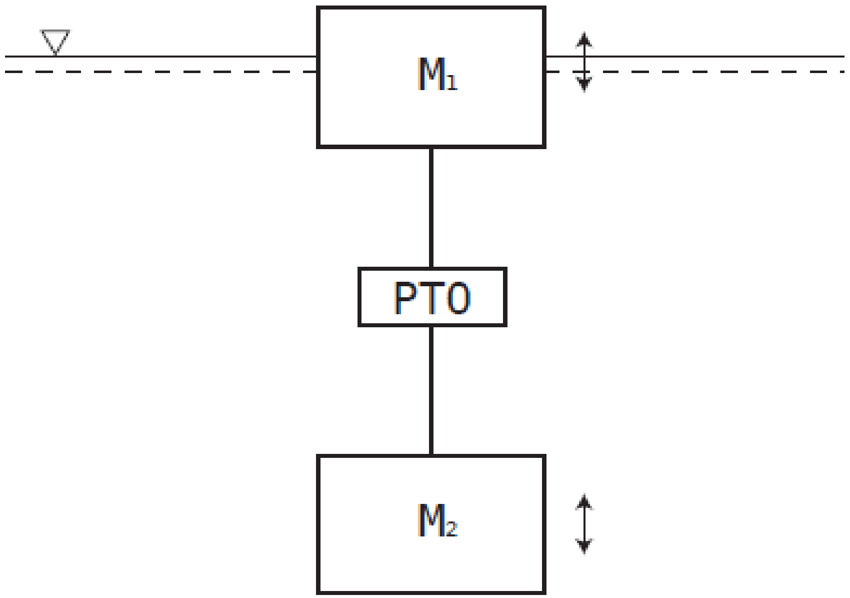


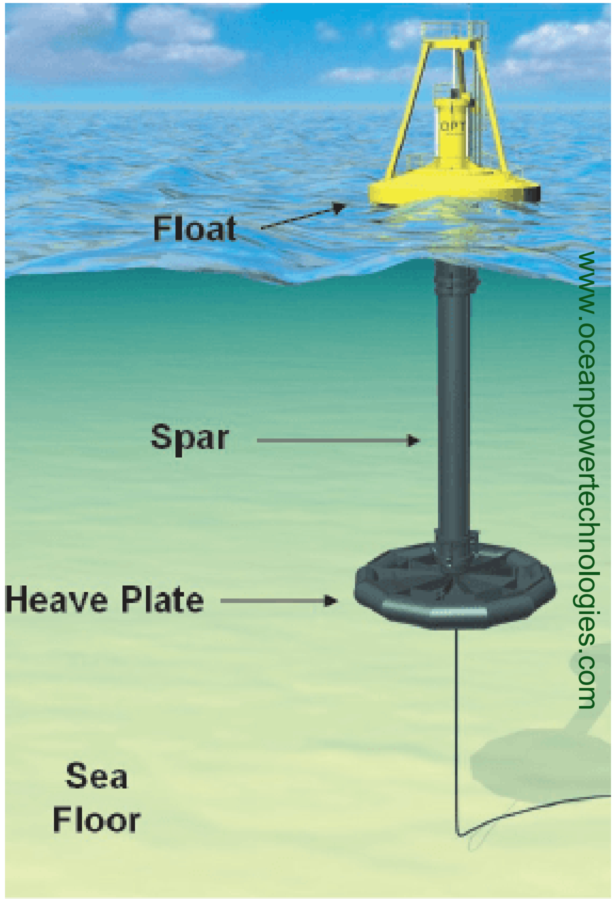
www.seabased.com/en/wave-energy

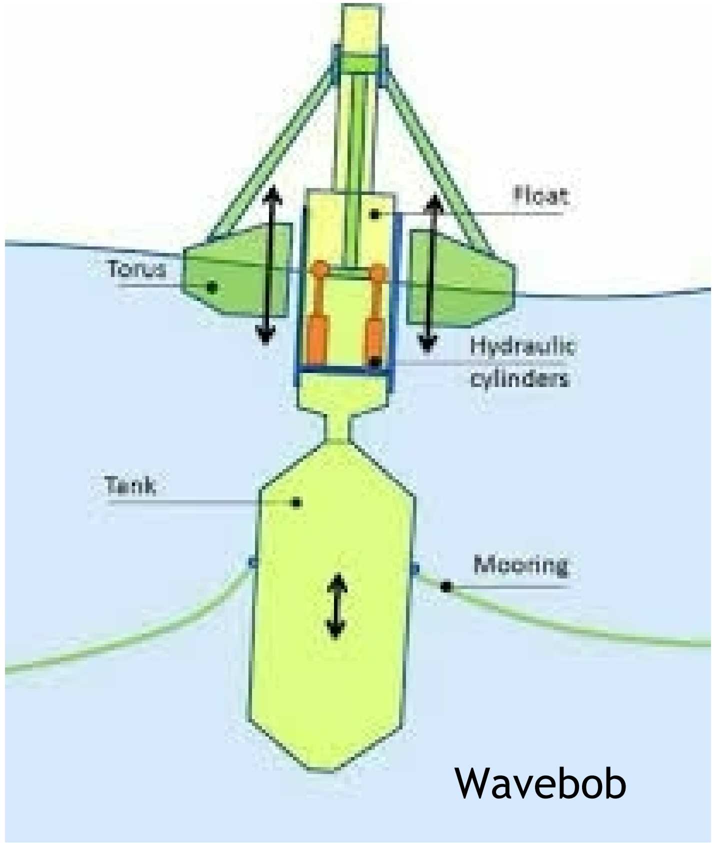
Wave energy concepts – pitching (flapping) device



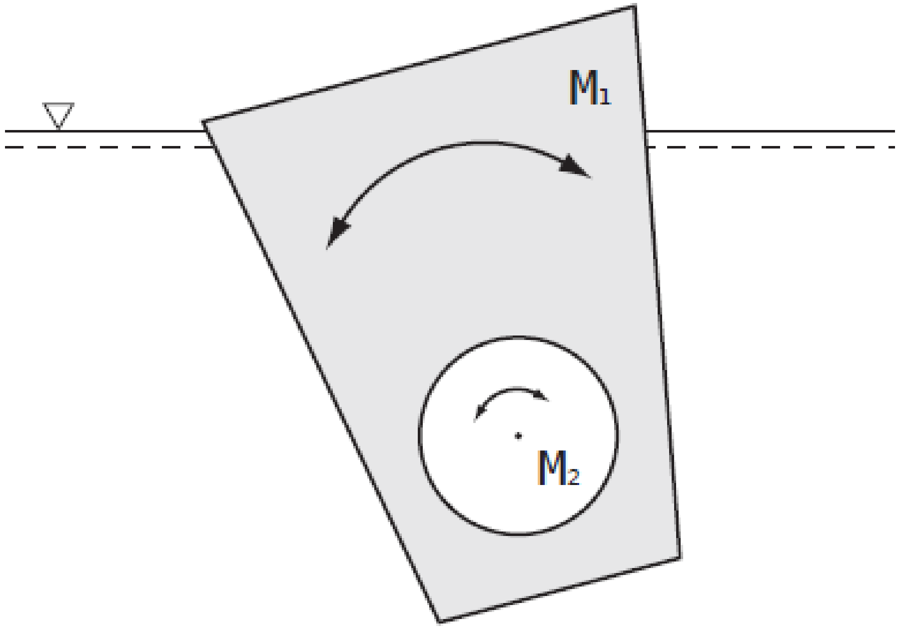
Wave energy concepts - Self-reacting point absorber

