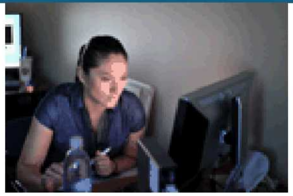
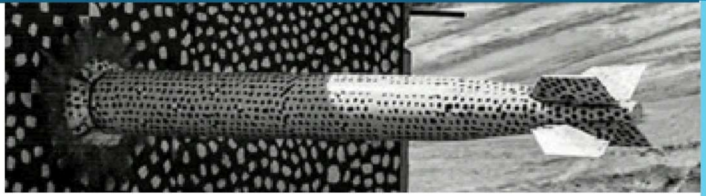
SAND2020-10043PE

WEC Co-design
September 2020 webinar



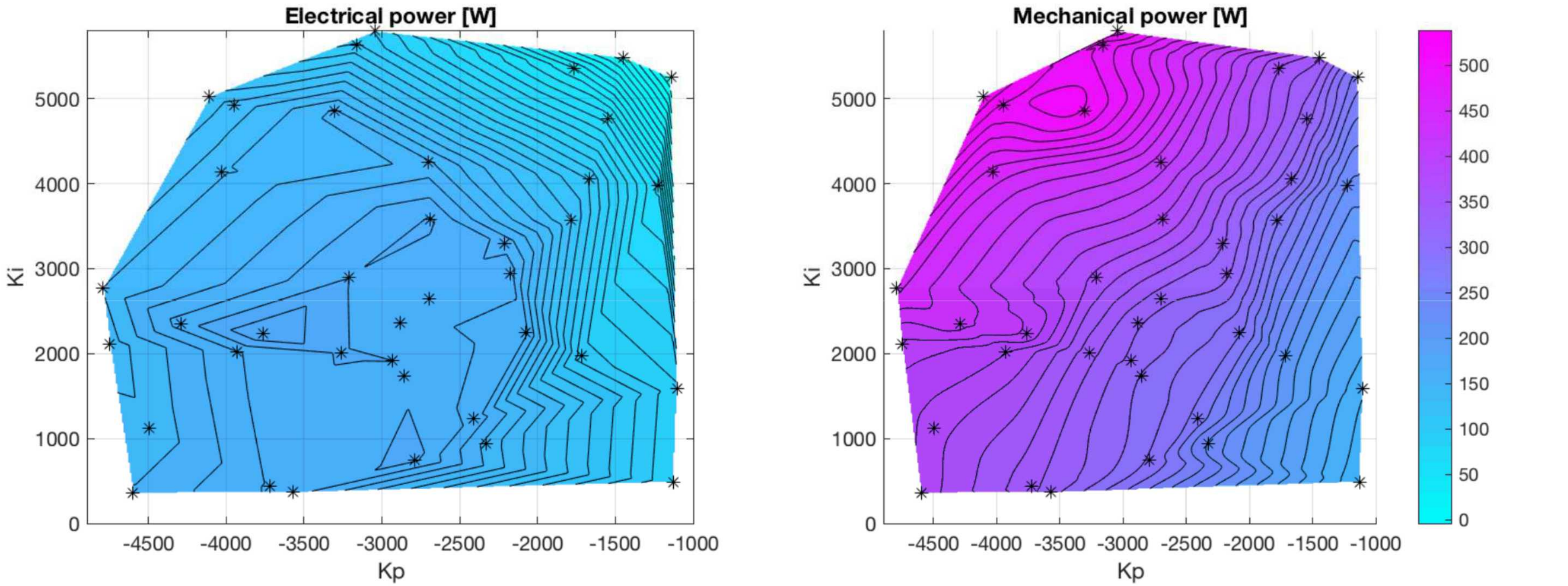


Presented by

Ryan Coe, Giorgio Bacelli, Dominic Forbush

Webinar agenda

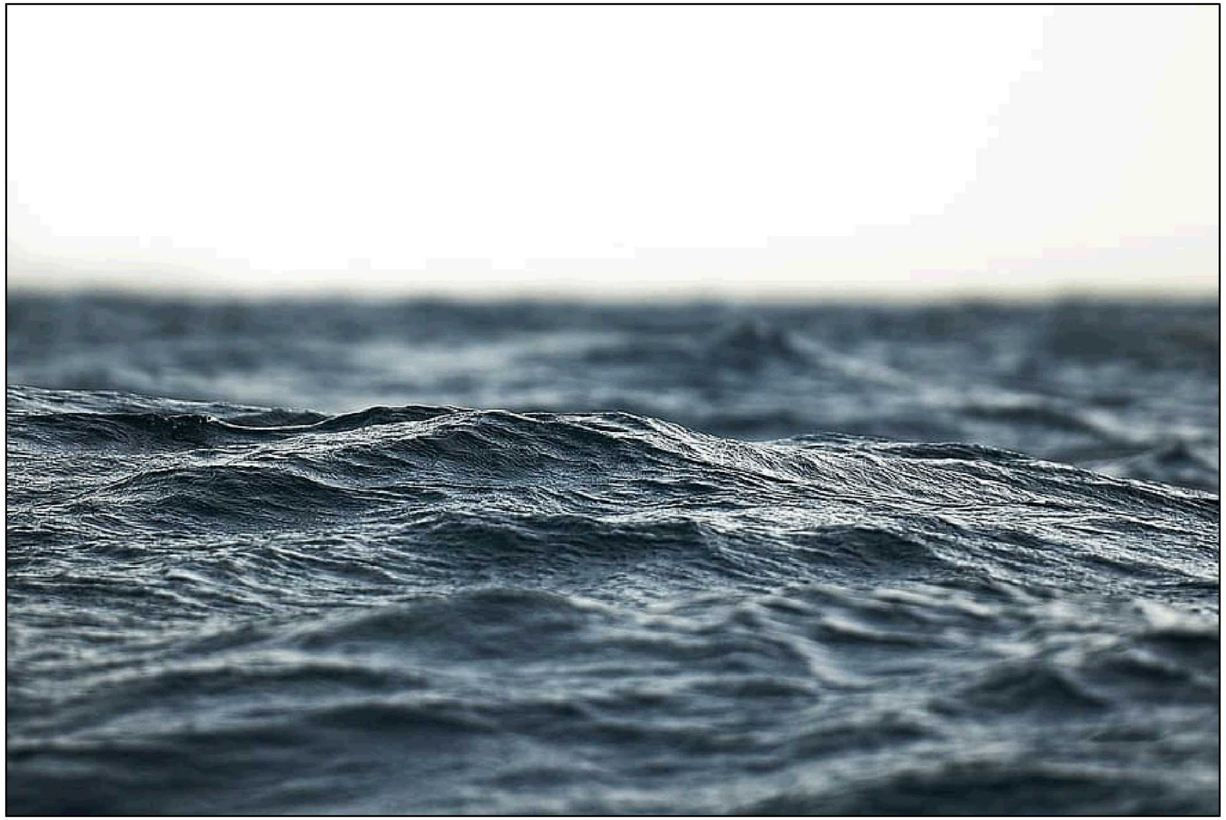
I. Background
II. Problem statement and approach
III. Examples in MATLAB



Background

Causal impedance matching approach

Why work in the frequency domain?



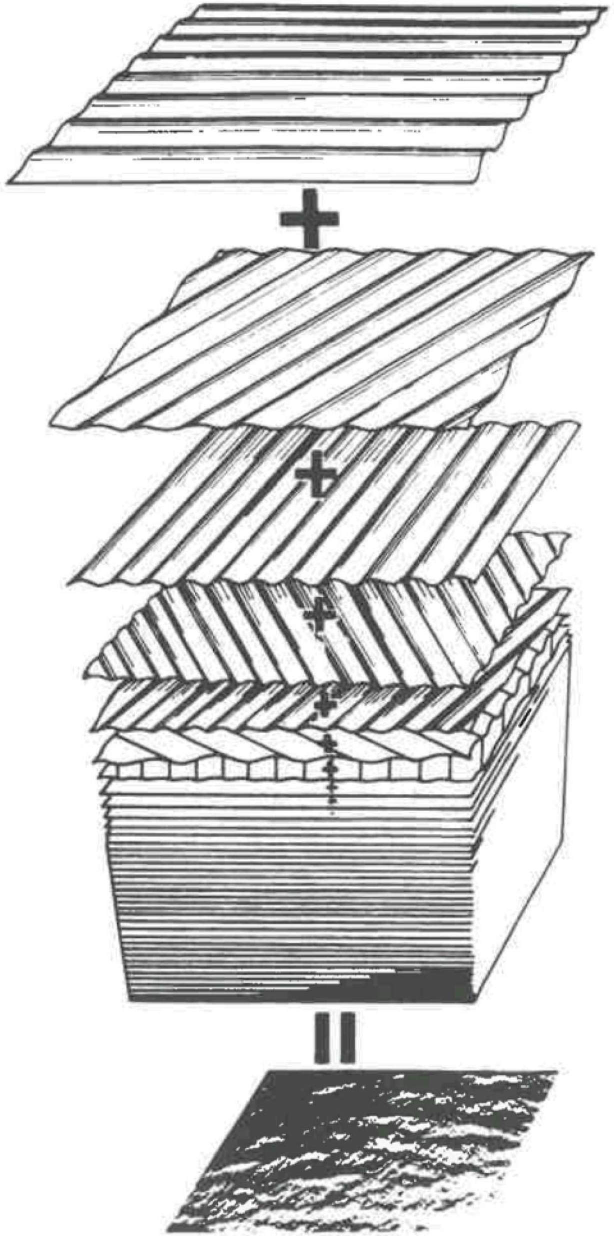
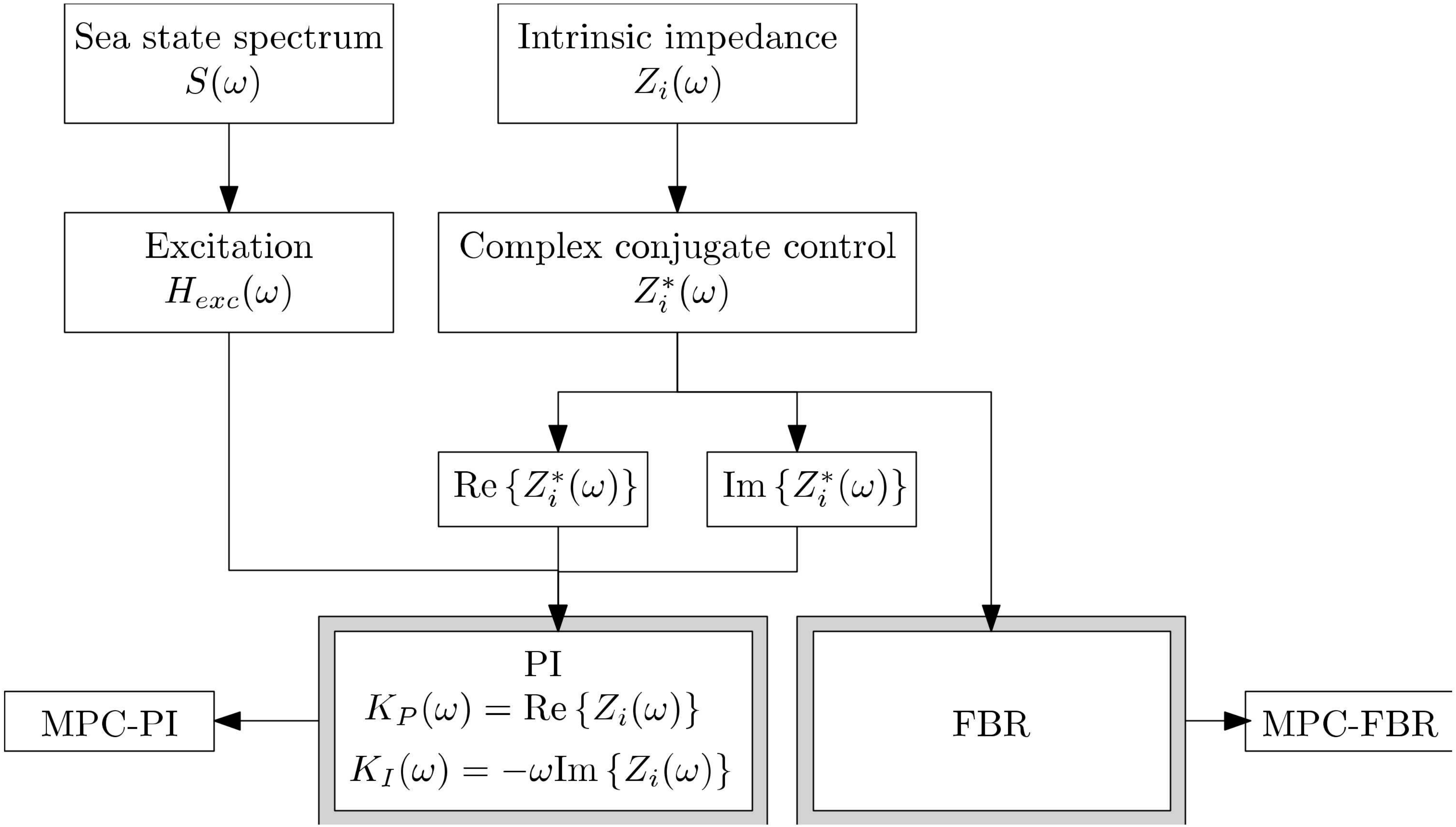


Fig. 1.3. Structure of random sea (Pierson *et al.*, 1958).