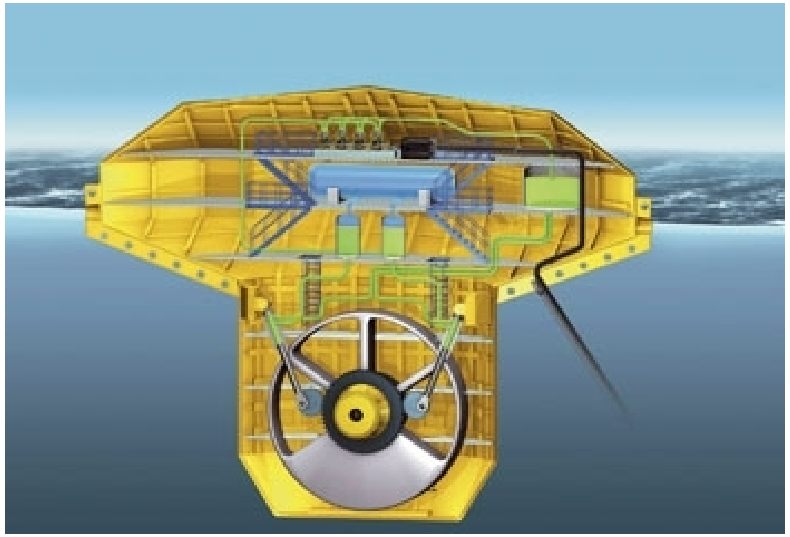


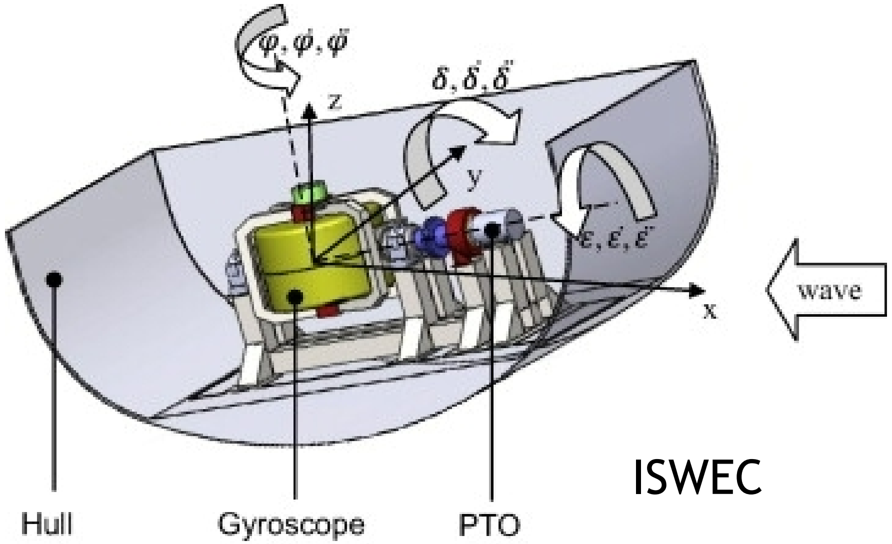




Wave energy concepts - Self-reacting wave energy converter with internal mass

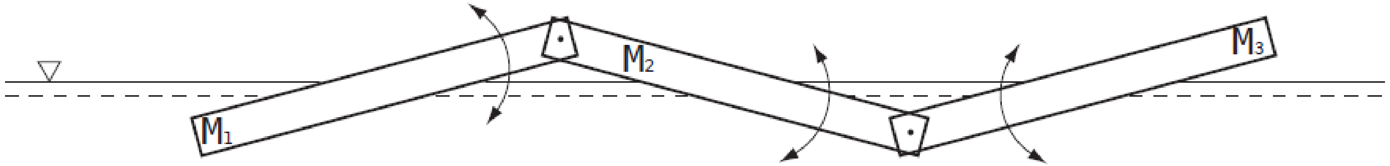






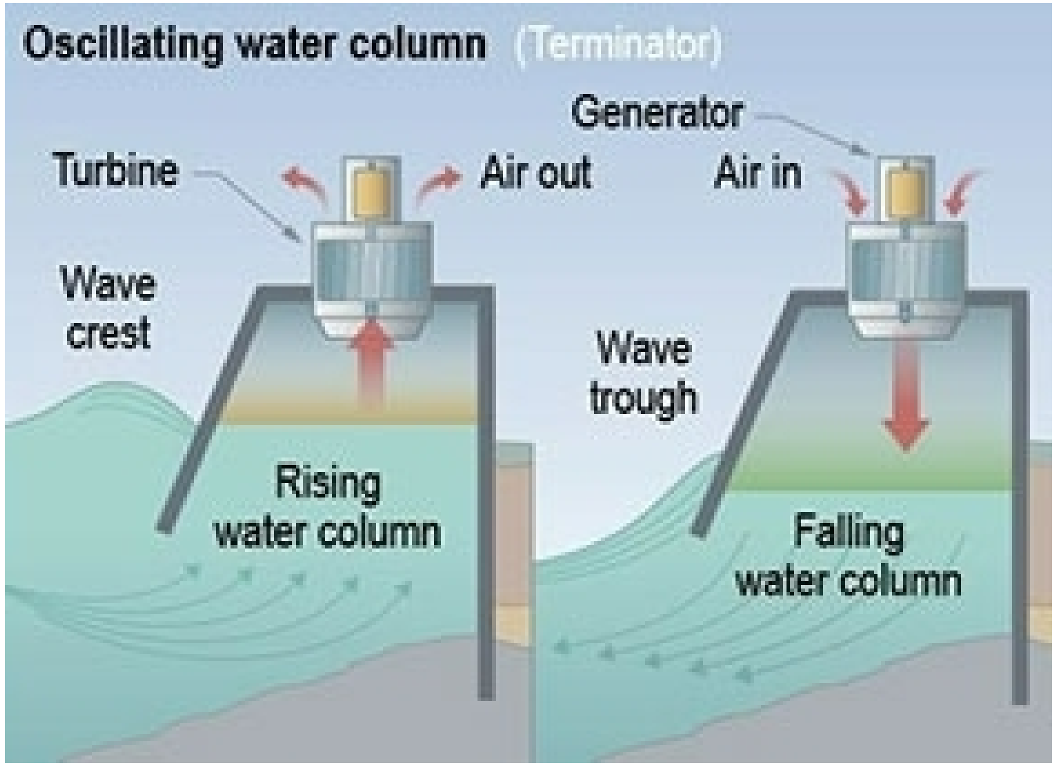
ISWEC

Wave energy concepts - attenuators



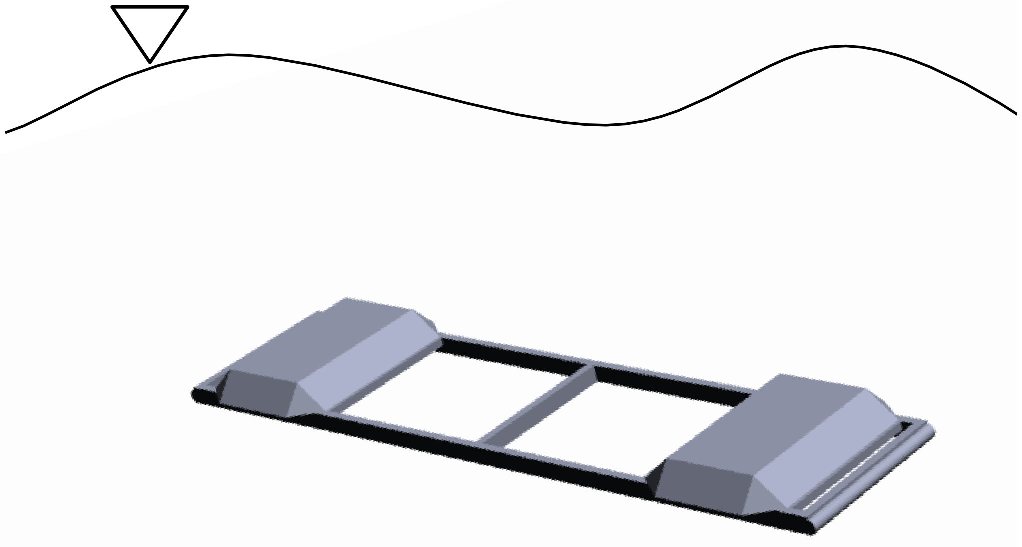
Pelamis wave energy

Wave energy concepts – oscillating water column (OWC)



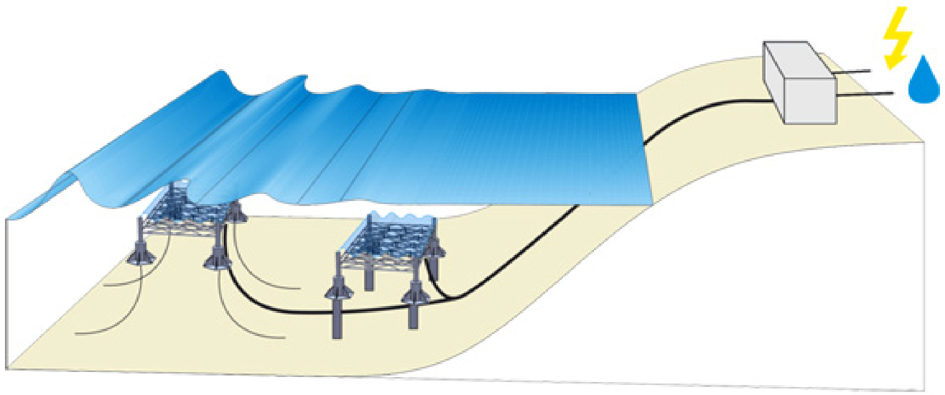
Wave energy concepts

Pressure differential devices



https://www.m3wave.com

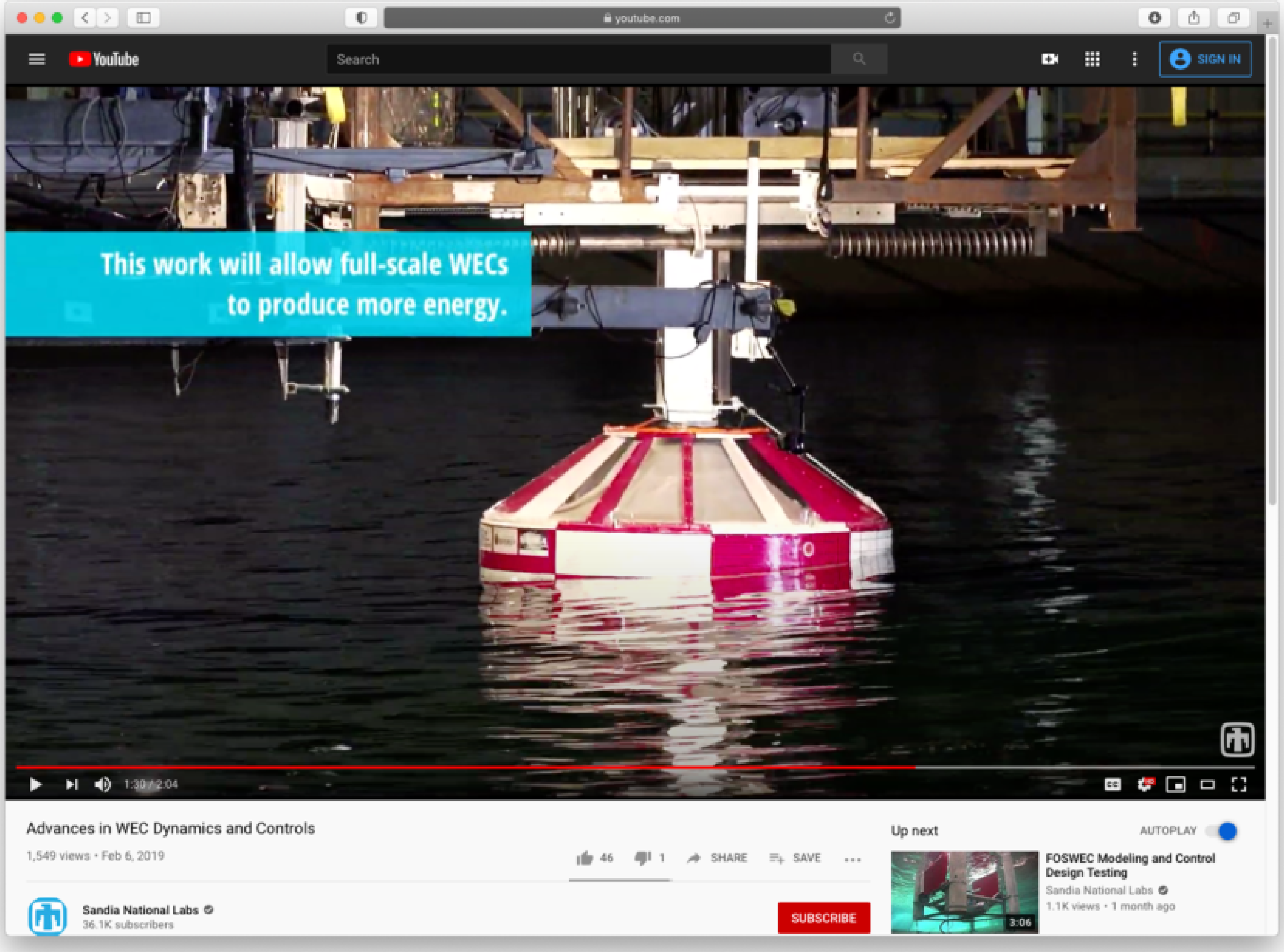
CalWave



http://calwave.org

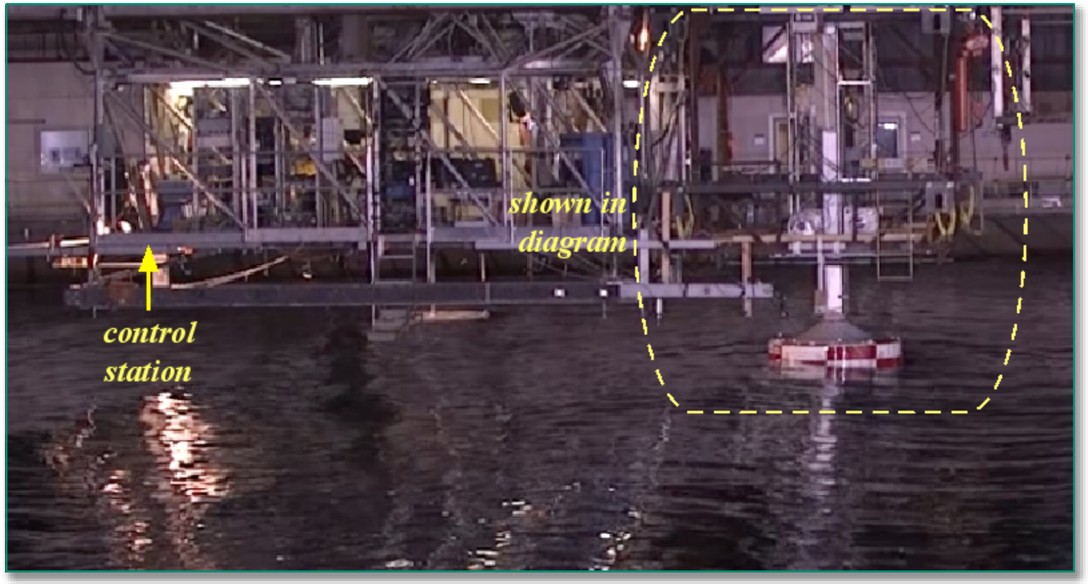
Study device – *the "WaveBot"*

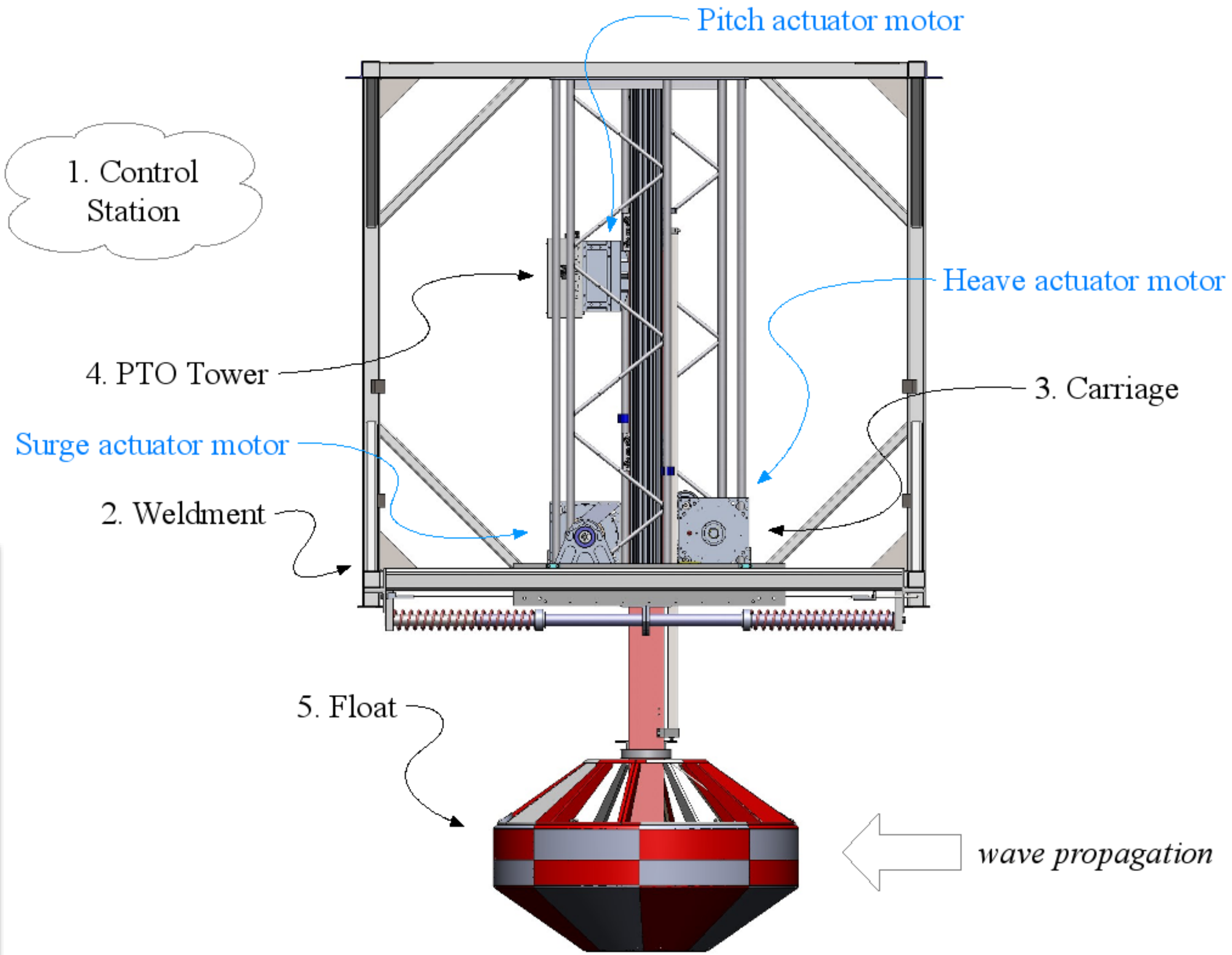
Parameter	Value
Displaced volume, $\forall$ [m^3]	0.858
Water density, ρ [kg/m^3]	1000
Inertia, heave [kg]	858
Inertia, surge [kg]	1420
Inertia, pitch [$kg\ m^2$]	84



https://youtu.be/c4npWk_-Pjk

Study device – *the "WaveBot" (cont.)*





Modeling a WEC

Resonance

Resonance is often something engineers try to avoid

Resonance

Resonance is often something engineers try to avoid

… but not always

How to make a swing resonate

Two key aspects:

1. ***Frequency*** $f = f_n$

2. ***Phase*** $\angle\left\{\frac{U}{F}\right\} = 0$

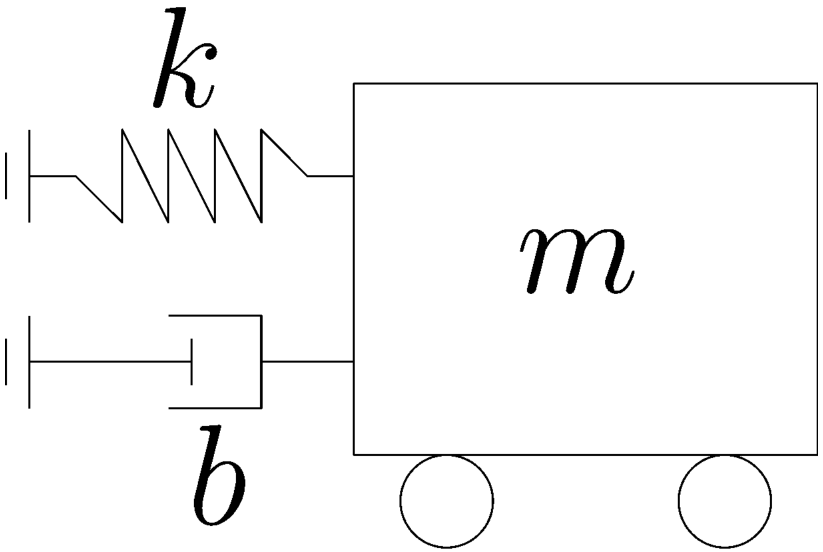
Resonance

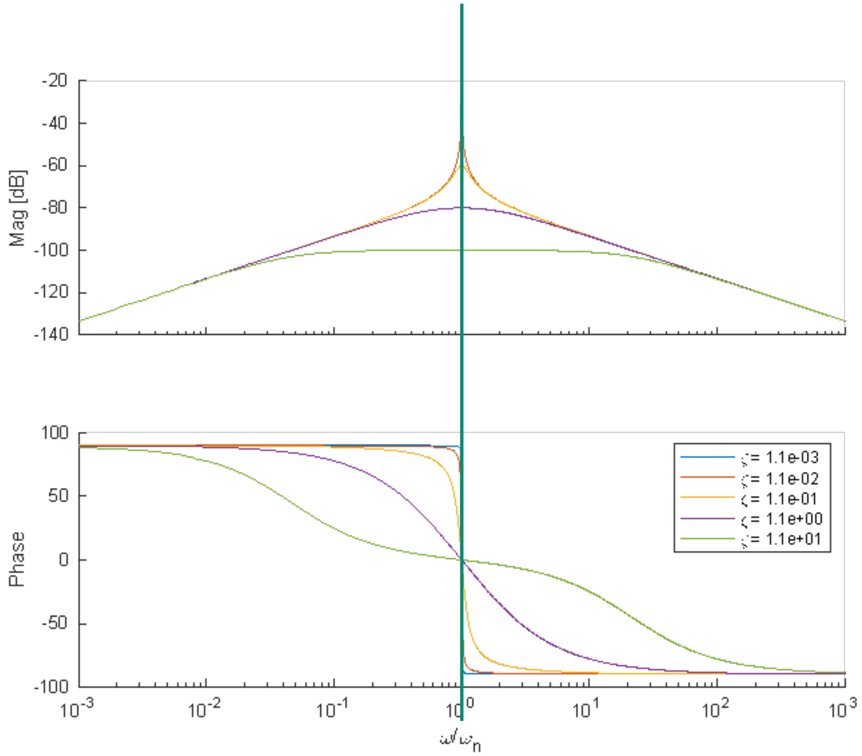
How do we define it?

$$\text{Natural frequency: } \omega_n = \sqrt{\frac{k}{m}}$$

stiffness

inertia

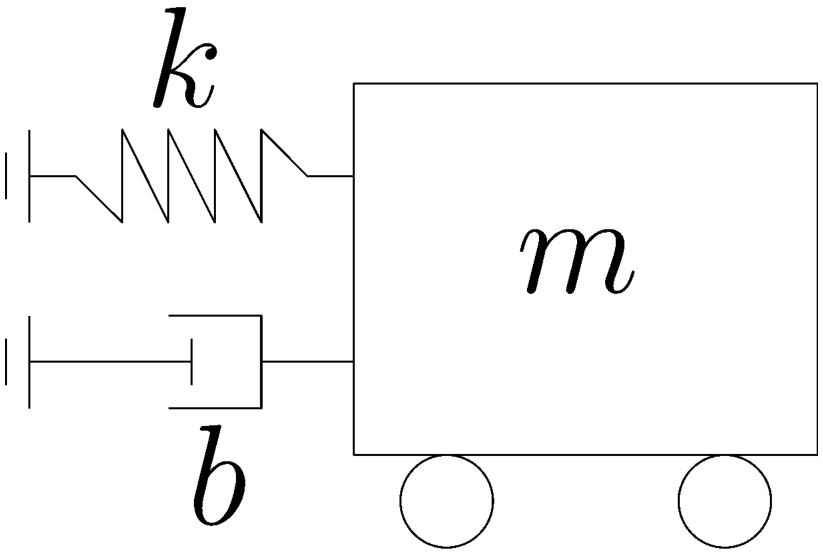


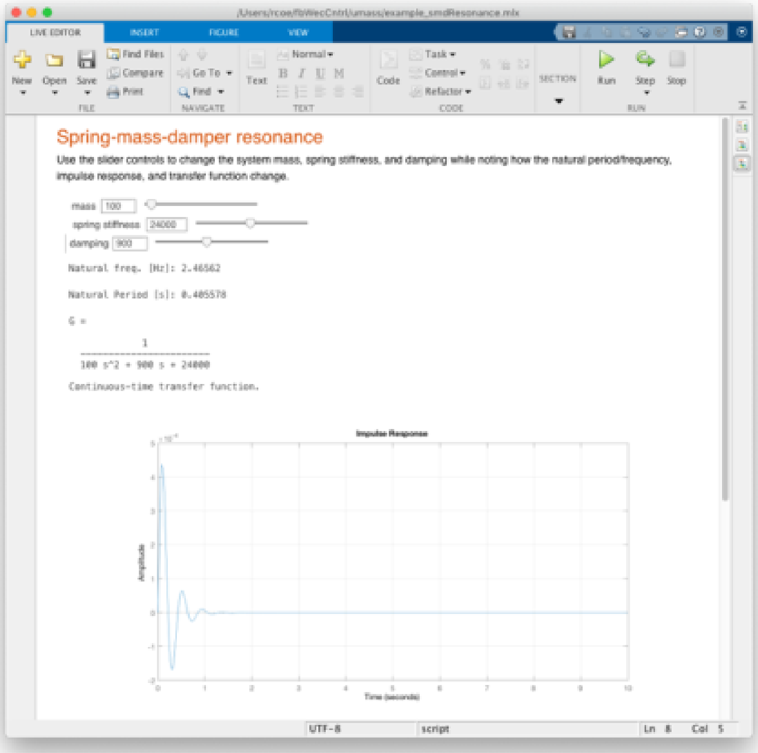


Resonance

How do we define it?

$$\text{Natural frequency: } \omega_n = \sqrt{\frac{k}{m}}$$





example_smdResonance.mlx

Impedance

What is impedance?

Tells us: "How does a structure respond to a force?"