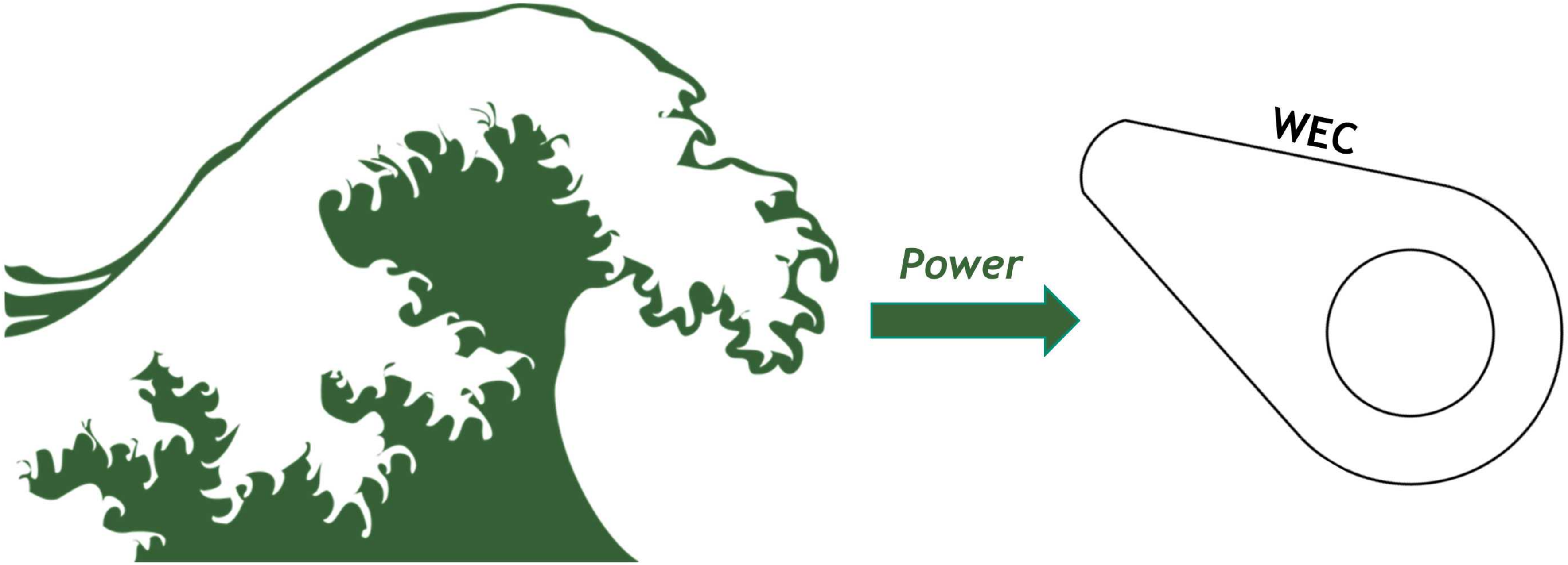
WEC control hierarchy



Impedance matching

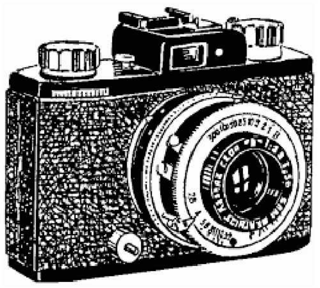
Maximum power transfer (from waves to PTO)

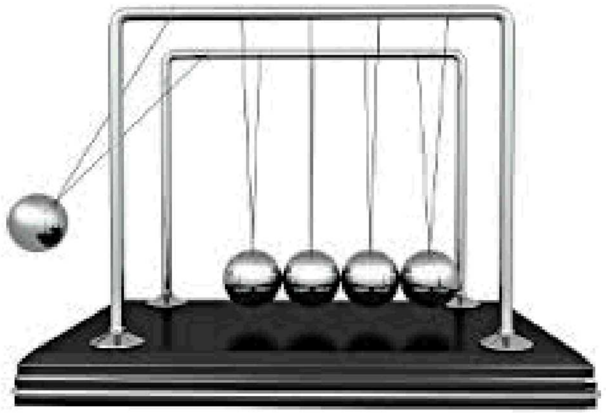
$$Z_{source} = Z_{load}^{*}$$



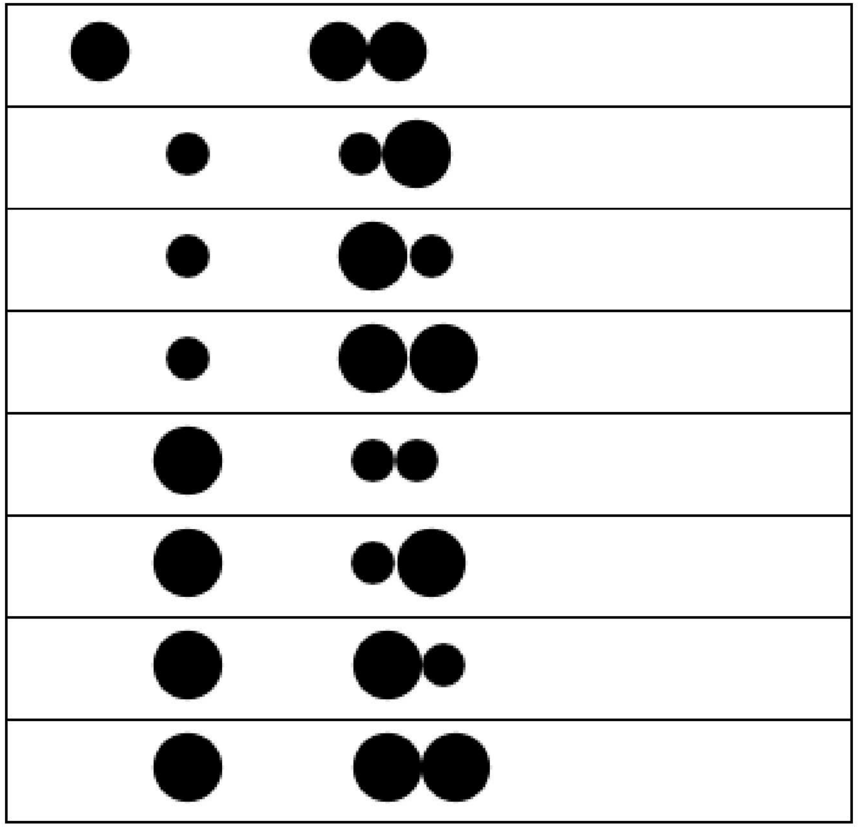
Impedance matching

Where else is this used?

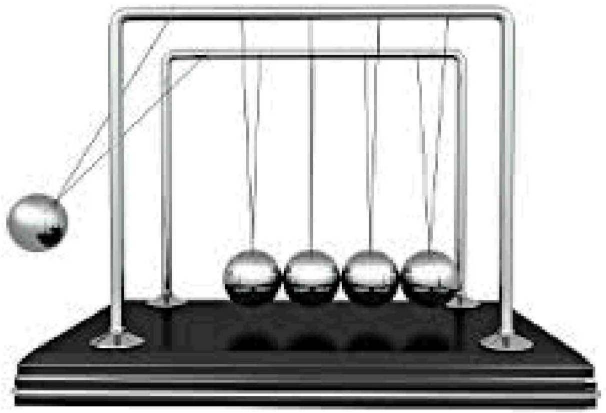




Impedance matching



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



Describing a WEC controller

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

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

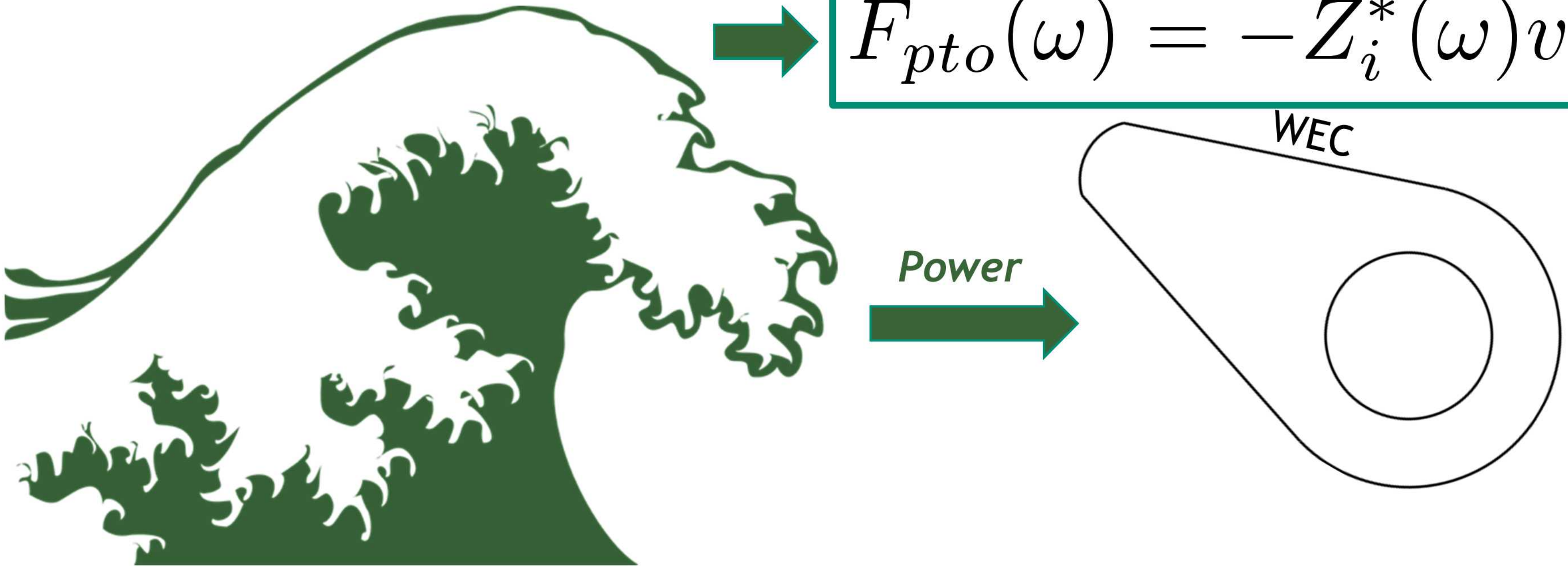
Impedance matching

Maximum power transfer (from waves to PTO)

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

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

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



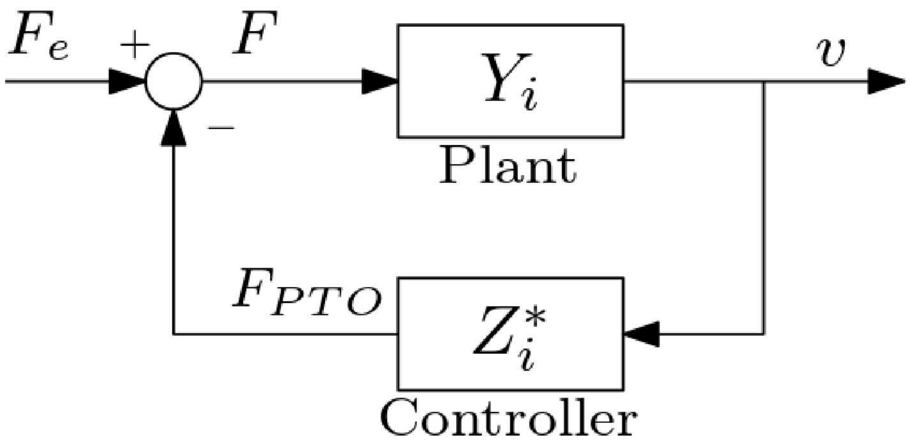
Impedance matching (cont.)

Maximum power transfer (from waves to PTO)

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

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

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



Acausality - Let's get things straight

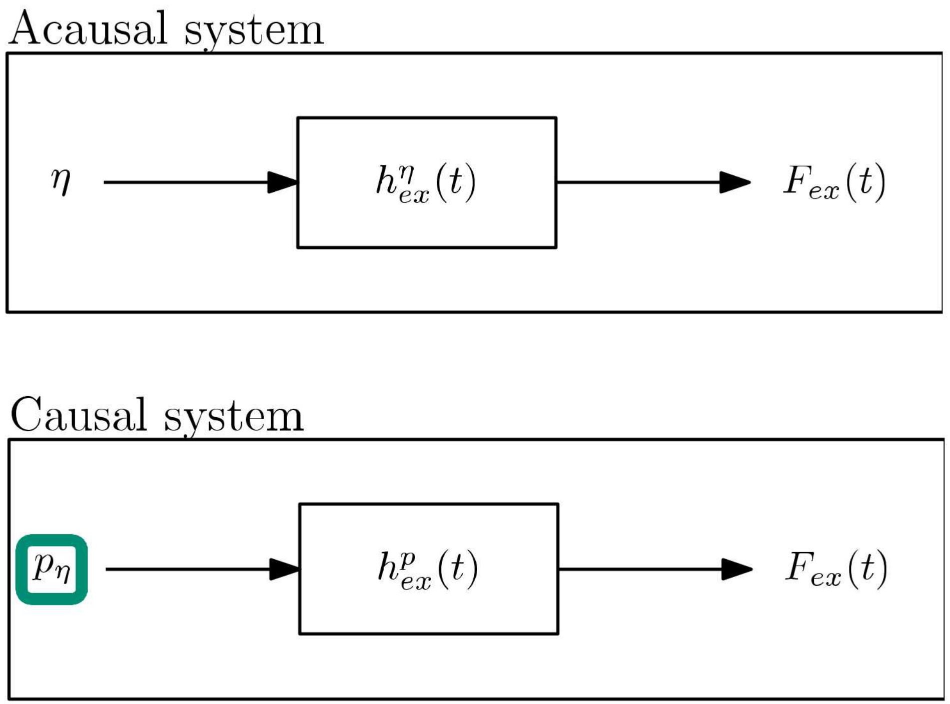
- Two components of noncausality
  - **Excitation:** *matter of perspective*
  - **Complex conjugate control:** *A common problem seen in other fields*

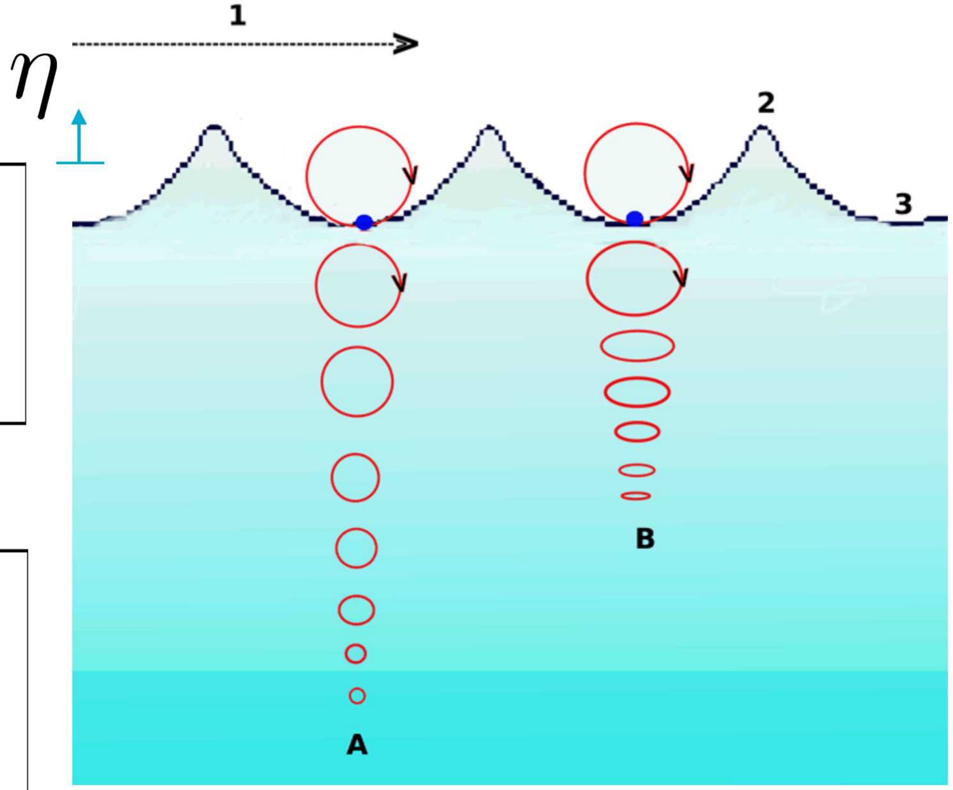
$$\text{Causal: } y_{\text{now}} = f(t \leq \text{now})$$

$$\text{Acausal: } y_{\text{now}} = f(0 \leq t \leq \text{tomorrow})$$

Acausality – excitation (cont.)