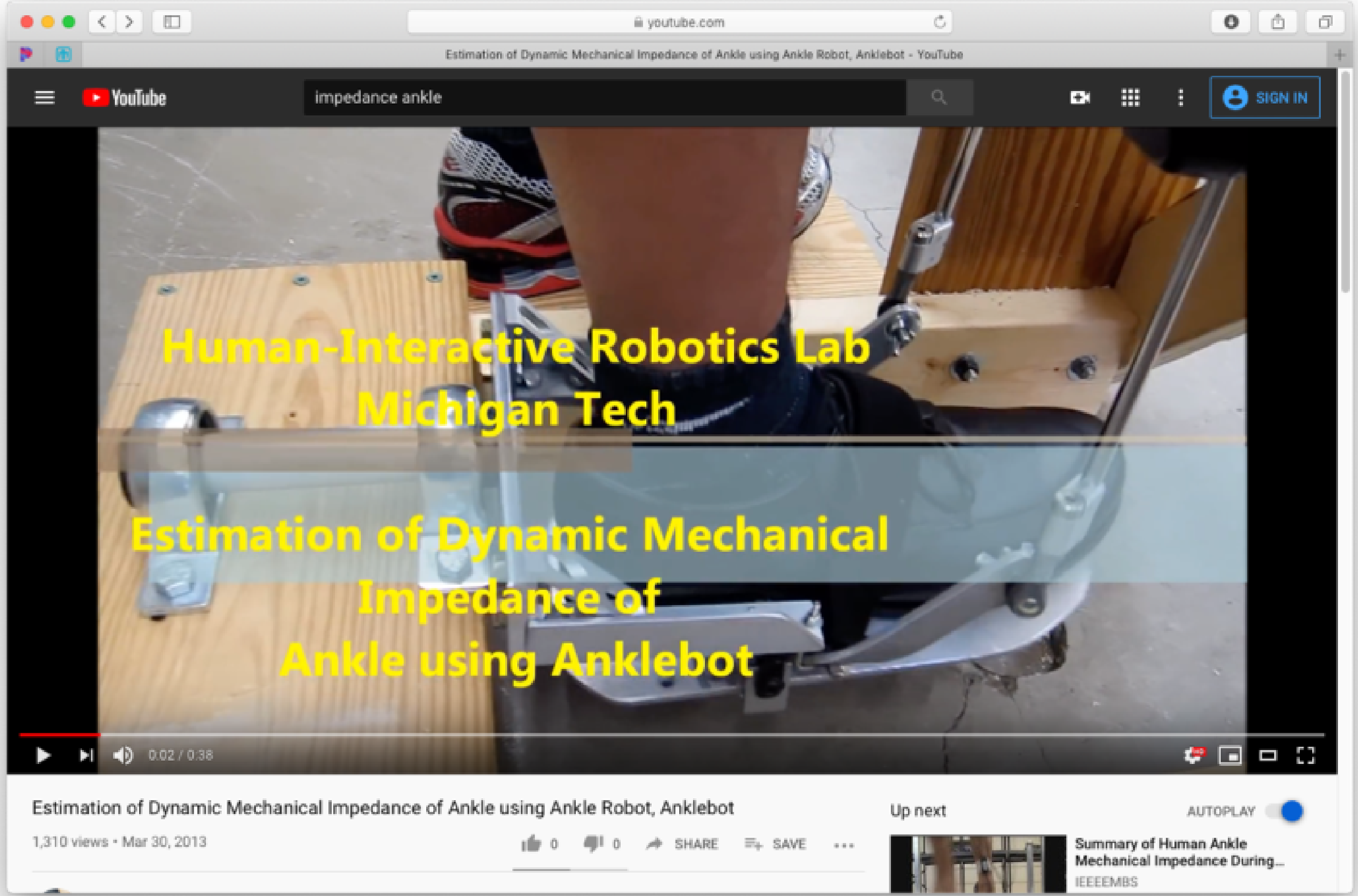
$$F(\omega) = \boxed{Z(\omega)} v(\omega)$$

Units?

$$Z = \frac{\text{``}potential\text{''}}{\text{``}flow\text{''}} \quad \text{e.g.,} \left[\frac{N}{m/s}\right] \text{ or } \left[\frac{V}{A}\right]$$

Impedance

Isn't this just for electrical engineers?



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

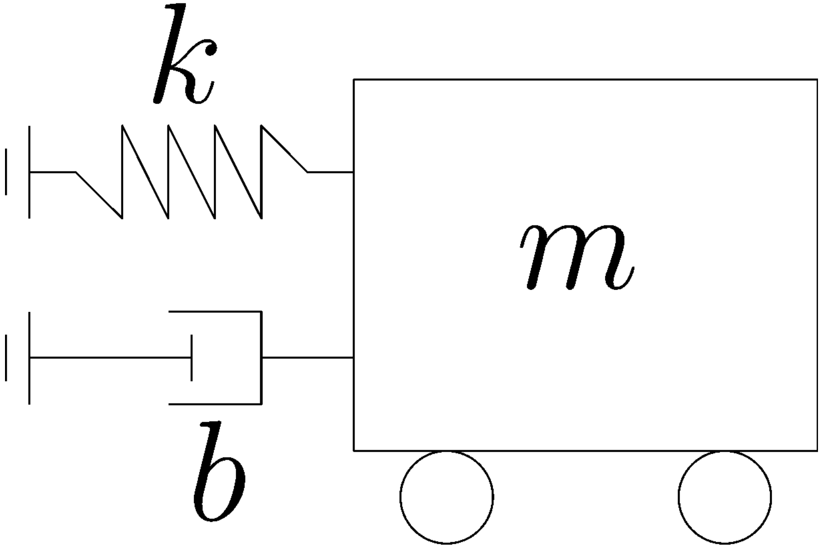
Spring-mass-damper

$$m\ddot{x} + b\dot{x} + kx = F_e$$

$$x(t) = \mathcal{R}\left\{\hat{x}e^{i\omega t}\right\}$$

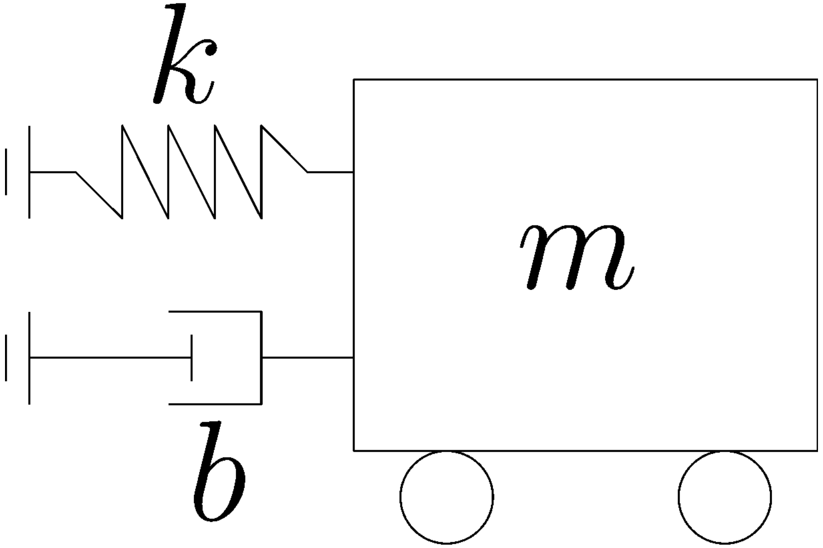
$$Z = b + i\left(\omega m - \frac{k}{\omega}\right)$$

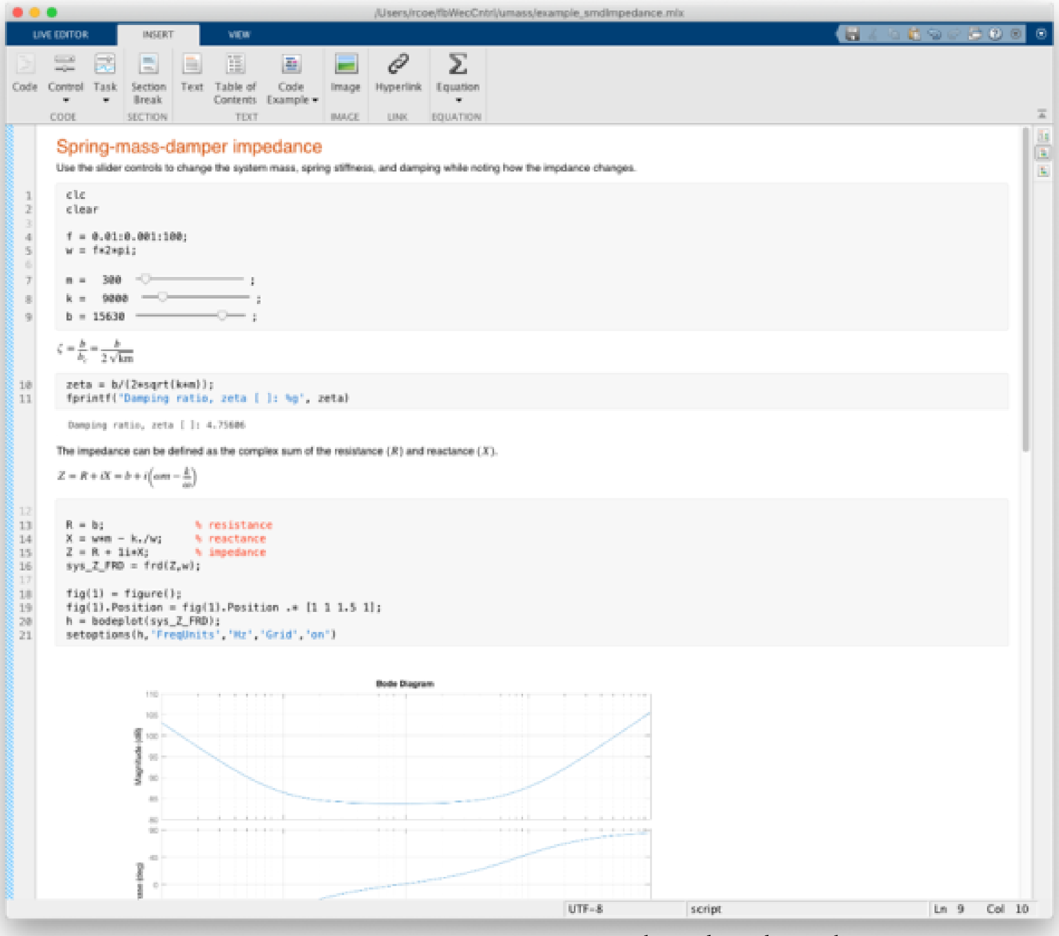
$$\hat{u} = \frac{\hat{F}_e}{Z}$$



Spring-mass-damper (cont.)

$$Z = b + i\left(\omega m - \frac{k}{\omega}\right)$$





example_smdImpedance.mlx

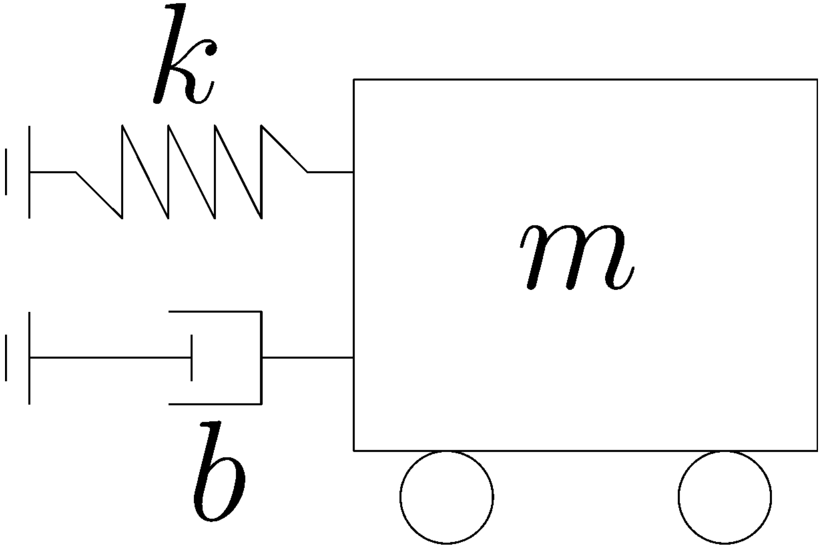
How do we define resonance?