- Two components of noncausality
  - **Excitation:** *matter of perspective*
  - **Complex conjugate control:** *A common problem seen in other fields*





Wikimedia Commons

Acausality – impedance matching

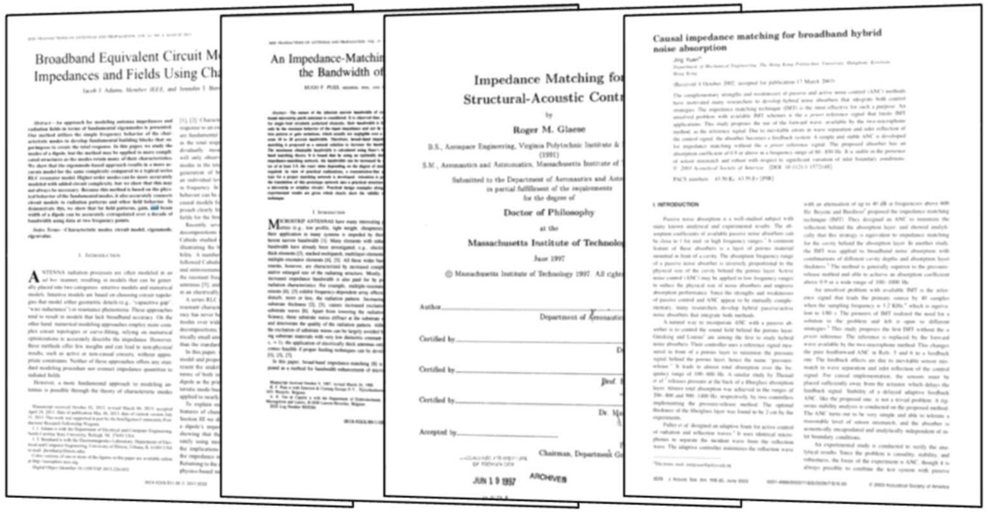
- Two components of noncausality
  - **Excitation:** *matter of perspective*
  - **Complex conjugate control:** *A common problem seen in other fields*

The complex conjugate of any causal system must be acausal

(proof left for your free time)

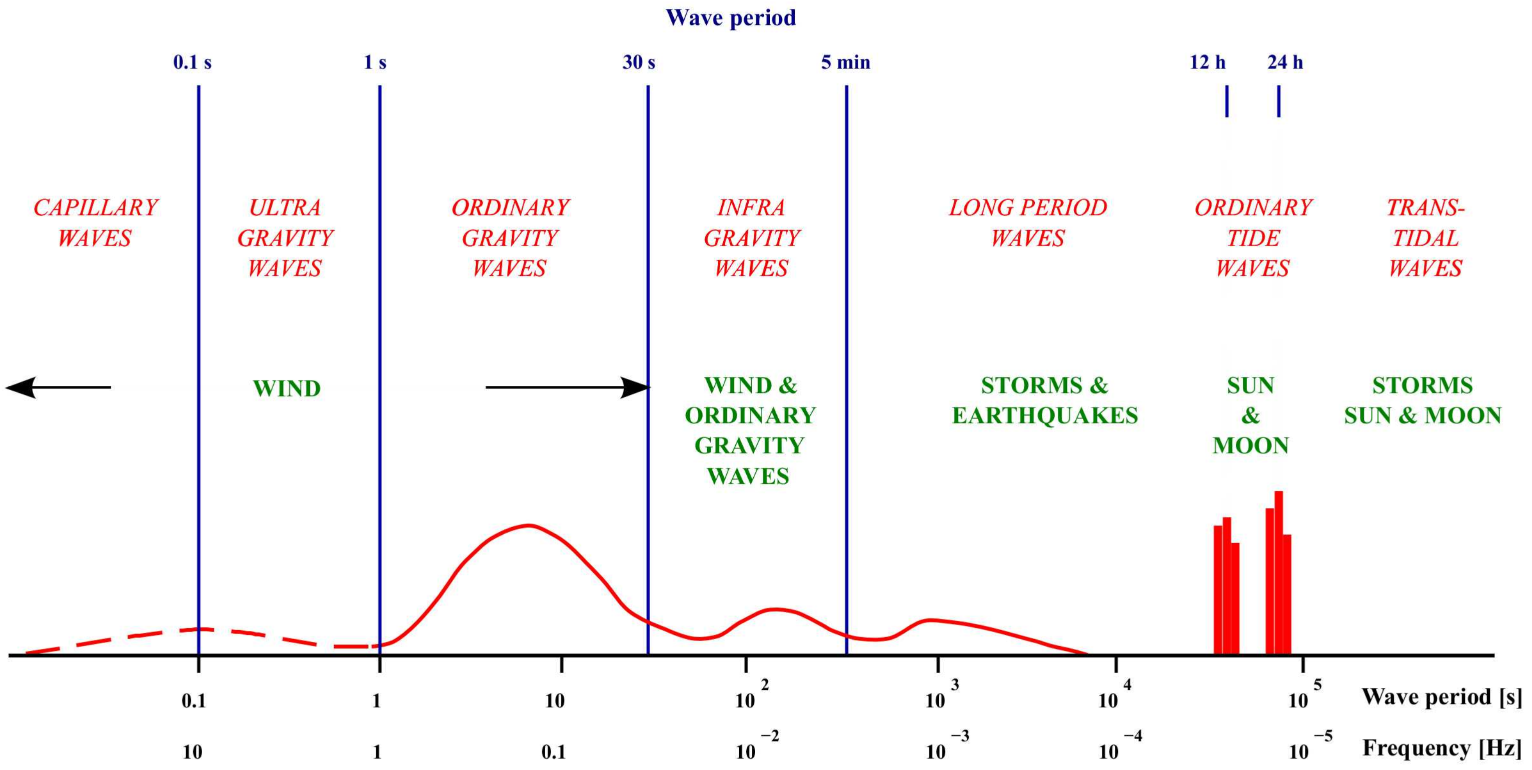
→ **Need an** ***engineering solution***

Acausality in impedance matching is a problem seen in many other fields



Band-limited input

System	Frequency range
US broadcast television	54-700 MHz
AM radio	0.6-1.6 MHz
Visible light	430-750 THz
Audible sound	20-20,000 Hz
Gravity water waves	0.05-1 Hz
Individual sea state (example)	0.1-0.2 Hz



Spectral distribution of ocean waves, W.H.Munk,Origin and generation of waves, in:Proceedings of First Conference on Coastal Engineering, Long Beach, CA, 1950 (by Mikhail Ryazanov, licensed by CC BY 3.0 / units abbreviated).

Causal realization

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

derivative gain — **proportional gain** — **integral gain**

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

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

“WEC control hierarchy"

Intrinsic impedance

$$Z_i(\omega)$$

Complex conjugate

$$Z_i^*(\omega)$$

Real and imaginary parts

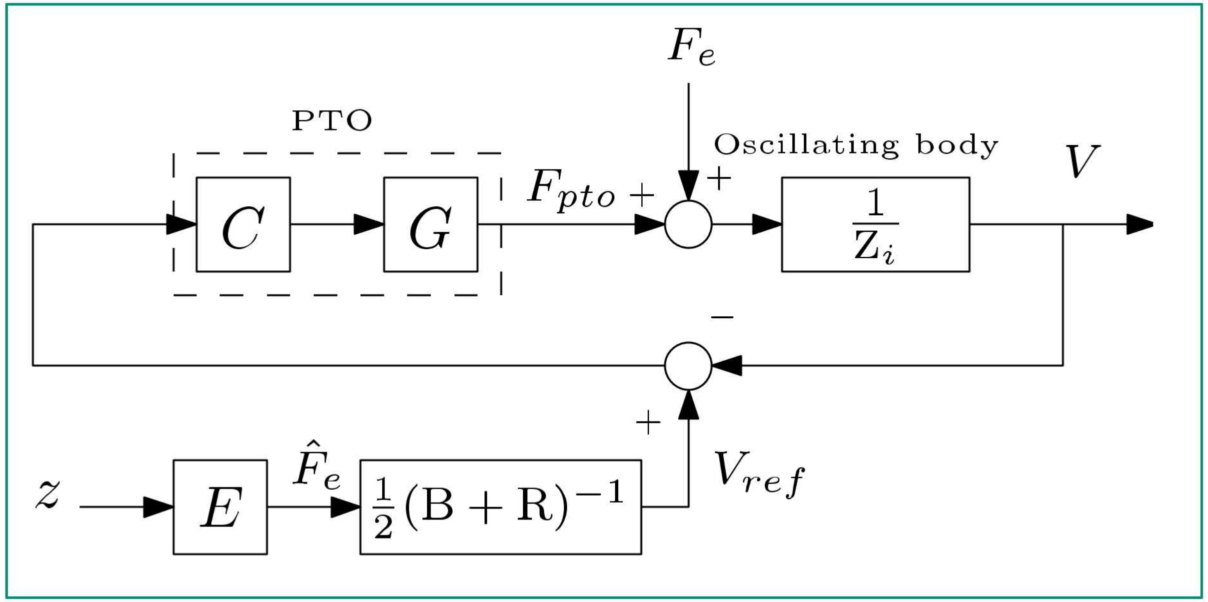
$$\Re\{Z_i^*(\omega)\} \qquad \Im\{Z_i^*(\omega)\}$$