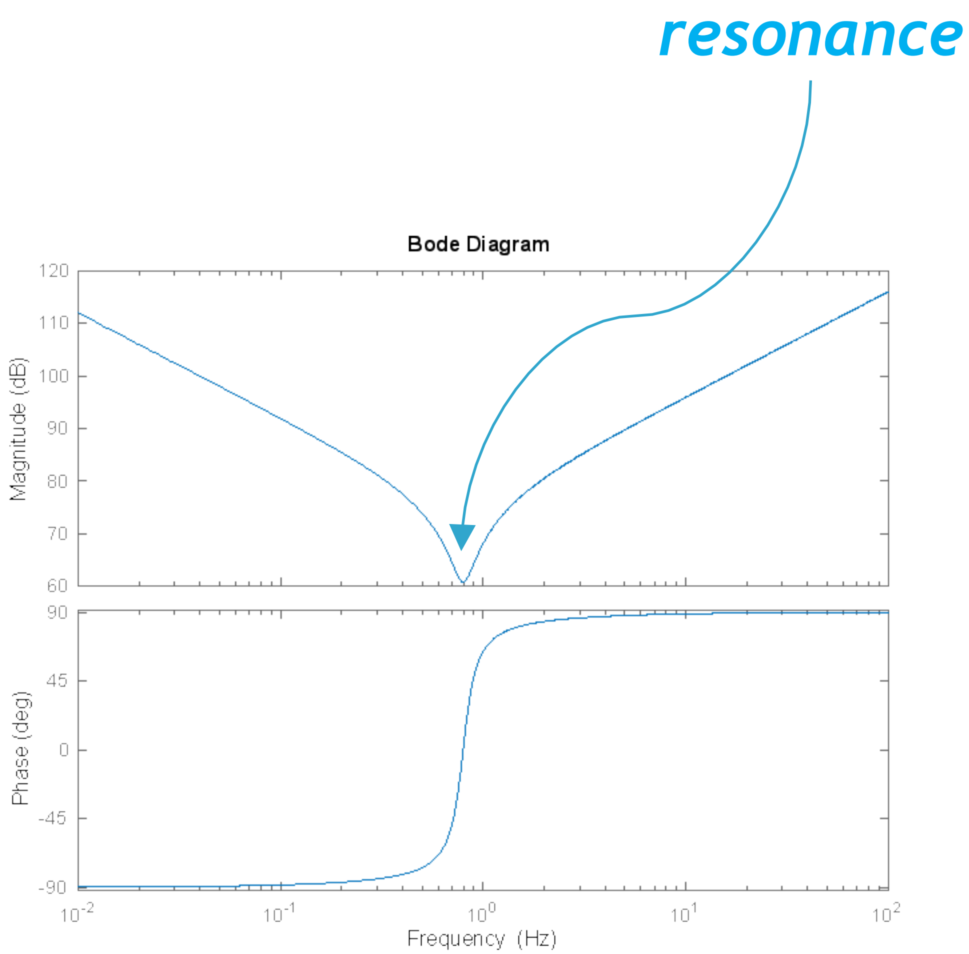
$$Z = b + i\left(\omega m - \frac{k}{\omega}\right)$$

$$\angle\left[\frac{F}{u}\right] = 0$$

$$\angle\left[Z\right] = 0$$

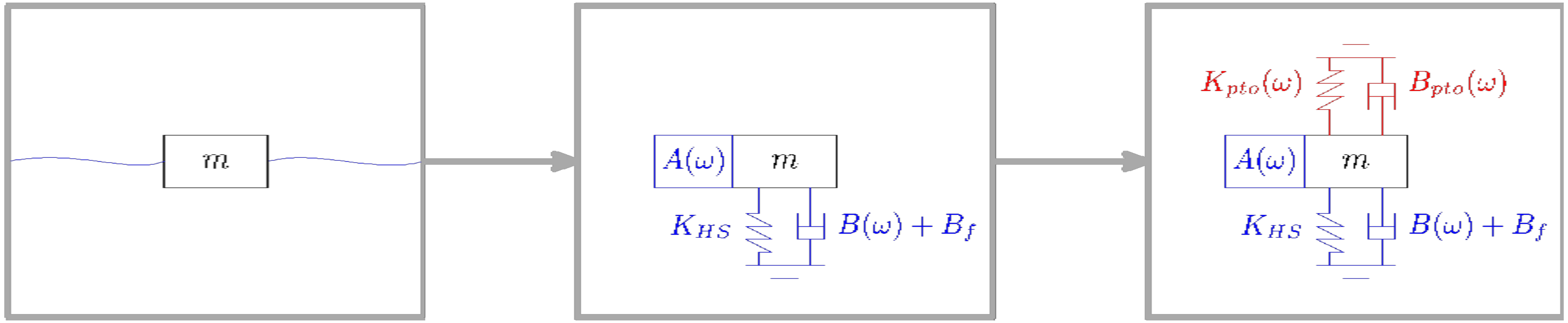
$$\Im\left\{Z\right\} = 0$$





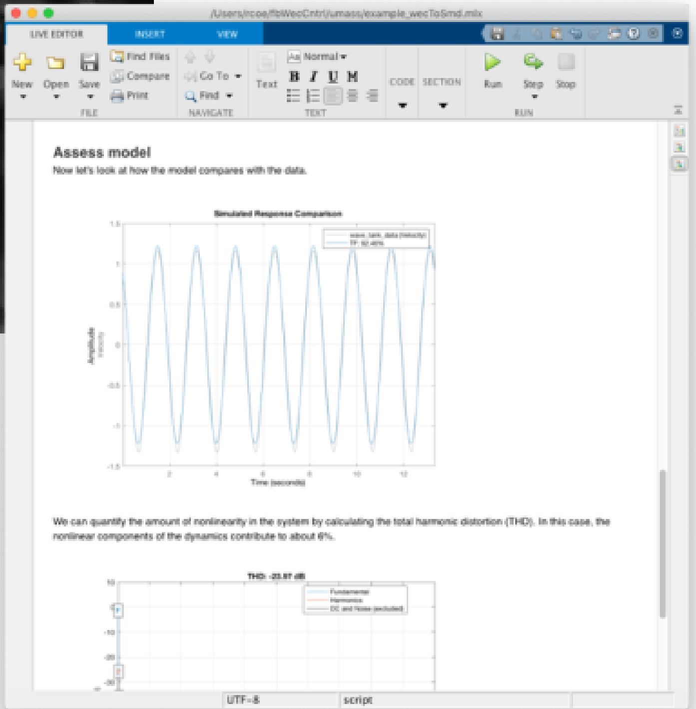
WEC to spring-mass-damper

This framework is powerful, practical, and realistic



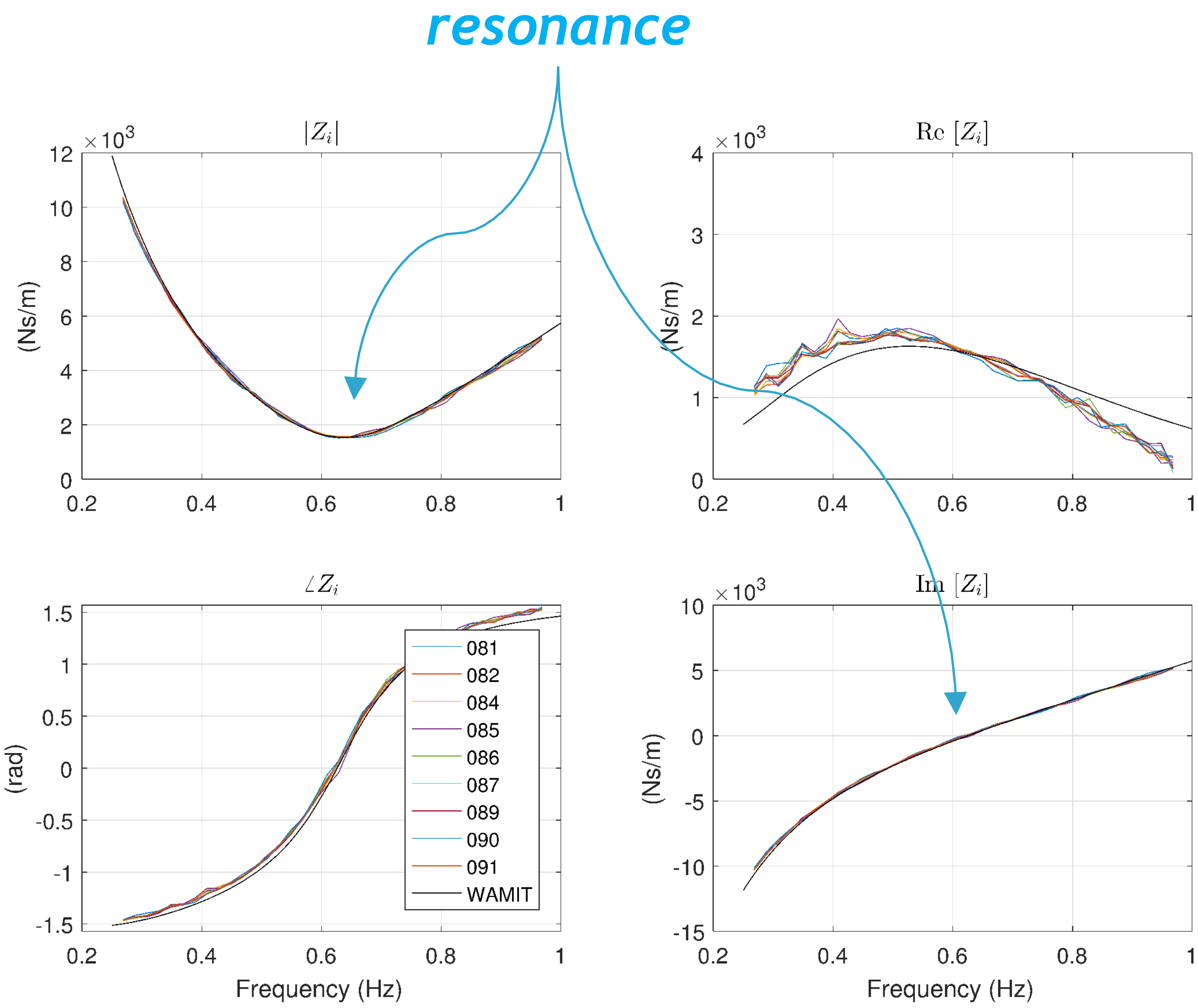
WEC to spring-mass-damper

How realistic can a spring-mass-damper model be?