Causal realization

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

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

Two paths - a WEC reformation

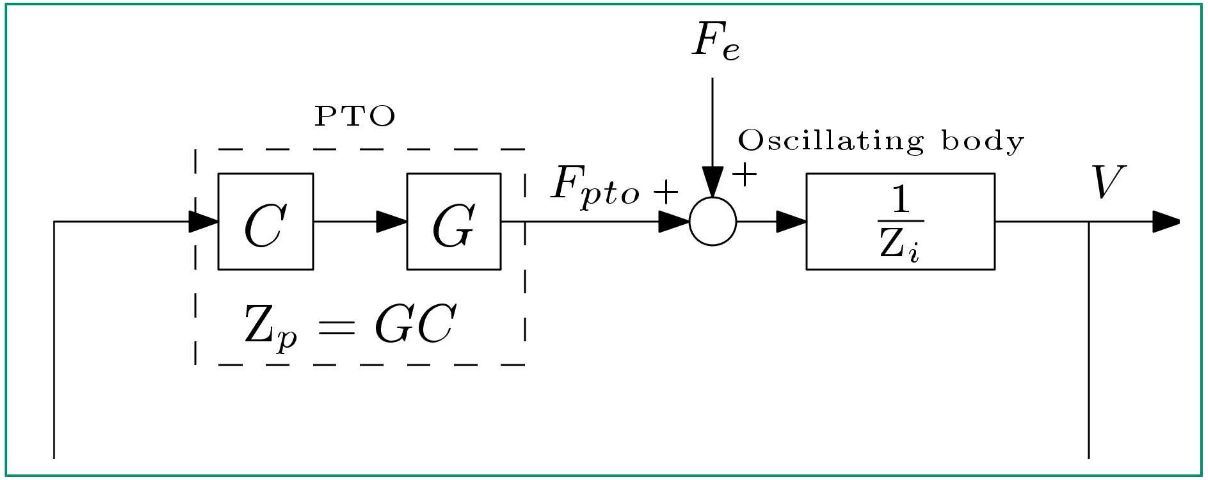


Velocity tracking controller structure

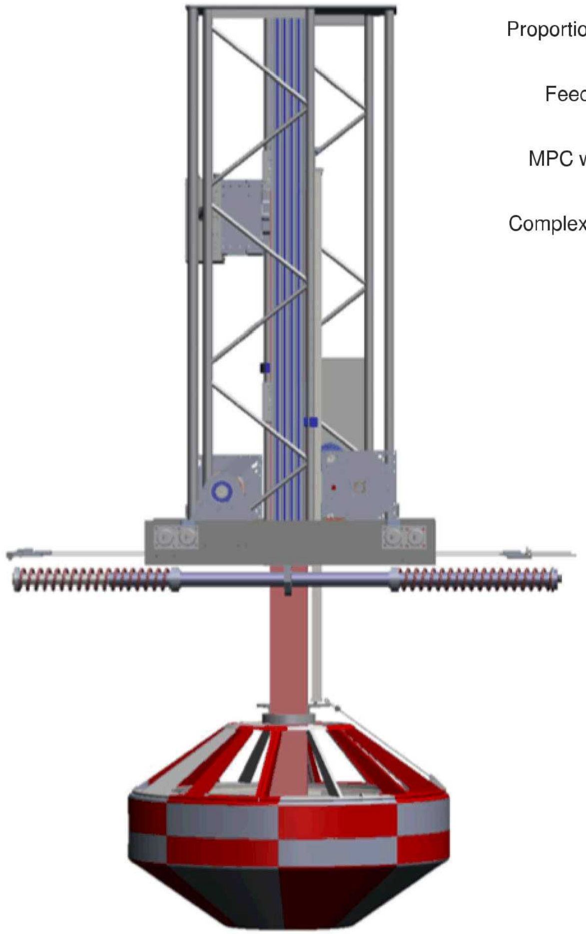
$$V_{ref} = \frac{F_e}{2\Re\{Z_i\}}$$

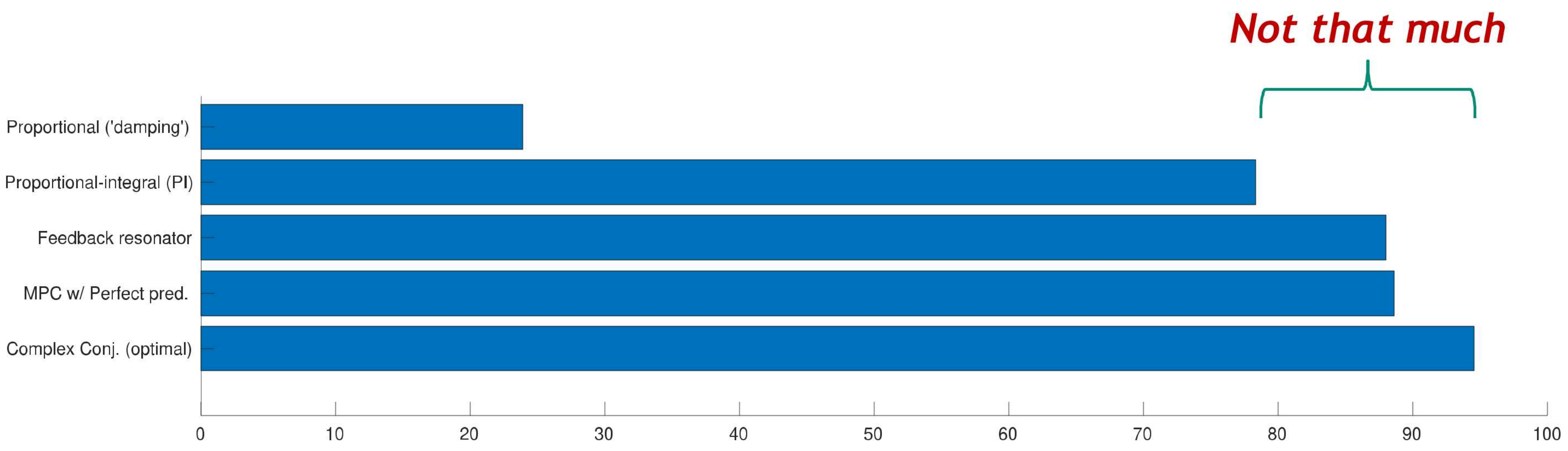
Impedance matching controller structure

$$Z_p = Z_i^*$$

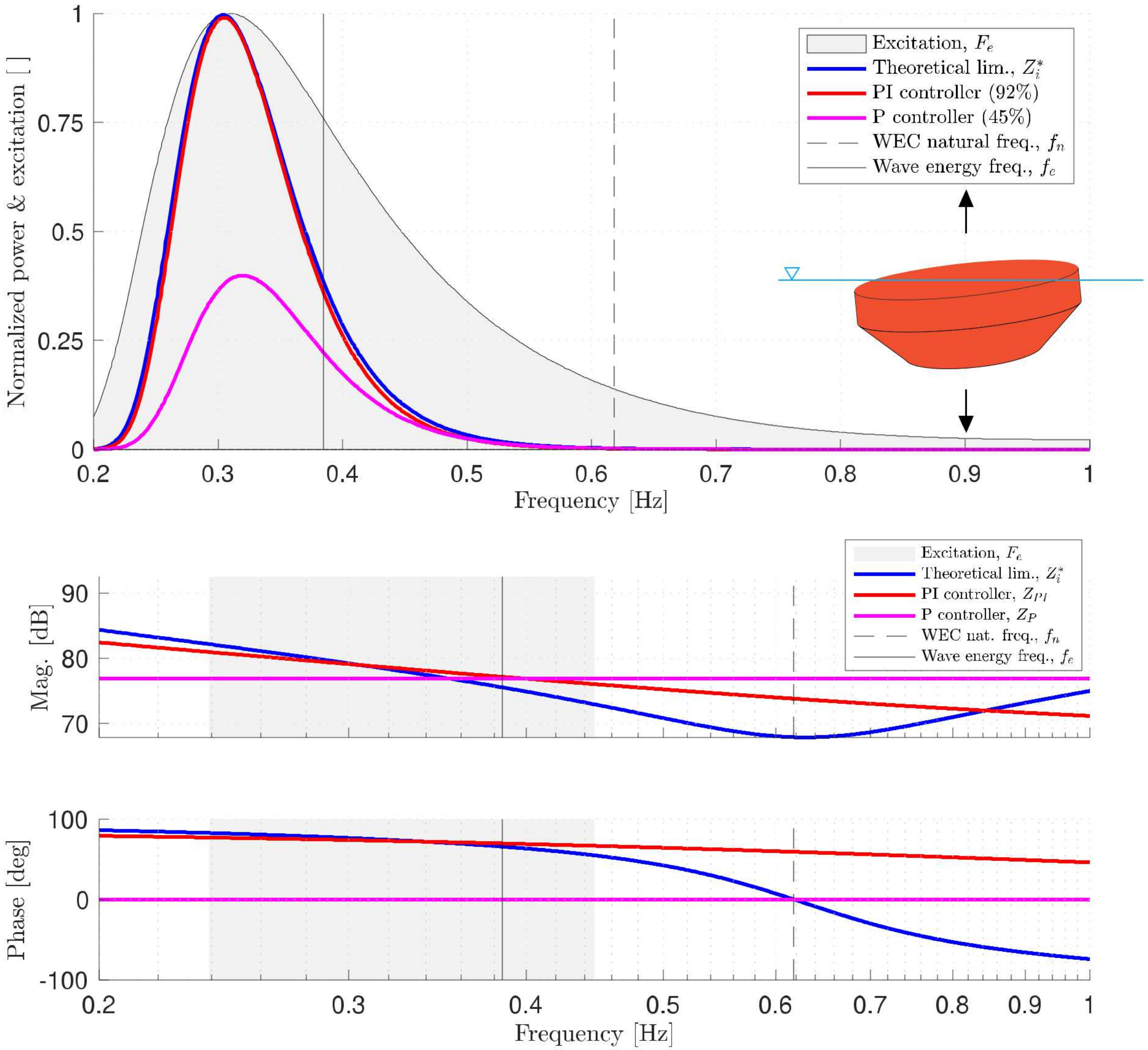


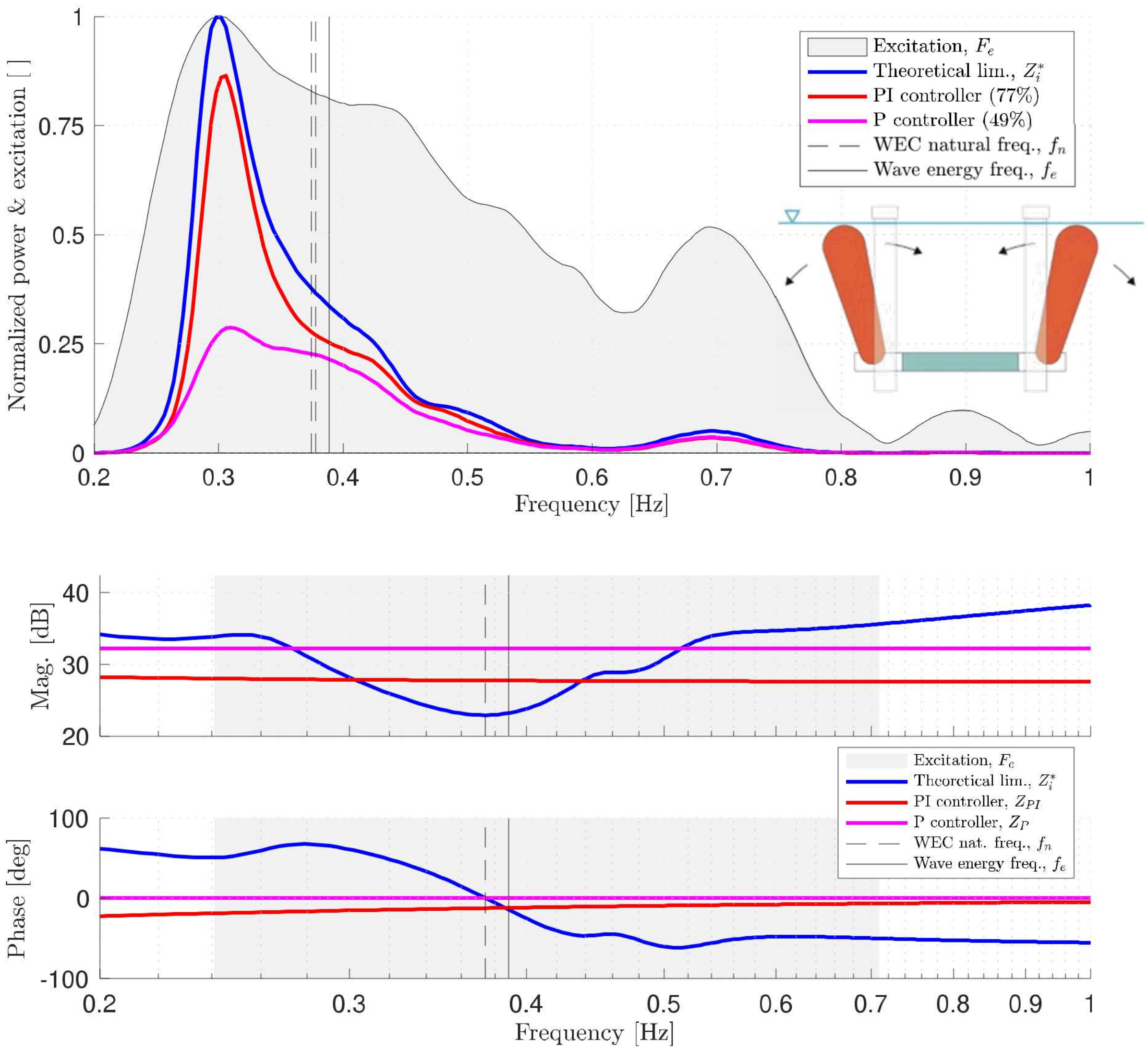
What am I missing out on?



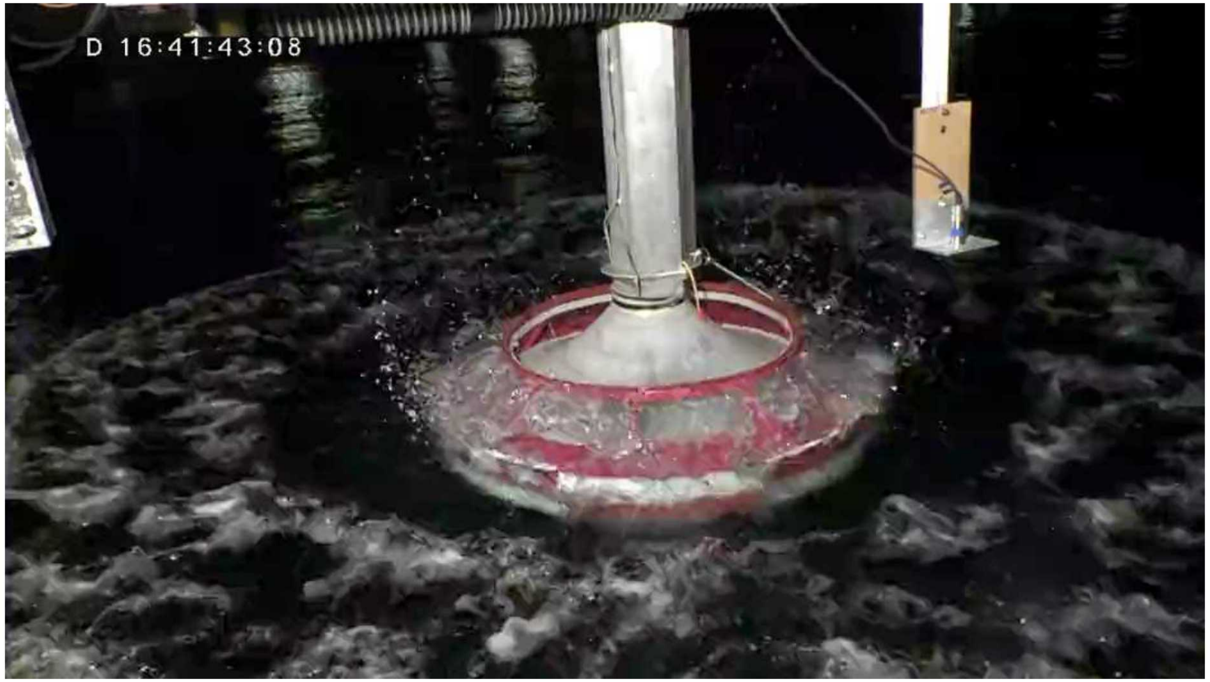


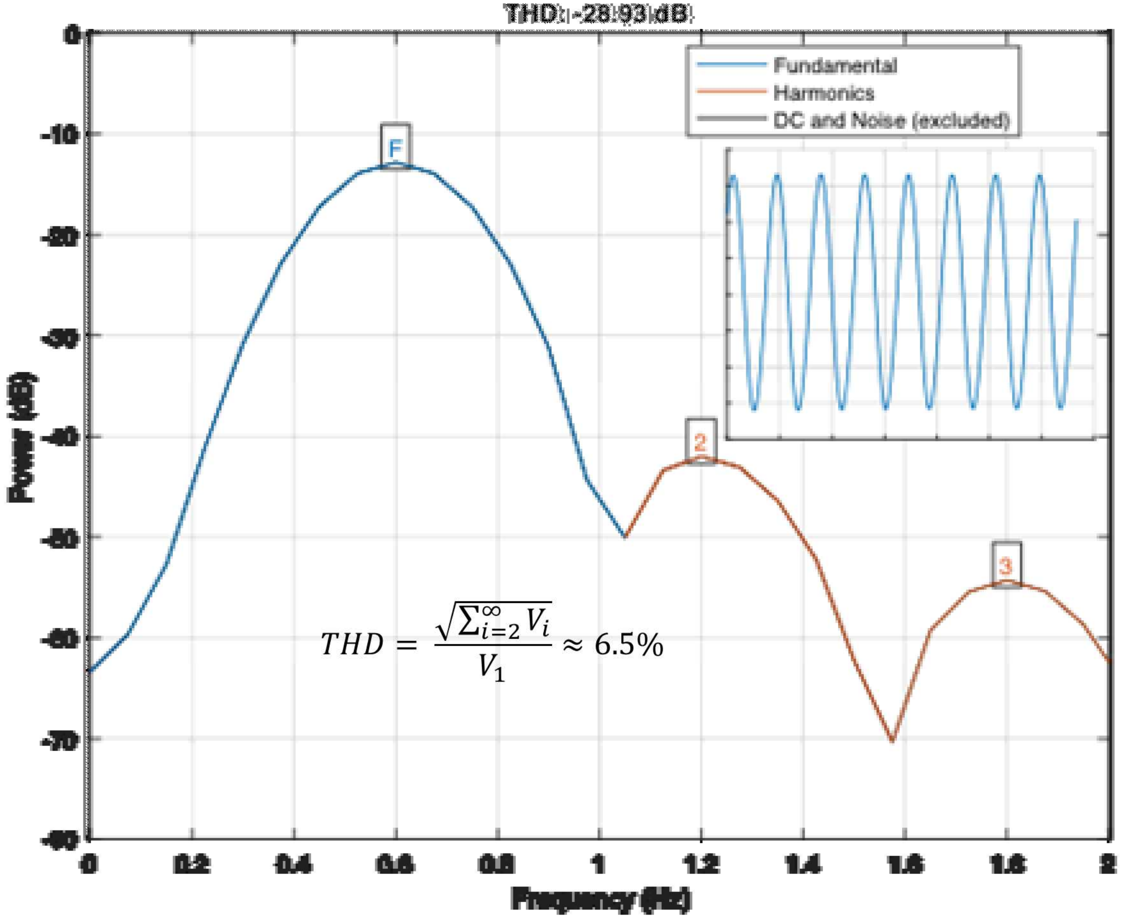
What am I missing out on (cont.)?





What about nonlinearities?