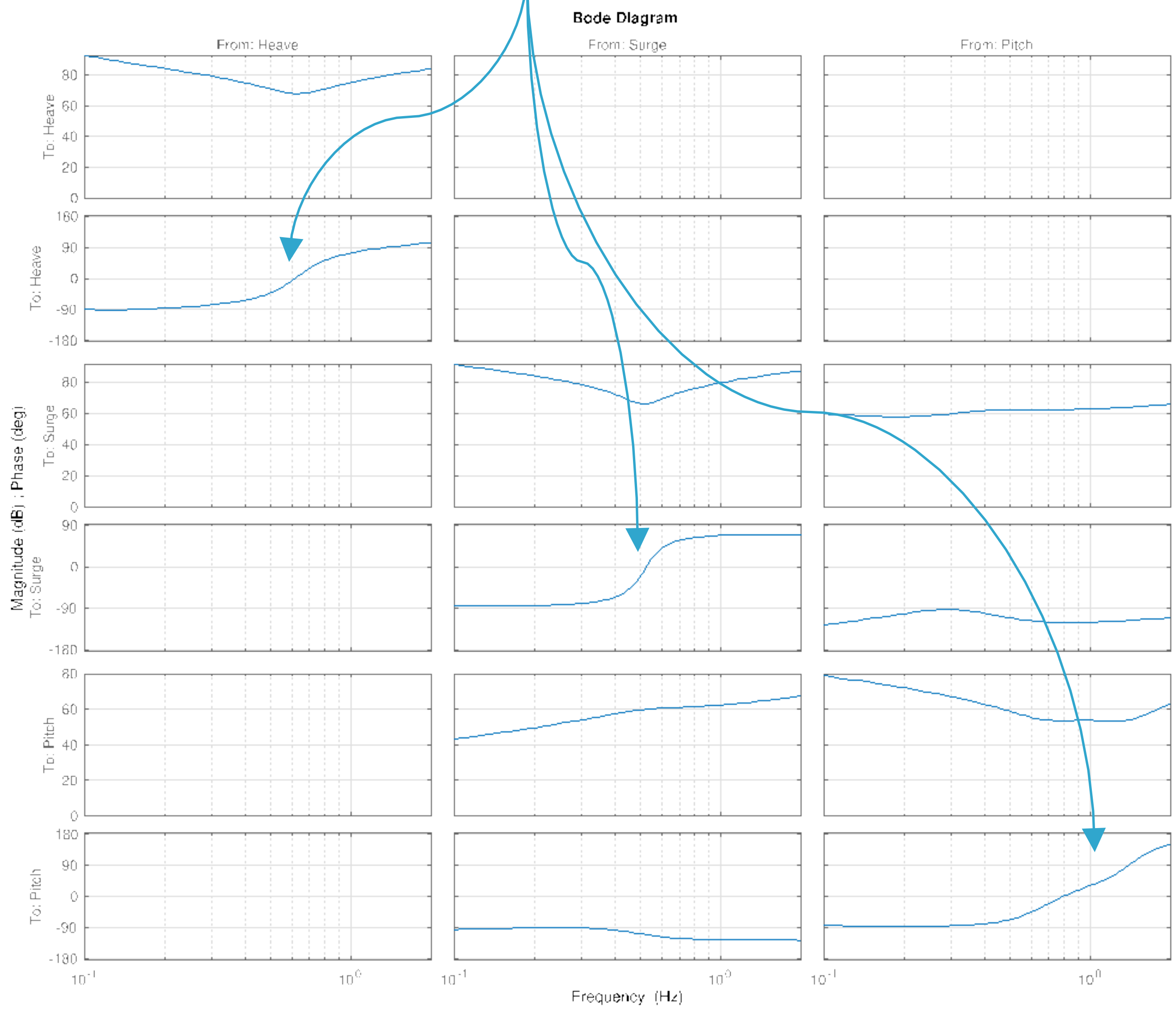
example_wecToSmd.mlx

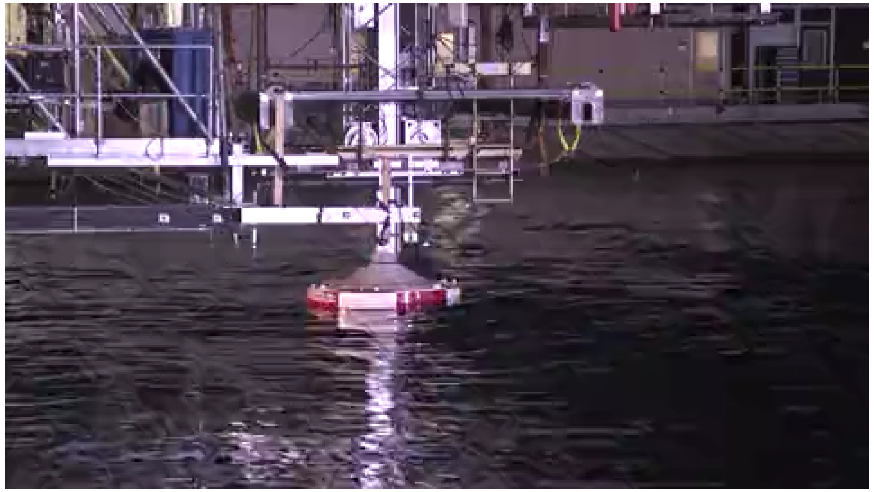
What does an impedance look like?



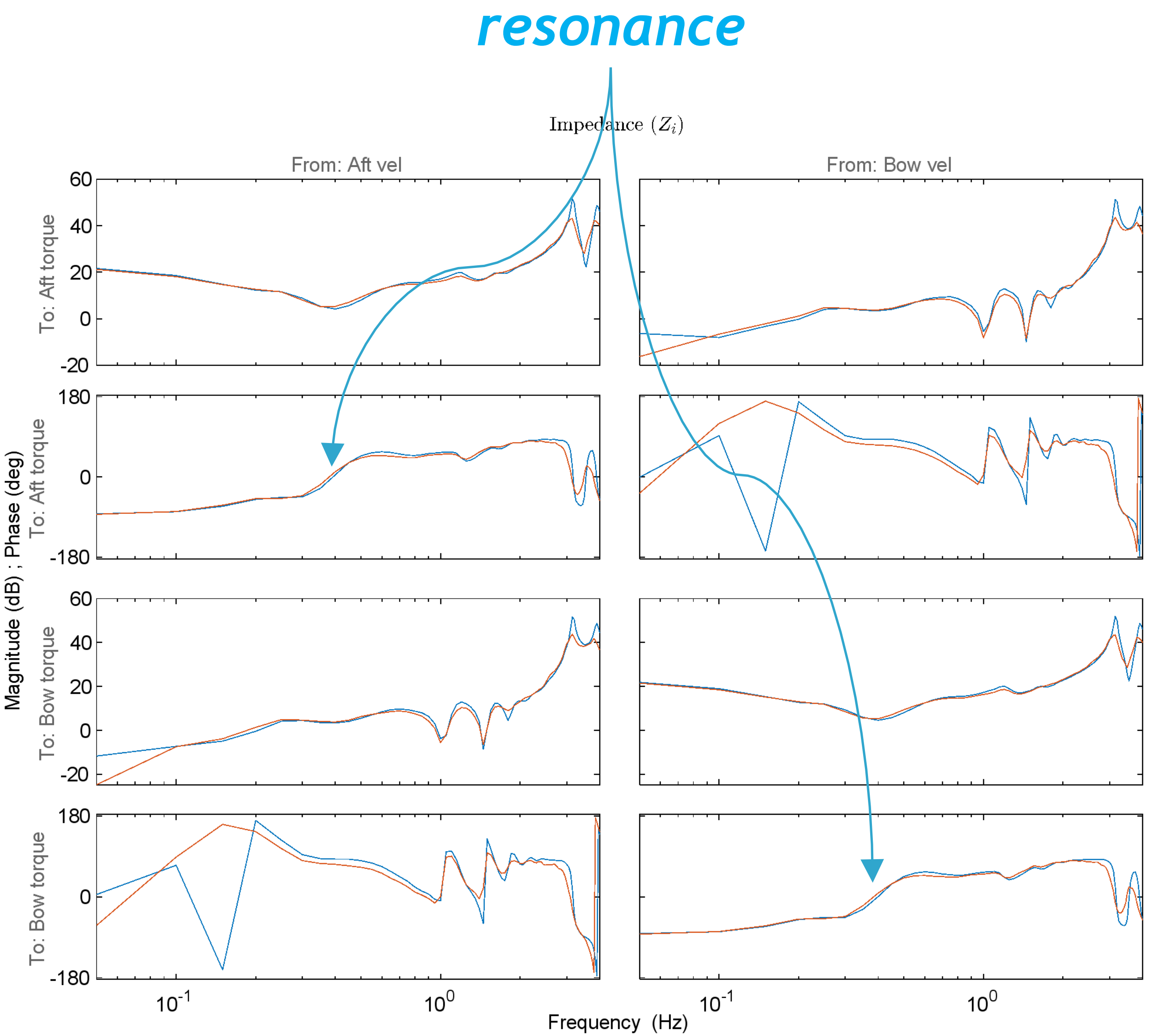
What does an impedance look like?

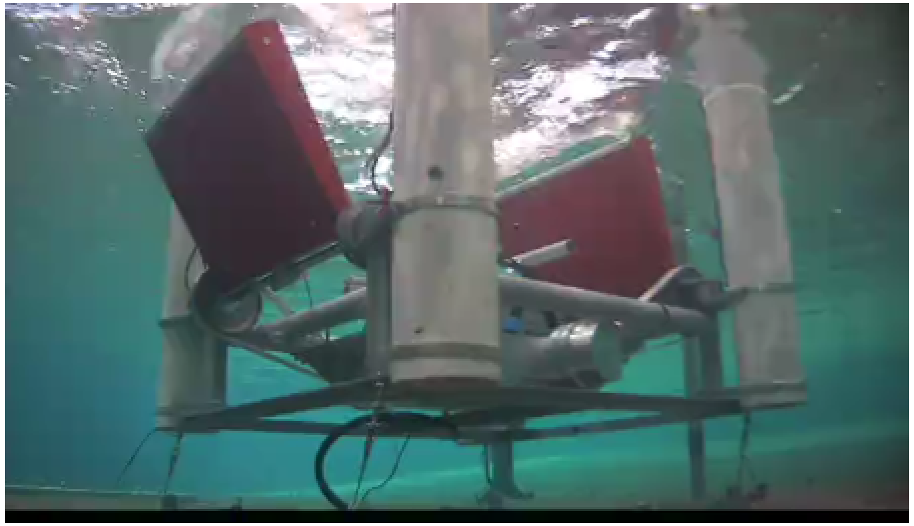
resonance





What does an impedance look like?



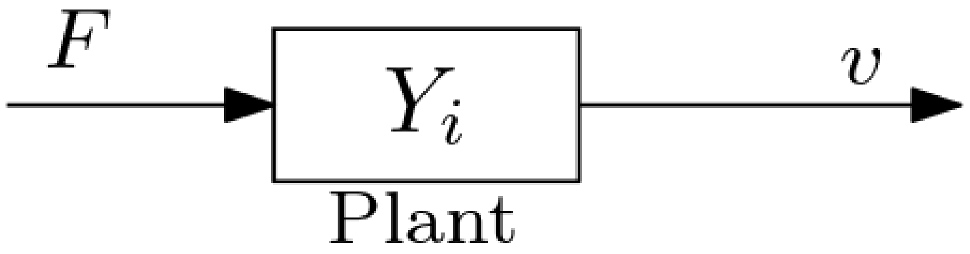


Admittance

What is admittance?

$$Y(\omega) = \frac{1}{Z(\omega)}$$

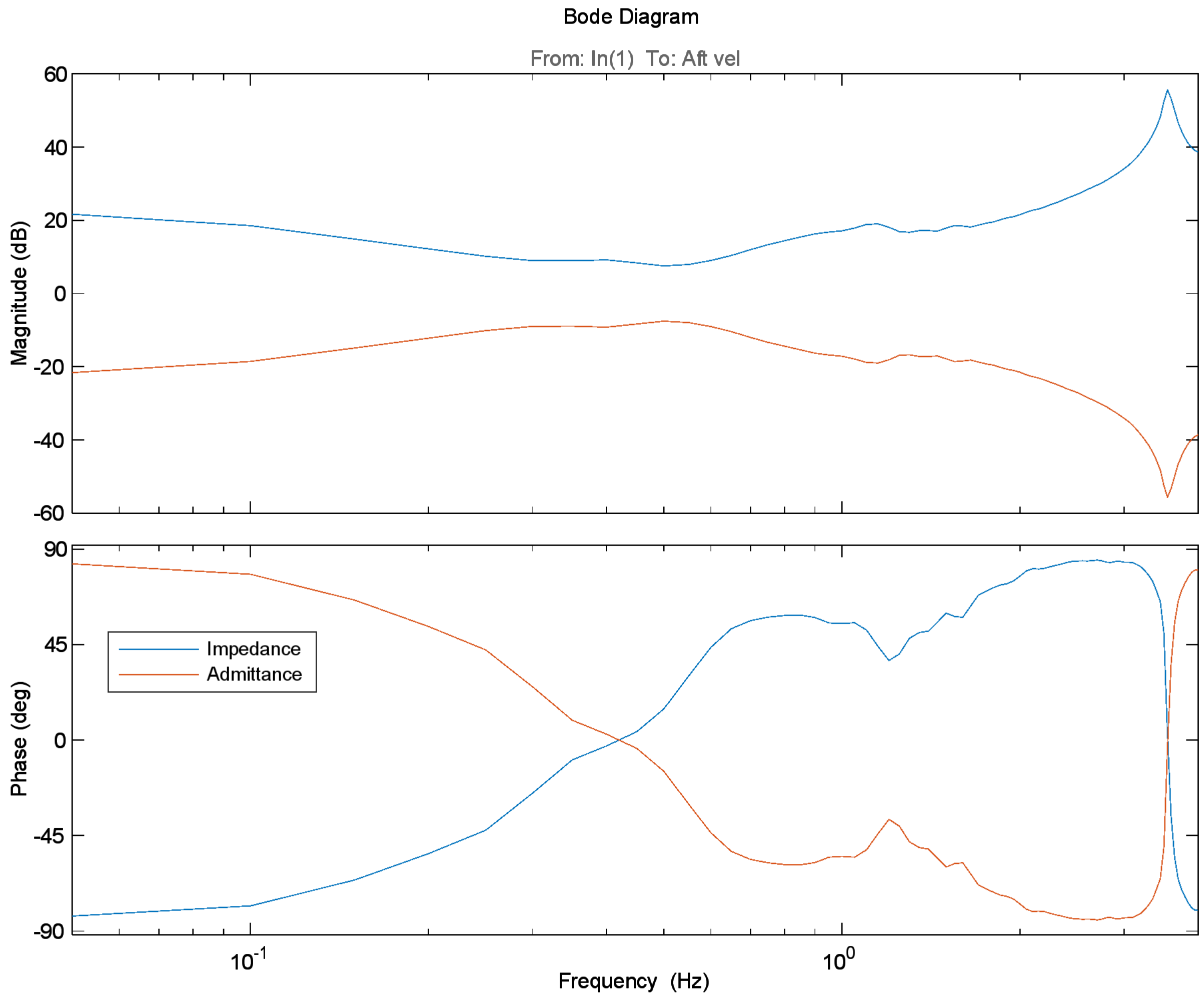
$$v(\omega) = \frac{F(\omega)}{Z(\omega)} = F(\omega)Y(\omega)$$



Admittance

What does it look like?

$$Y(\omega) = \frac{1}{Z(\omega)}$$



$$Z(\omega) = \frac{F(\omega)}{u(\omega)}$$

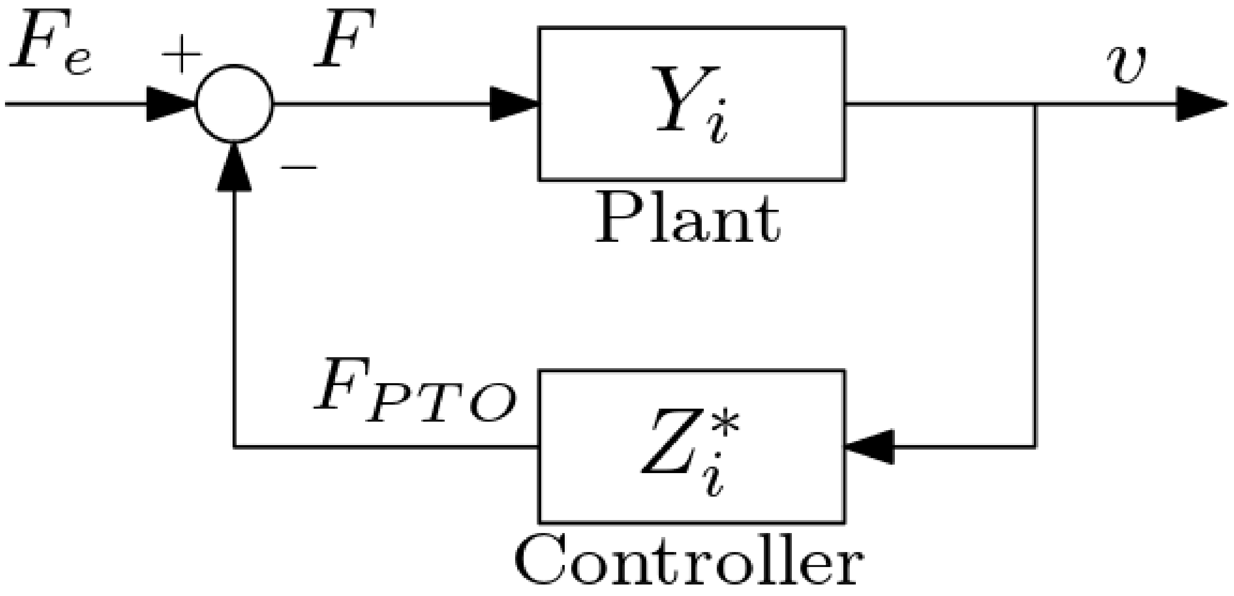
$$Y(\omega) = \frac{u(\omega)}{F(\omega)}$$

Impedance

and control

We can use the impedance (or admittance) to cleanly model a WEC

$$Z_i(\omega) = i\omega\underbrace{(M + m(\omega))}_{\text{mass}} + \underbrace{B_v + R(\omega)}_{\text{damping}} + \underbrace{\frac{S}{i\omega}}_{\text{stiffness}}$$

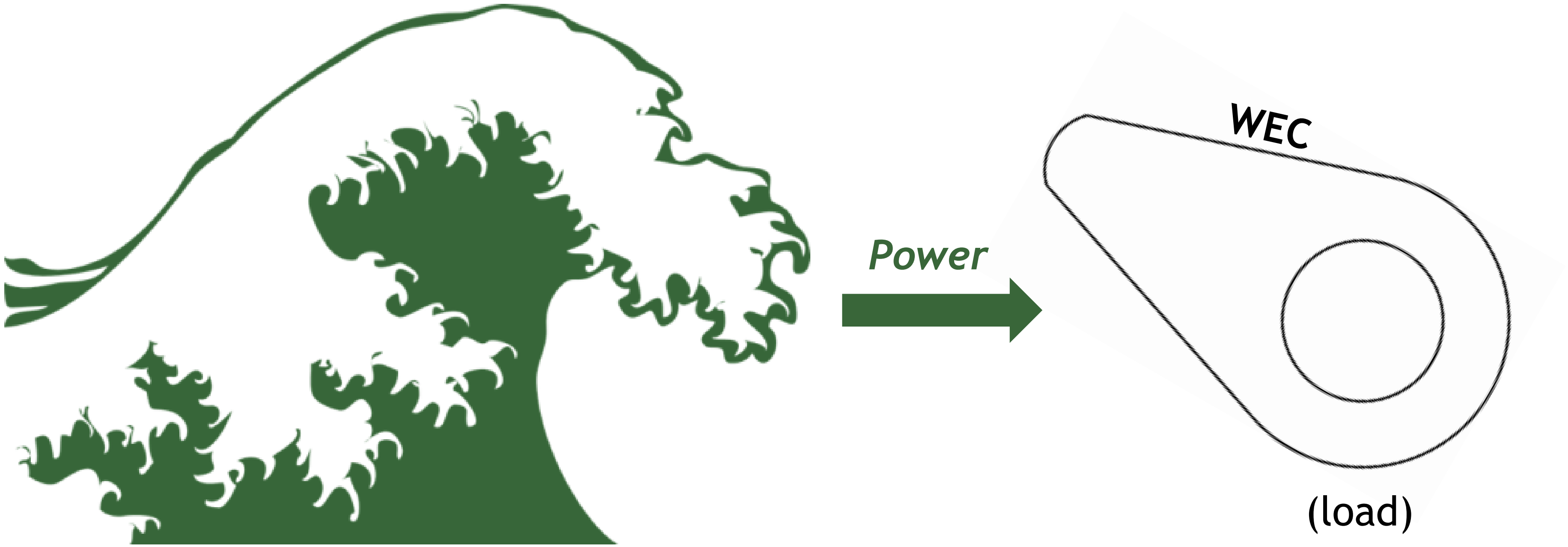


Controlling a WEC

Impedance matching

Maximum power transfer (from waves to PTO)

$$Z_{source} = Z_{load}^*$$

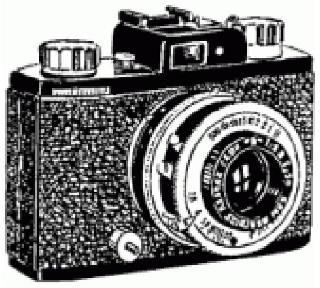


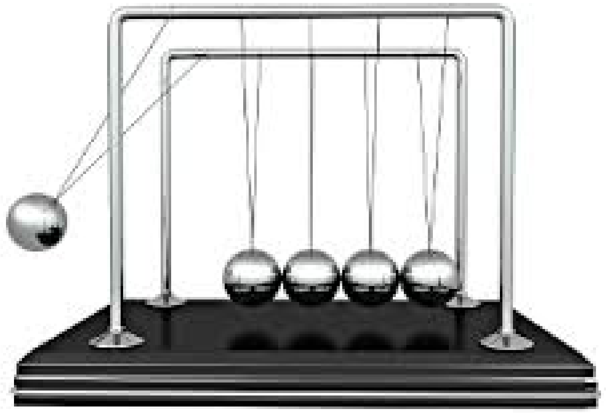
(source)

(load)

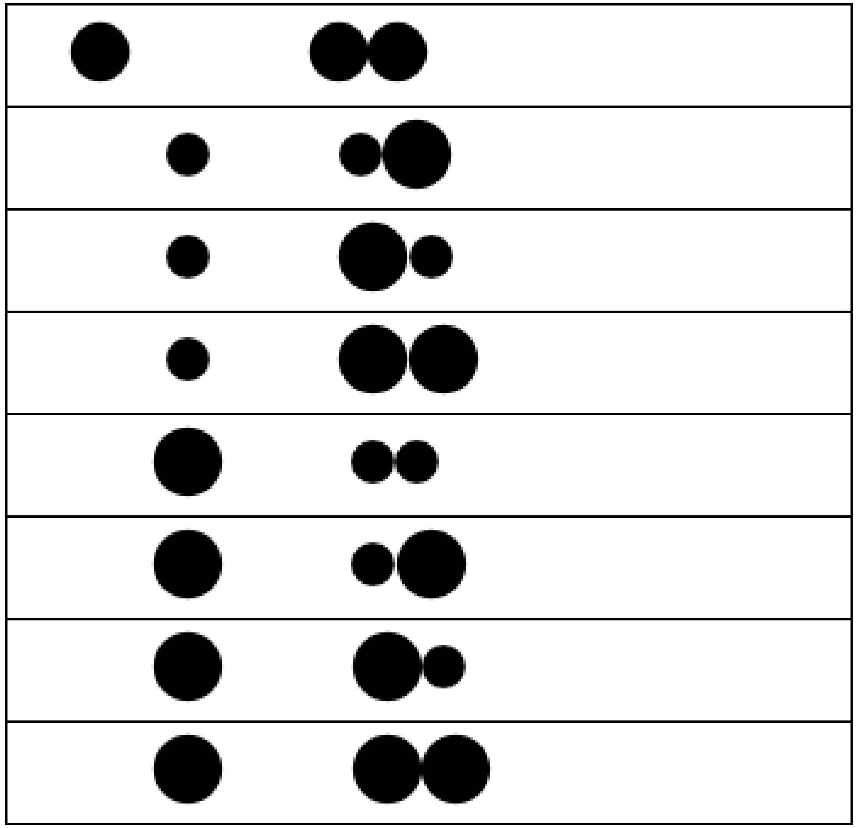
Impedance matching

Where else is this used?