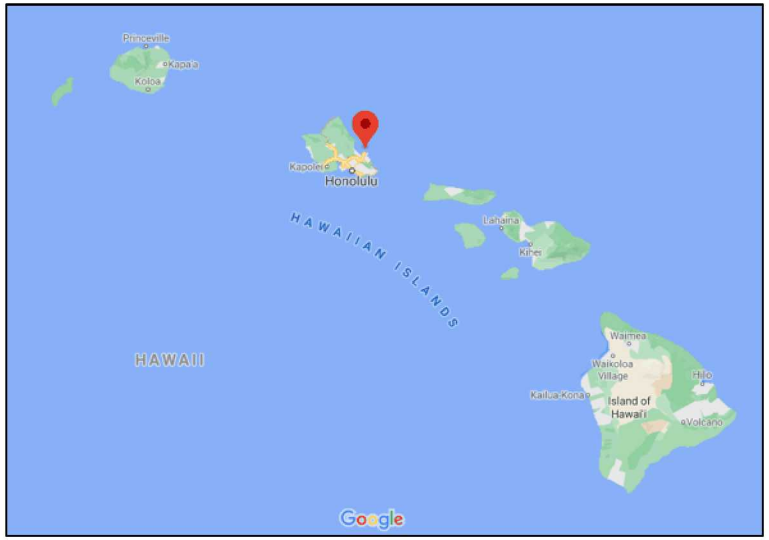


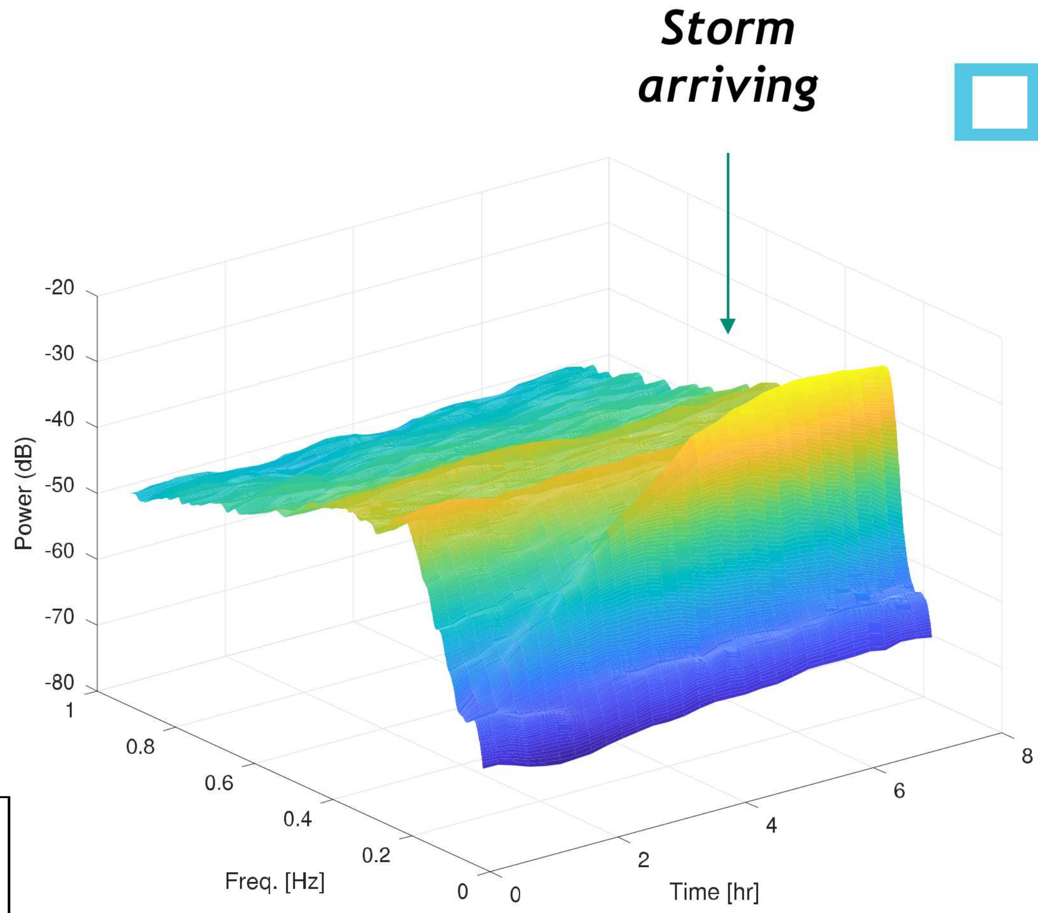


$$THD = \frac{\sqrt{\sum_{i=2}^{\infty} V_i}}{V_1} \approx 6.5\%$$

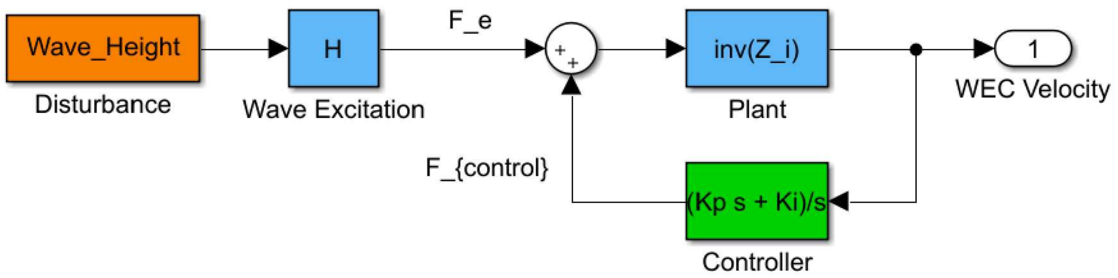
Isn’t PI too narrow-banded?

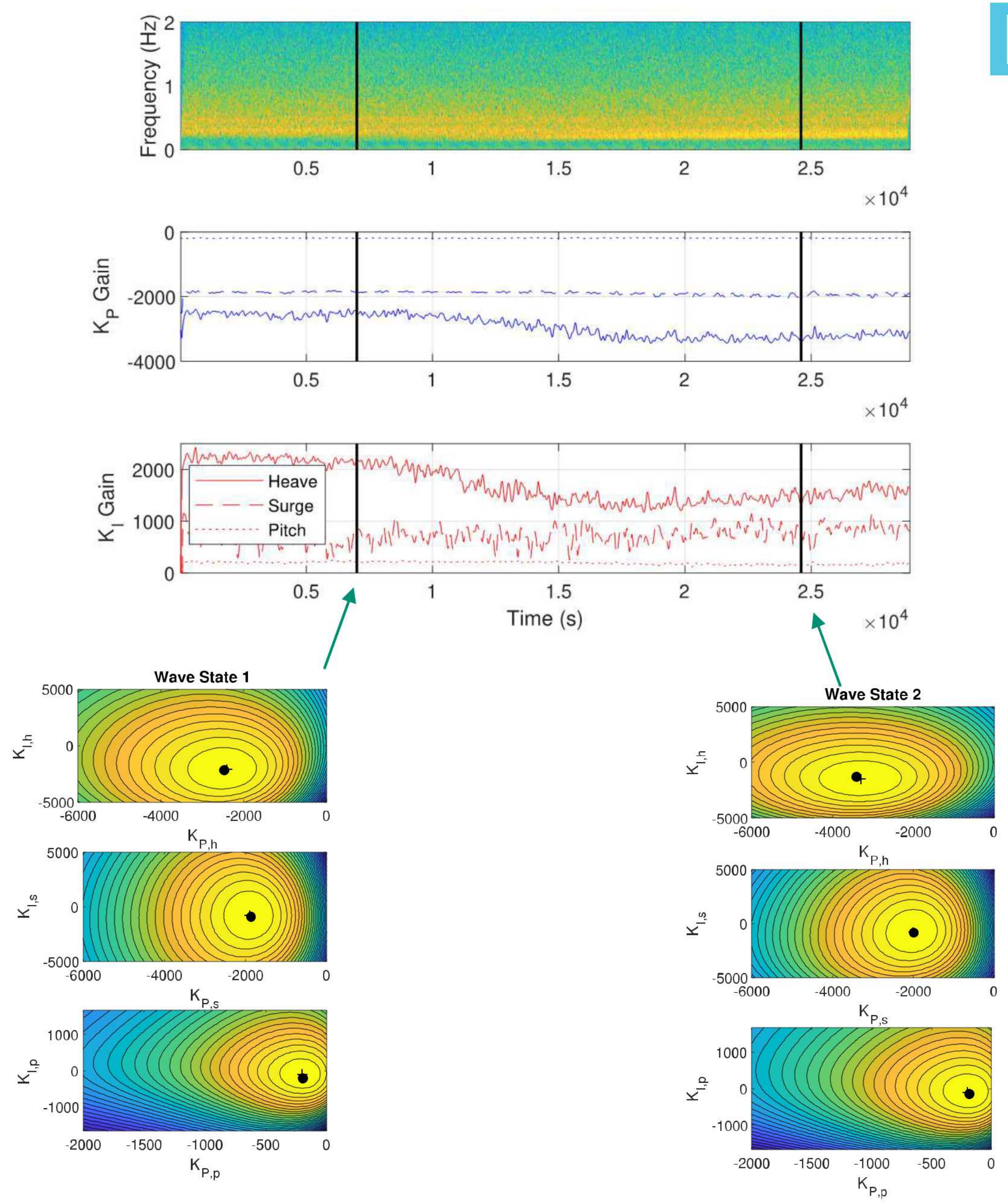
CDIP225, KANEOHE BAY, WETS, HI





Isn't PI too narrow-banded (cont.)?





Isn't PI too narrow-banded (cont.)?

Bode-Fano limit: there will always be a tradeoff between bandwidth and accuracy (reflection coefficient)

$$\int_0^\infty \ln \frac{1}{|\Gamma(\omega)|} \mathrm{d}\omega \leq M < \infty$$

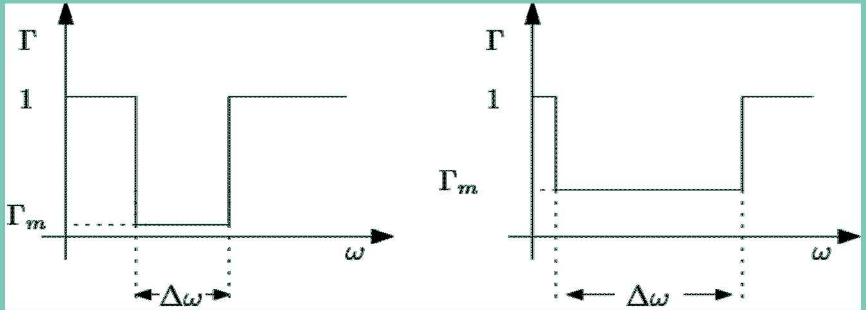
Γ Reflection coefficient

$\Gamma = 1$ → NO power transferred to the load

$\Gamma = 0$ → All power transferred to the load (perfect match)

Example

$$\Delta\omega \ln \frac{1}{\Gamma_m} \leq M$$



Hendrik Bode

https://en.wikipedia.org/wiki/Hendrik_Wade_Bode

Robert Fano

https://en.wikipedia.org/wiki/Robert_Fano

- Narrow banded devices (High Quality factor Q) have lower M
- Narrow banded WECs are not the best choice (e.g. spar buoy)

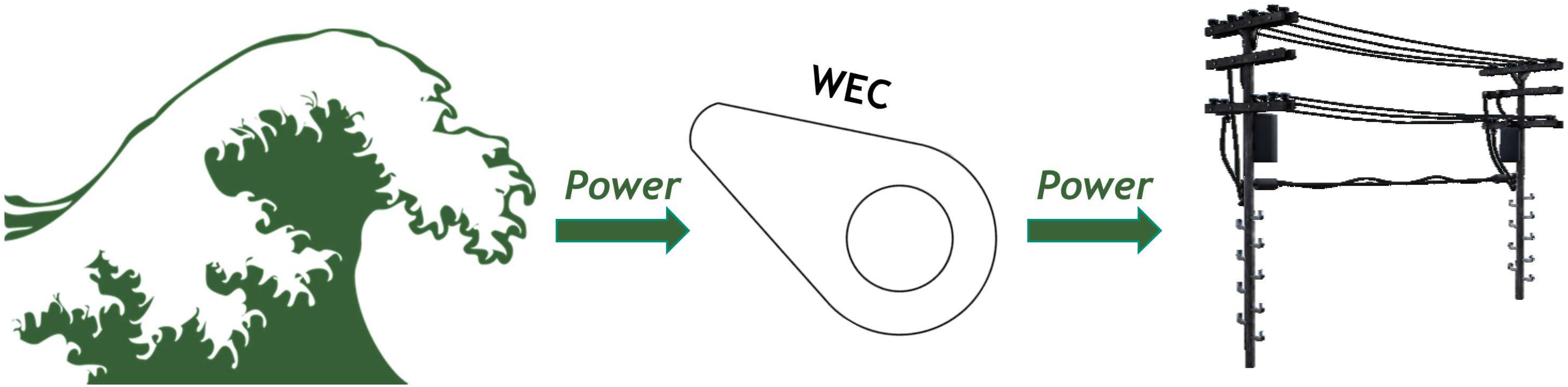
→ Another good reason not to design narrow-banded WECs

Impedance matching

Maximum power transfer (from waves to PTO)

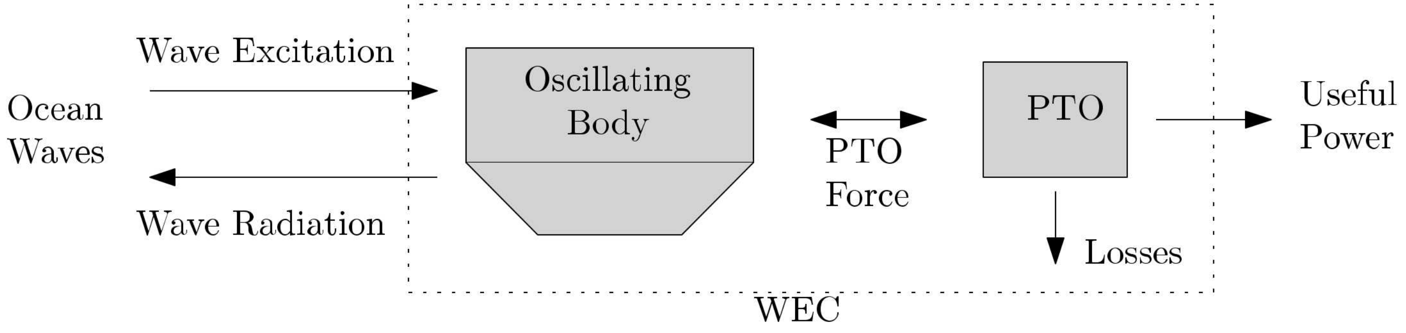
$$Z_{source} = Z^{*}_{load}$$

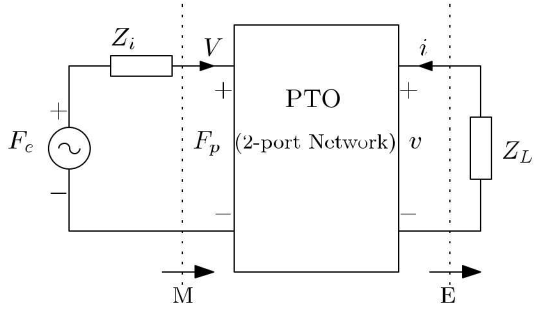
…actually, the real problem is closer to



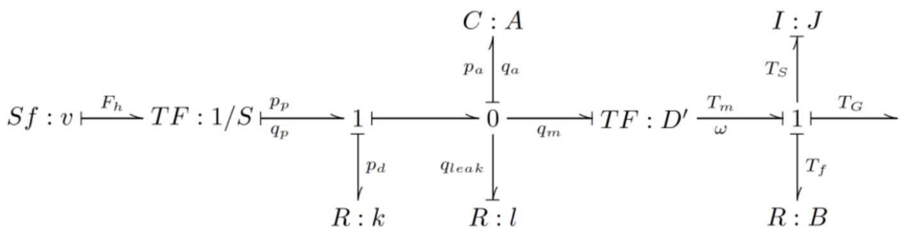
Co-design problem and approach

Description of power flow





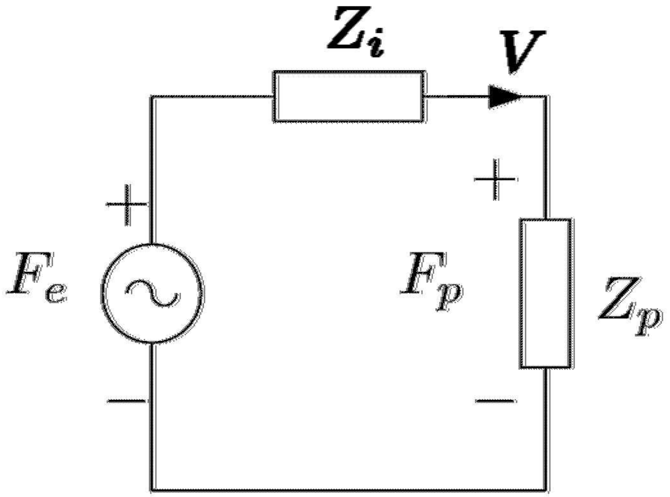
Multiport



Bond-graph

Why use Multiport theory?

It gives condition for maximum power transfer:



Impedance matching

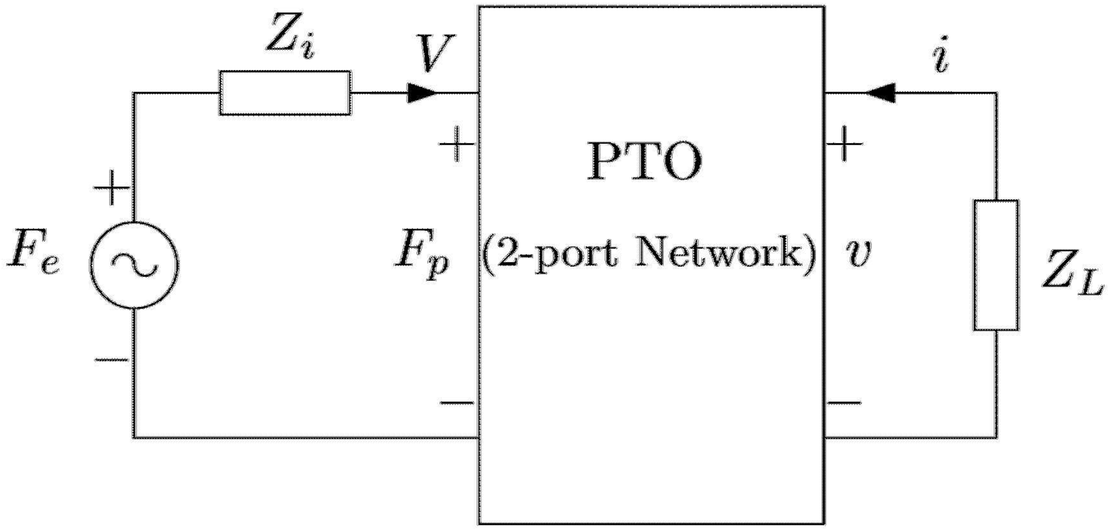
$$Z_p = Z_i^*$$

Maximum power transferred from F_e to Z_p

How to account for the dynamics and efficiency of the PTO?

Objective:
Transfer max power to load Z_L

Thevénin
equivalent transformation



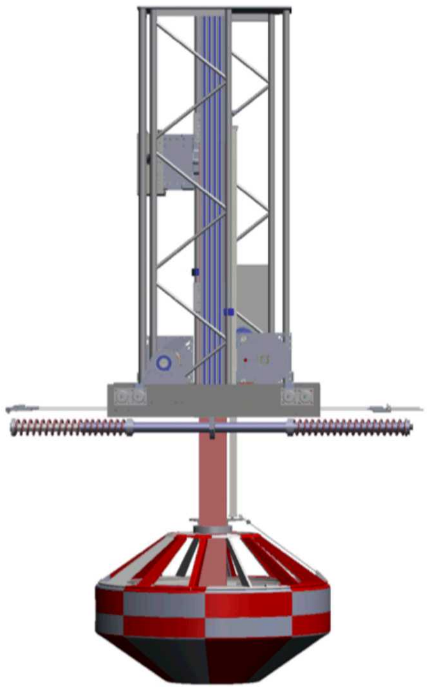
Impedance matching condition for Max power transfer to Z_L

$$Z_L = Z_{th}^*$$

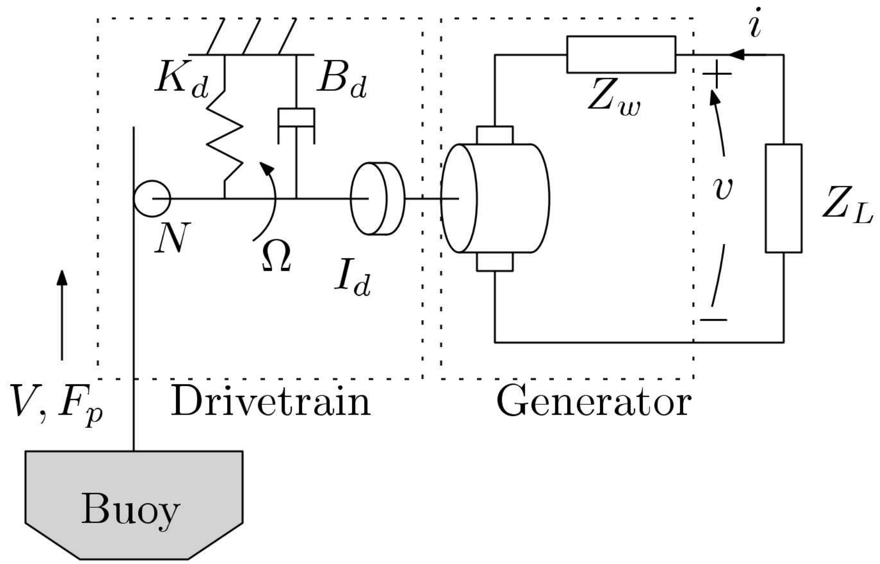
Z_{th} depends on the PTO → Control system can be designed to account for PTO

How to account for the dynamics and efficiency of the PTO?

Example:



Simplified PTO diagram

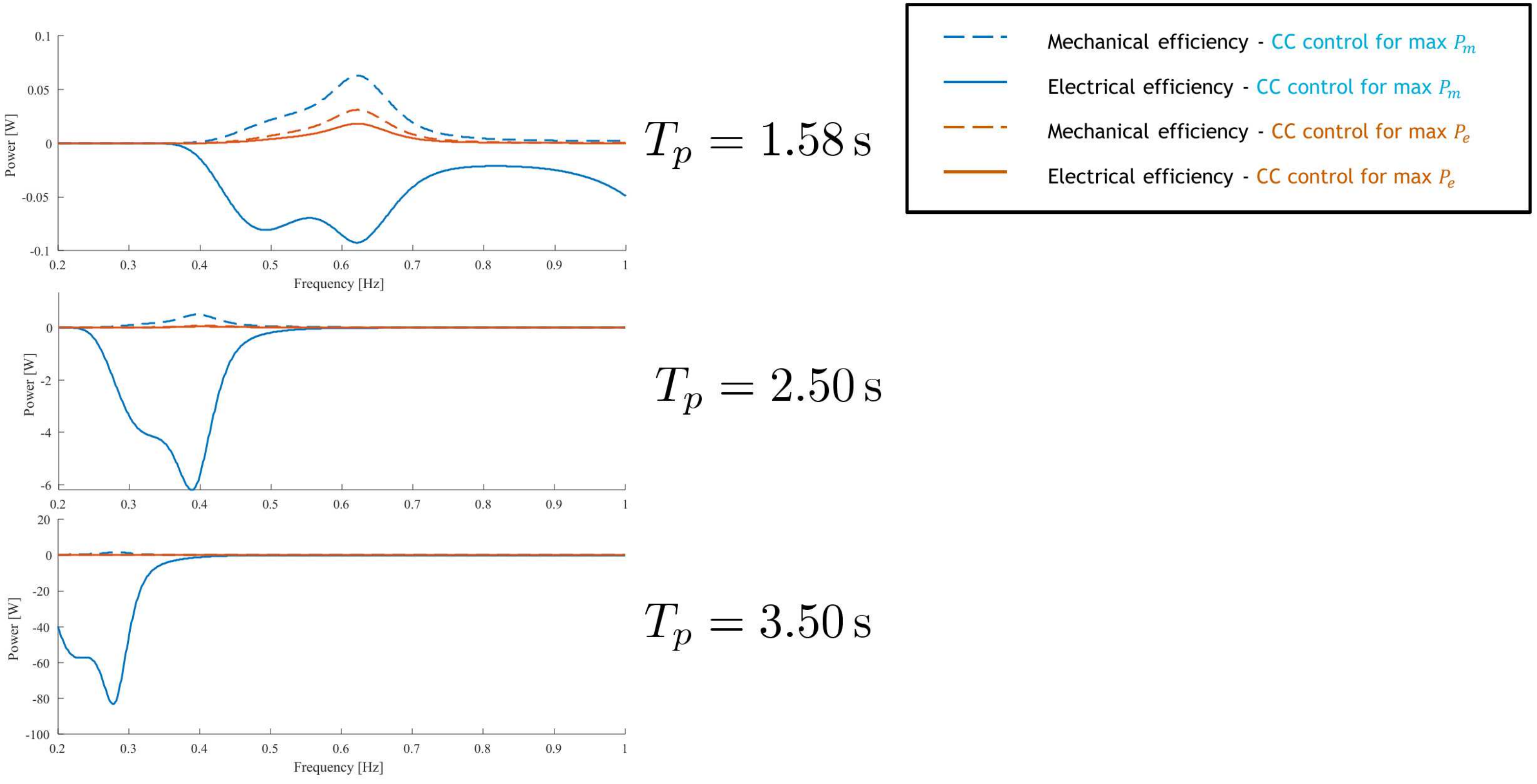


$$Z_{th} = Z_w + \frac{\frac{2}{3} K_t^2 N^2}{N^2 Z_d + Z_i} \Rightarrow C = Z_L = Z_{th}^*$$

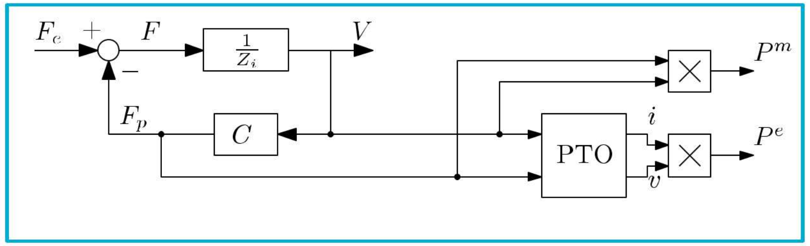
Control systems designed to account for PTO dynamics and efficiency

Electrical vs. Mechanical power

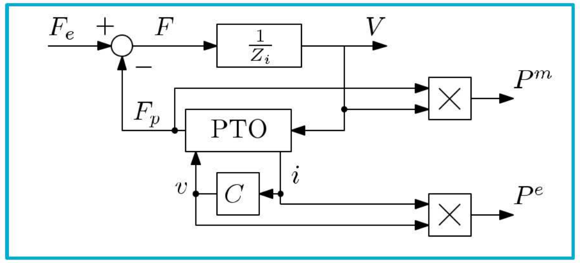
	$T_p = 1.58\,\mathrm{s}$				$T_p = 2.5\,\mathrm{s}$				$T_p = 3.5\,\mathrm{s}$			
	P_m [W]	η_m	P_e [W]	η_e	P_m [W]	η_m	P_e [W]	η_e	P_m [W]	η_m	P_e [W]	η_e
CC on mech	1.06E+1	1.00	-2.91E+1	-2.74	5.21E+1	1.00	-7.47E+2	-14.34	1.29E+2	1.00	-7.85E+3	-60.69
PI on mech	9.72E+0	0.92	-1.8E+1	-1.70	4.96E+1	0.95	-6.29E+2	-12.08	1.21E+2	0.94	-5.85E+3	-45.26
CC on elec	4.41E+0	0.42	2.52E+0	0.24	8.26E+0	0.16	4.39E+0	0.08	6.8E+0	0.05	3.5E+0	0.03
PI on elec	4.38E+0	0.41	2.51E+0	0.24	8.22E+0	0.16	4.37E+0	0.08	6.77E+0	0.05	3.5E+0	0.03



Mechanical power

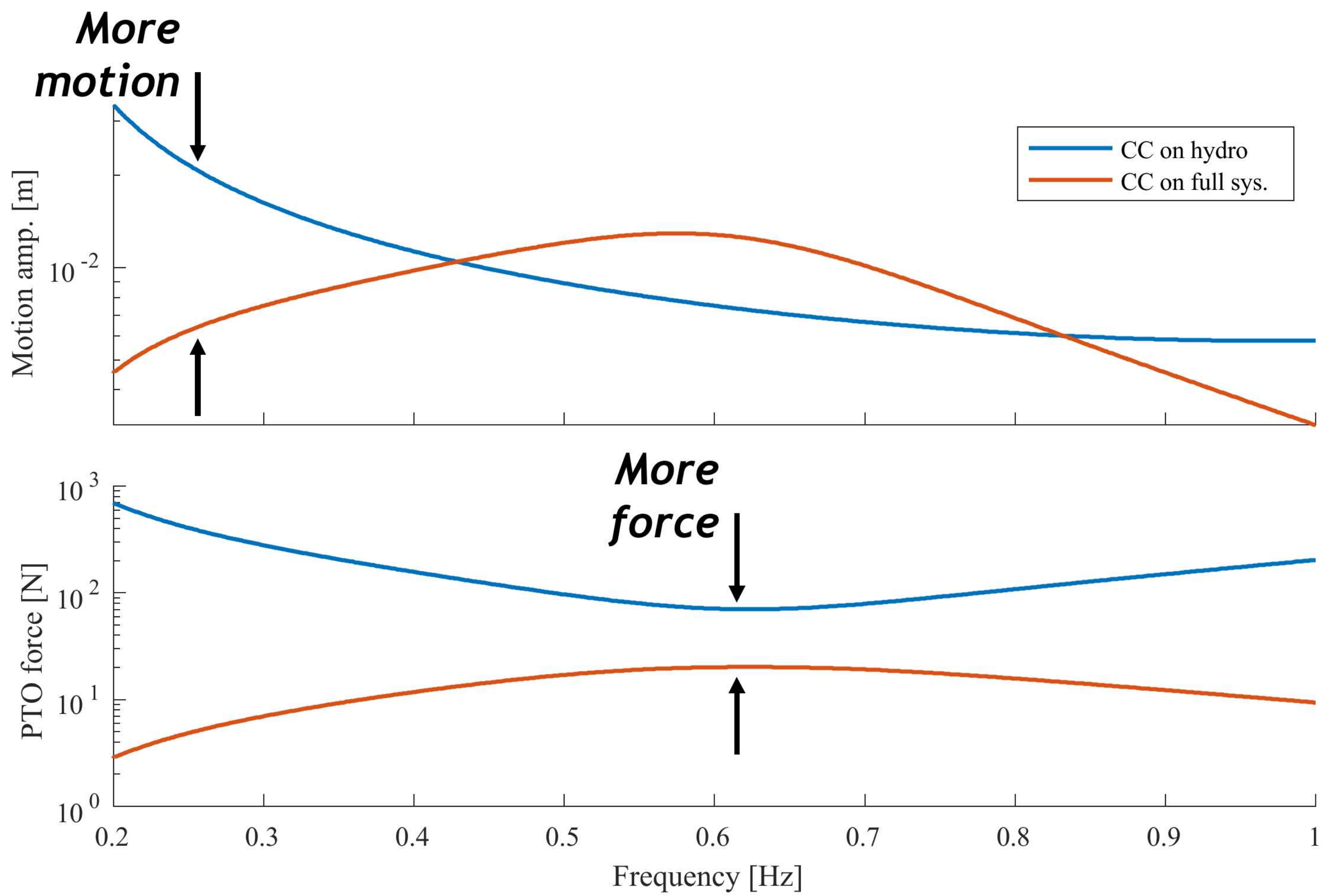


Electrical power



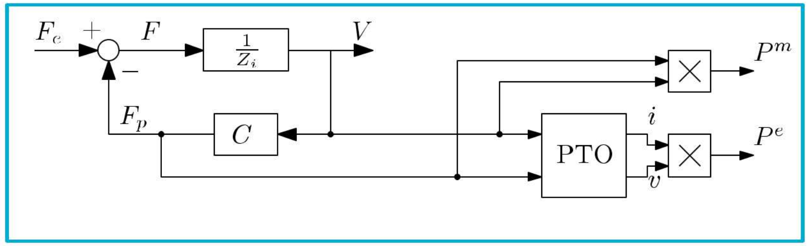
https://github.com/SNL-WaterPower/fbWecCntrl/blob/codesign/codesign/codesign_powerTable.m

Electrical vs. Mechanical power (cont.)