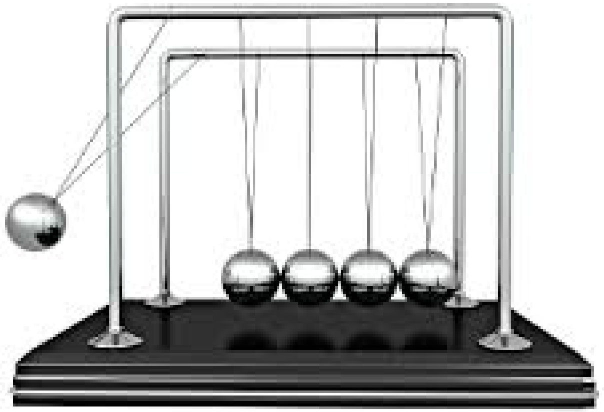




Impedance matching



http://www.lockhaven.edu/~dsimanek



Describing a WEC controller

$$Z_i(\omega) = i\omega(\underbrace{M + m(\omega)}_{\text{mass}}) + \underbrace{B_v + R(\omega)}_{\text{damping}} + \underbrace{\frac{S}{i\omega}}_{\text{stiffness}}$$

$$\begin{aligned} F_u(\omega) &= f(v(\omega)) \\ &= -Z_u(\omega)v(\omega) \end{aligned}$$

Impedance matching

Maximum power transfer (from waves to PTO)

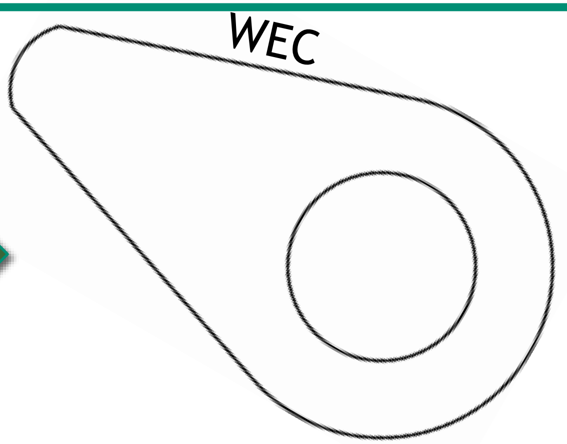
$$Z_{source} = Z_{load}^*$$

$$Z_i = Z_u^* \quad \rightarrow (Z_i^* = Z_u)$$

$$F_{pto}(\omega) = -Z_i^*(\omega) v(\omega)$$

(source)

Power



(load)

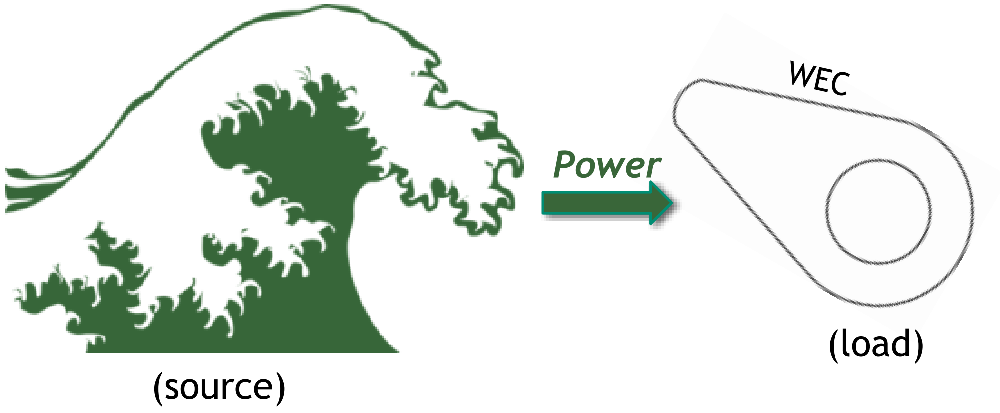
Impedance matching (cont.)

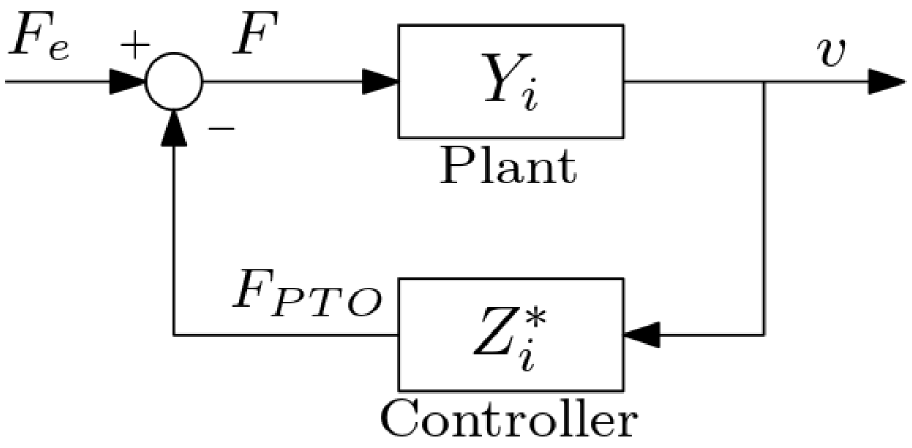
Maximum power transfer (from waves to PTO)

$$Z_{source} = Z_{load}^*$$

$$Z_i = Z_u^* \quad \rightarrow (Z_i^* = Z_u)$$

$$\Rightarrow F_{pto}(\omega) = -Z_i^*(\omega)v(\omega)$$





“WEC control hierarchy"

Intrinsic impedance

$Z_i(\omega)$

↓

Complex conjugate

$Z_i^*(\omega)$

↓

Real and imaginary parts

$\Re\{Z_i^*(\omega)\}$ $\Im\{Z_i^*(\omega)\}$

↓

Causal realization

$$K_p(\omega) = \Re\{Z_i^*(\omega)\}$$

$$\begin{aligned} K_I(\omega) &= \omega\,\Im\{Z_i^*(\omega)\} \\ &= -\omega\,\Im\{Z_i(\omega)\} \\ &= -\omega^2(M + m(\omega)) + S. \end{aligned}$$

Causal realization

While perfectly implementing impedance matching in a causal controllers is not possible, we can come quite close

derivative gain (K_D), **proportional gain** (K_P), **integral gain** (K_I), **high frequency pole** (p)

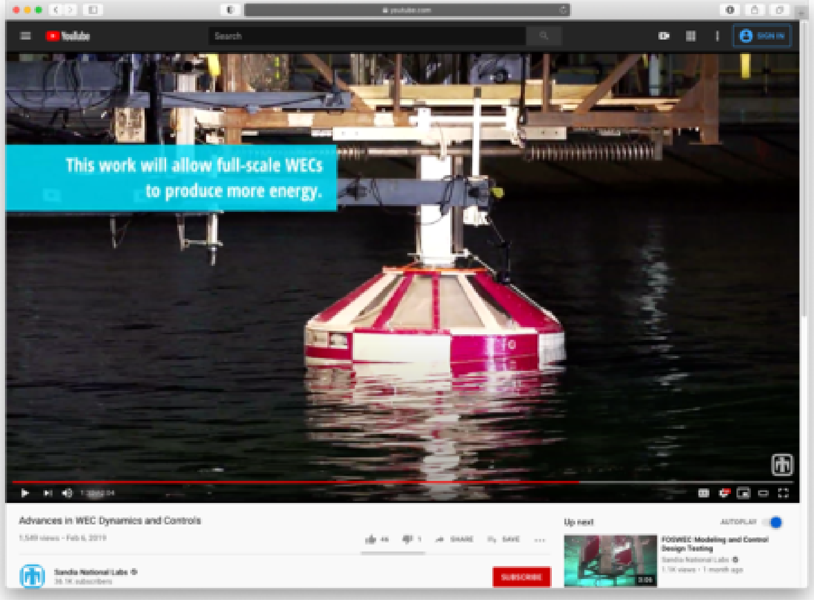
$$C_{PID}(s) = \frac{K_D s^2 + K_P s + K_I}{s} \frac{1}{s+p}$$

*most of us learn about “PID” in the context of error minimization, this is not really the intent here

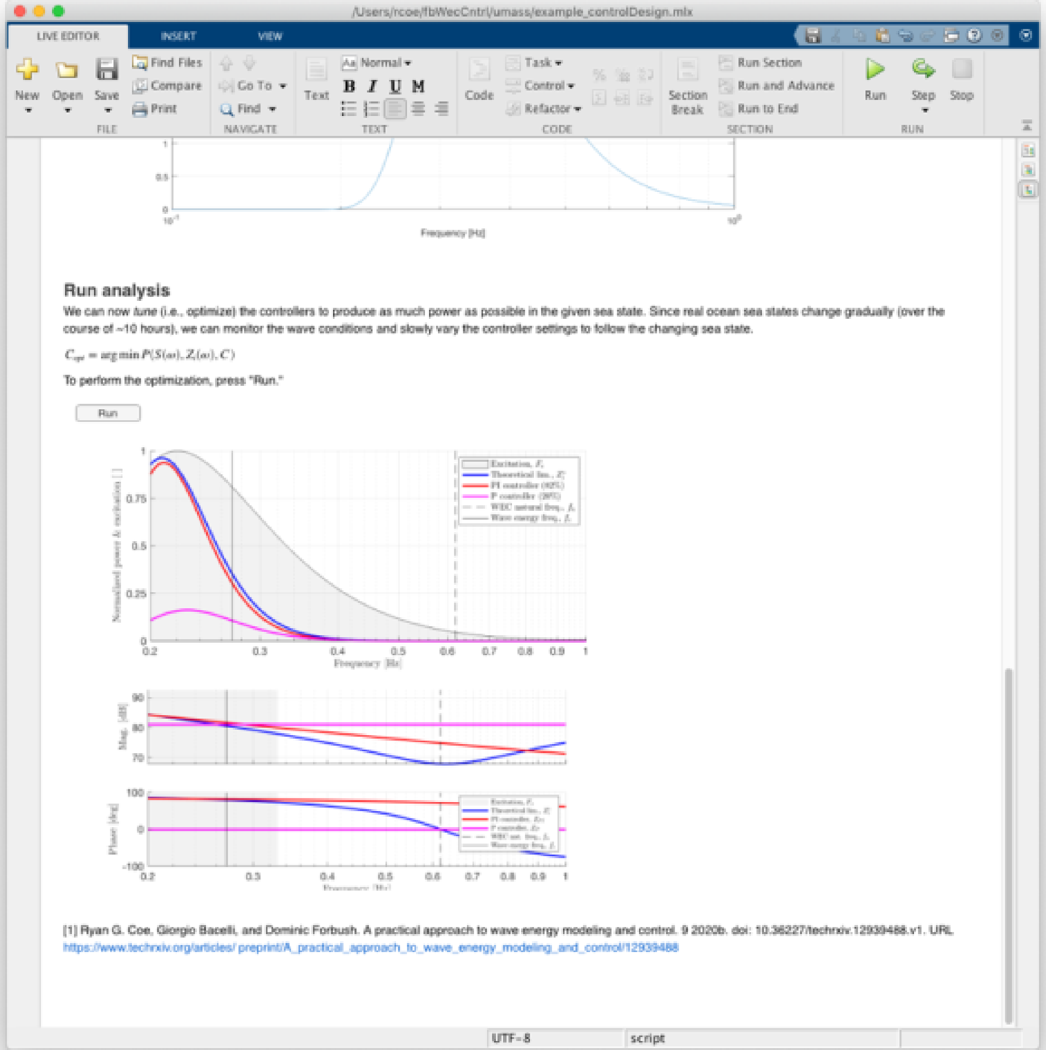
Example: Designing P and PI controllers for a WEC

$$C_{opt} = \arg\min P(S(\omega), Z_i(\omega), C)$$

Vary controller to maximize power



https://youtu.be/c4npWk_-Pjk



example_controlDesign.mlx