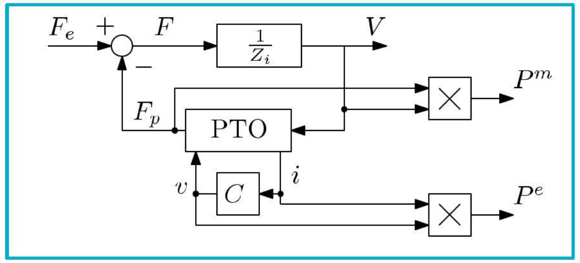


Making other design decisions without a good approximation of the control and PTO is problematic

Mechanical power



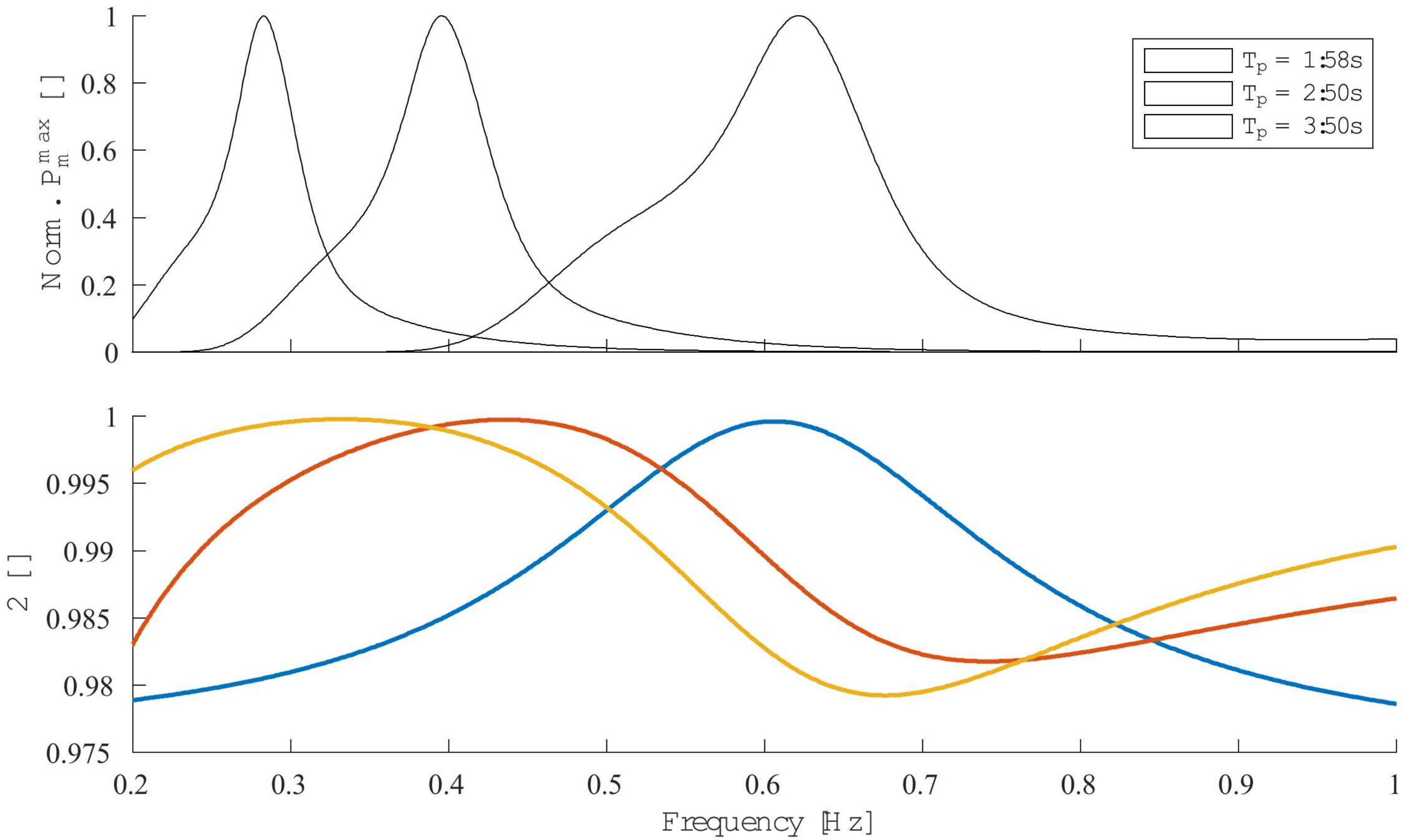
Electrical power



https://github.com/SNL-WaterPower/fbWecCntrl/blob/codesign/codesign/codesign_efficiencyFig.m

PTO design is the important problem

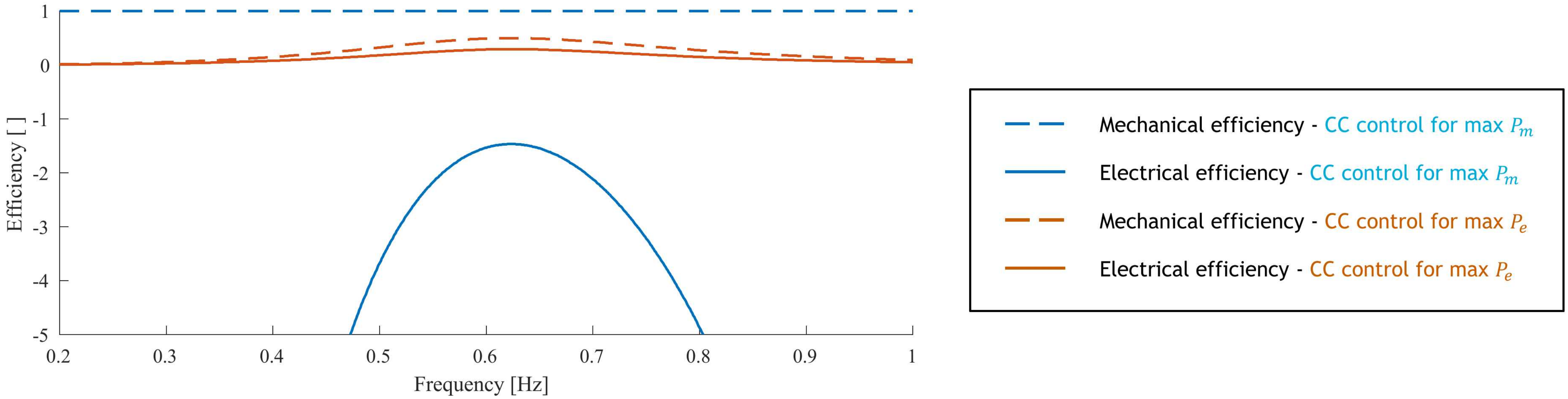
$$\eta = \frac{P_L}{P_m^{max}}$$



A ***perfect*** controller is not that much better than a ***good*** controller, especially when the PTO is not optimized

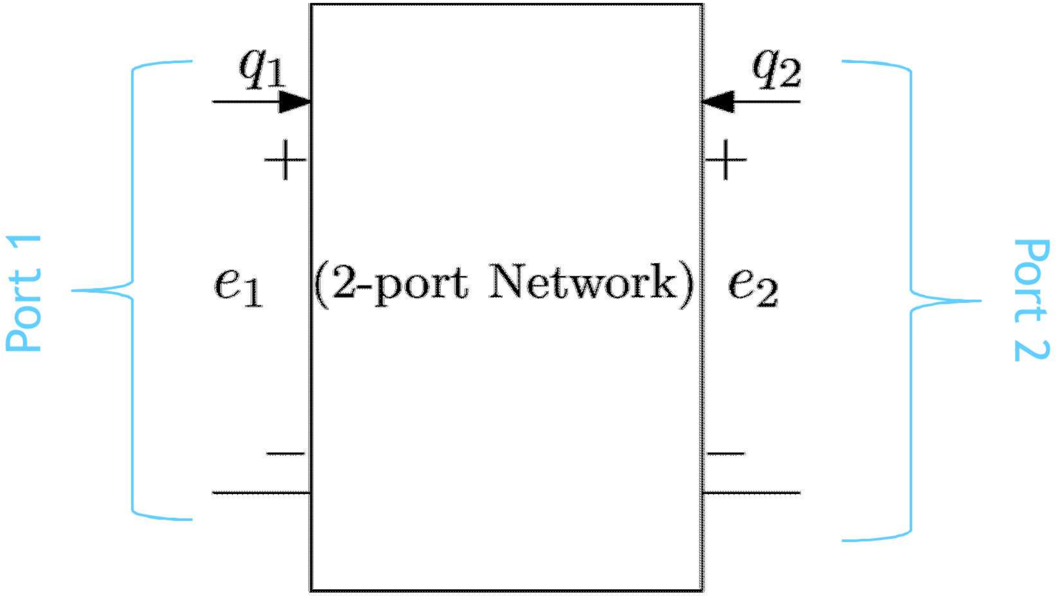
https://github.com/SNL-WaterPower/fbWecCntrl/blob/codesign/codesign/codesign_powerTable.m

Efficiency is highly frequency dependent



Multiport framework

Example: Generic 2-port



e_1, e_2: effort (across) variables

q_1, q_2:flow (through) variables

2-port Impedance:

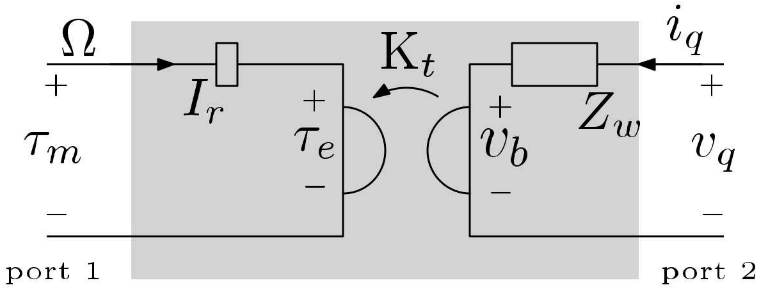
$$\begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}$$

$$Z_{11} = \left.\frac{e_1}{q_1}\right|_{q_2=0} \quad Z_{12} = \left.\frac{e_1}{q_2}\right|_{q_1=0}$$

$$Z_{21} = \left.\frac{e_2}{q_1}\right|_{q_2=0} \quad Z_{22} = \left.\frac{e_2}{q_2}\right|_{q_1=0}$$

Multiport framework (cont.)

Example: Electric generator



Electrical generator
(2-port network)

$$e_1 = \tau_m$$
$$e_2 = v_q$$
$$q_1 = \Omega$$
$$q_2 = i_q$$

$$\tau_m = I_r\, j\omega\Omega + \tau_e$$
$$v_q = v_b + Z_w\, i_q$$
$$\tau_e = -\sqrt{3/2}\, K_t\, i_q$$
$$v_b = \sqrt{3/2}\, K_t\, \Omega$$

$$Z_{11} = \left.\frac{e_1}{q_1}\right|_{q_2=0} \quad Z_{12} = \left.\frac{e_1}{q_2}\right|_{q_1=0}$$
$$Z_{21} = \left.\frac{e_2}{q_1}\right|_{q_2=0} \quad Z_{22} = \left.\frac{e_2}{q_2}\right|_{q_1=0}$$

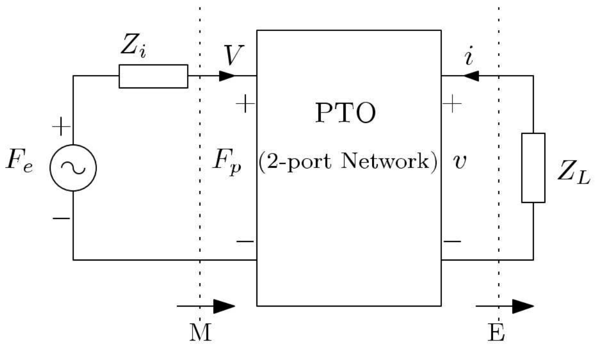
$$Z_{gen} = \begin{bmatrix} j\omega I_r & -\sqrt{\frac{3}{2}}\, K_t \\ \sqrt{\frac{3}{2}}\, K_t & Z_w \end{bmatrix}$$

How do we optimize PTO?

How can we tune the controller to account for the PTO?

How can we design a good PTO simultaneously with a controller?

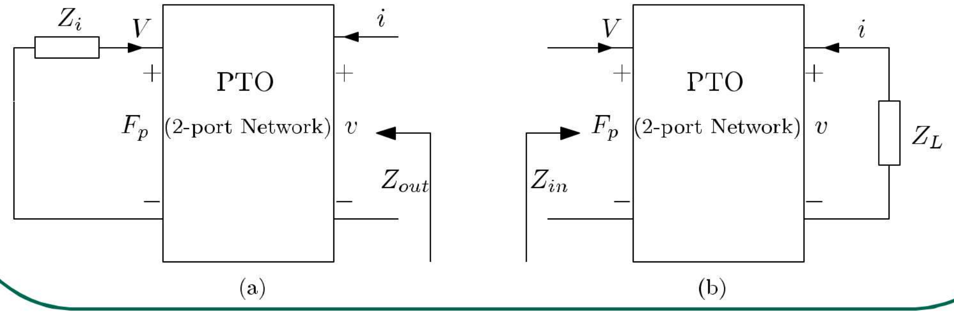
Consider the PTO as an impedance matching network and design it to maximize the power delivered to the load.



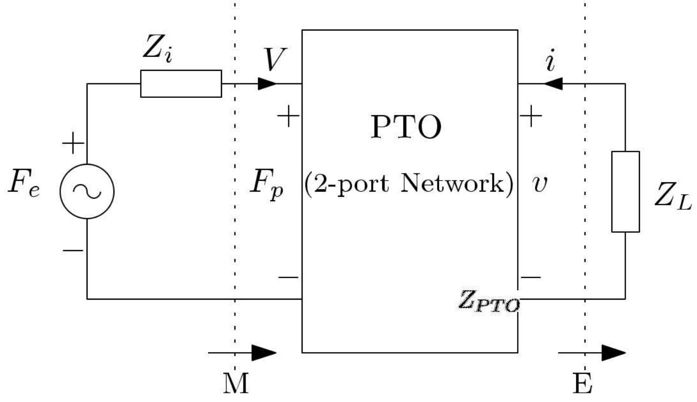
2 matching conditions for maximization of electrical power

$$Z_L = Z_{out}^*$$ Output matching

$$Z_i = Z_{in}^*$$ Input matching



Power and efficiency



$$Z_{PTO} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}$$

Theoretical upper bound for mechanical power

$$P_m^{max} = \frac{|F_{\text{exc}}|^2}{8\,R_i}$$

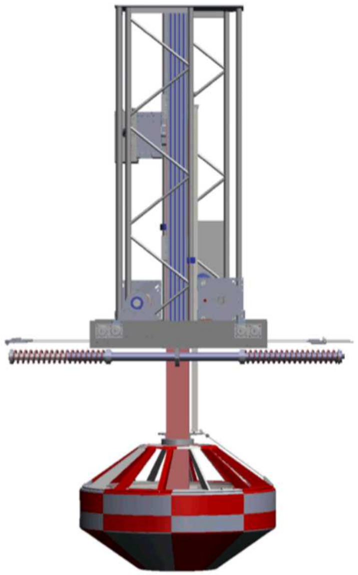
Power on the load as function of the PTO and Controller ($C = Z_L$)

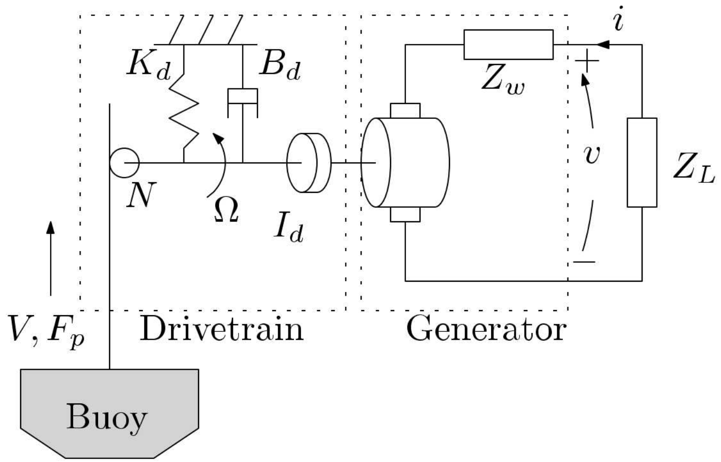
$$P_L = \left| \frac{Z_{21}}{(Z_{11}+Z_i)(Z_{22}+Z_L) - Z_{12}\,Z_{21}} \right|^2 \frac{|F_e|^2}{2} R_L$$

Electrical conversion efficiency

$$\eta = \frac{P_L}{P_m^{max}} = \left| \frac{Z_{21}}{(Z_{11}+Z_i)(Z_{22}+Z_L) - Z_{12}\,Z_{21}} \right|^2 4R_iR_L$$

Power and efficiency: WaveBot





$$P_L = \frac{\frac{3}{2}\, K_t^2 N^2 \, |F_e|^2 \, R_L}{2 \left| (N^2 \, Z_d + Z_i) \, (Z_w + Z_L) + \frac{3}{2} K_t^2 N^2 \right|^2}$$

$$\eta = \frac{6 \, K_t^2 N^2 \, R_i \, R_L}{2 \left| (N^2 \, Z_d + Z_i) \, (Z_w + Z_L) + \frac{3}{2} K_t^2 N^2 \right|^2}$$

Co-Optimization of PTO and control

Simultaneous optimization of PTO and control

$$\arg\max_{C,\Theta} P_L(F_{\text{exc}}, Z_i, Z_{PTO}(C,\Theta), Z_L(C,\Theta))$$

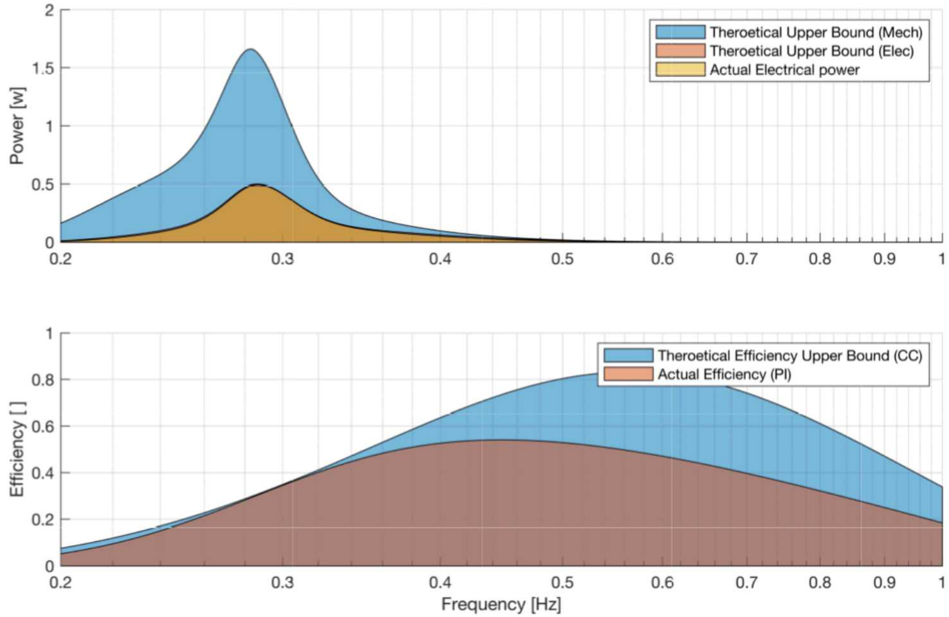
$$Z_{PTO} = Z_{PTO}(C,\Theta) \qquad Z_L = Z_L(C,\Theta)$$

$\Theta = \{N, I_d, K_d, \ldots\}$ PTO parameters

$C = \{K_p, K_i\}$ Control parameters (e.g. PI)

Example 1: Co-optimization of PTO and control

Nominal PTO



Optimized PTO

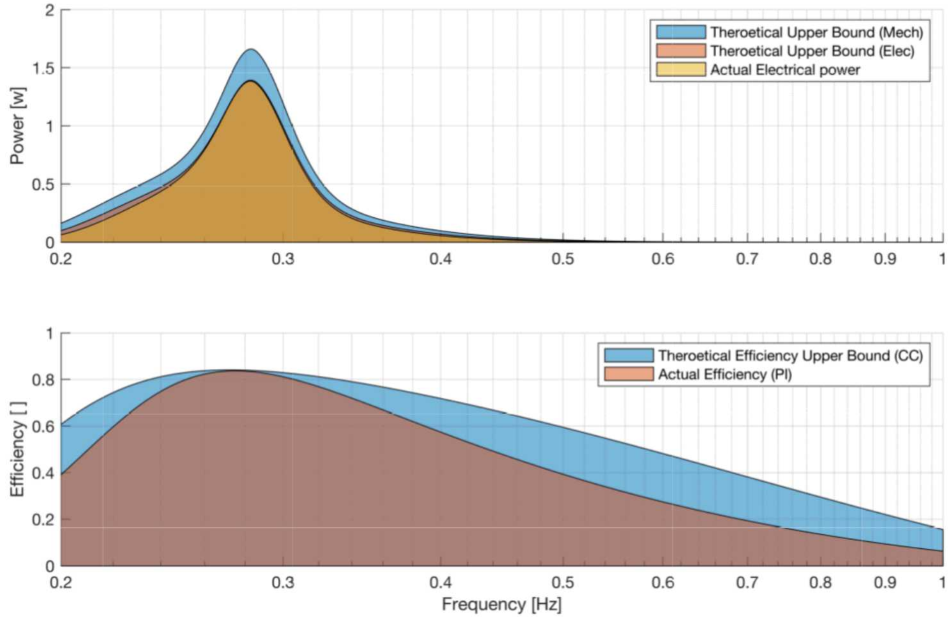


Table 1: Performance improvements with a co-optimized PTO

	Non co-optimized PTO		Co-optimized PTO	
	P[W]	η	P[W]	η
Mechanical (CC)	129.3	1	129.3	1
Electrical (CC)	41.2	0.32	103.7	0.80
Electrical (PI)	38.2	0.30	97.4	0.75

PTO parameters to be optimized:

$$\Theta = \{N, I_d, K_d\}$$

Example 2: Co-optimization of PTO and control with non-colocated controller

$$i = C\,\Omega$$

Measure angular velocity of the shaft Ω
Control the current on the generator i

Non-colocated controller
$C \neq Z_L$

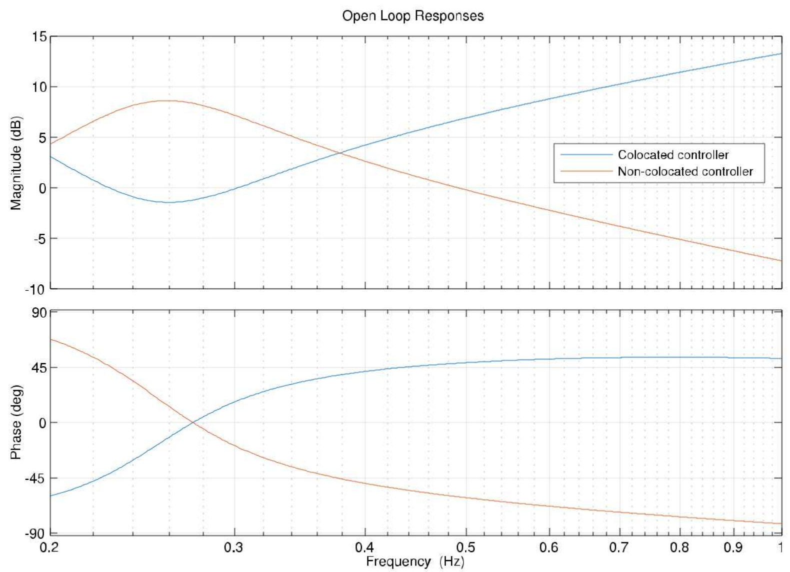
$$Z_L = Z_w + \frac{3\,K_t}{2\,C}$$

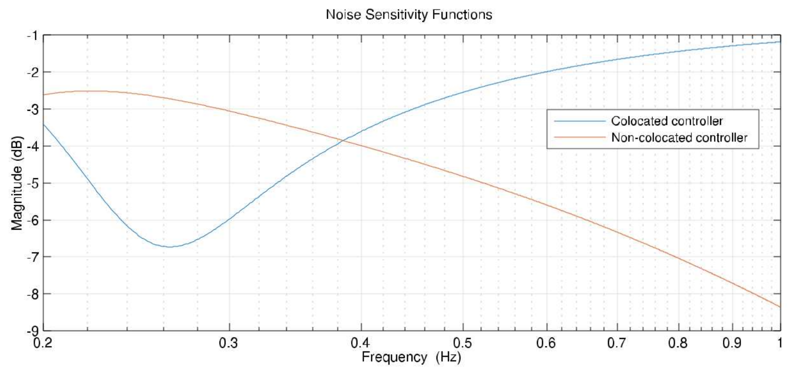
Table 1: Performance improvements with a co-optimized PTO and non-colocated controller

	Non co-optimized PTO		Co-optimized PTO	
	P[W]	η	P[W]	η
Mechanical (CC)	129.3	1	129.3	1
Electrical (CC)	41.2	0.32	103.7	0.80
Electrical (PI)	40.3	0.31	97.4	0.75

Example 2: Co-optimization of PTO and control with non-colocated controller (cont.)

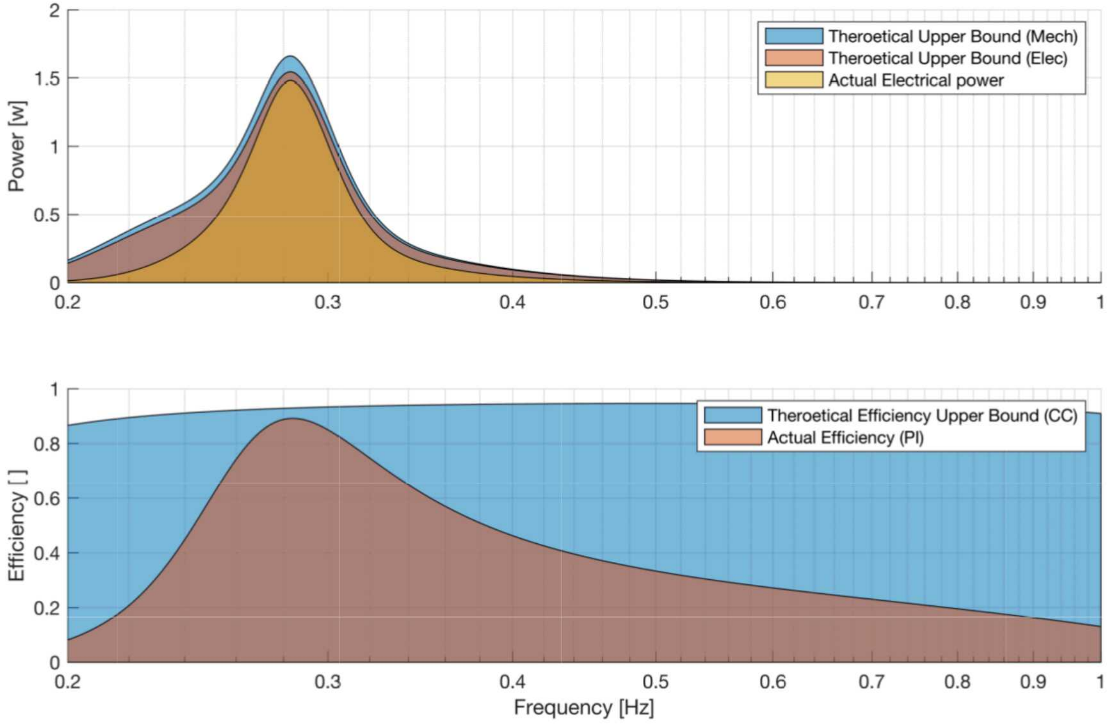
- NC controller has same power performance as collocated
- NC controllers have to be implemented when cannot measure and control directly quantities related to power
- Structure of the feedback loop depends on the availability and quality of measurements (sensors) and actuators.
- Very different dynamic behavior





Example 3: Reducing winding resistance vs co-optimization

Nominal PTO with very small (1 mΩ) R_w



Optimized PTO with larger (100 mΩ) R_w

$\boldsymbol{\Theta} = \{N, I_d, K_d\}$

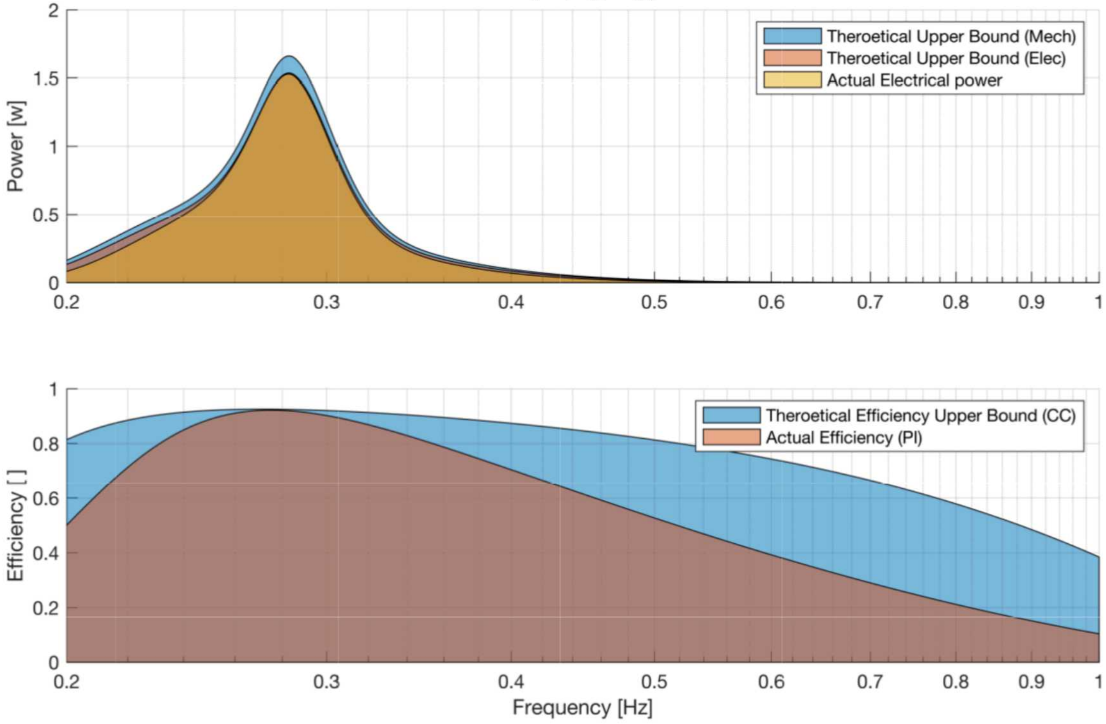


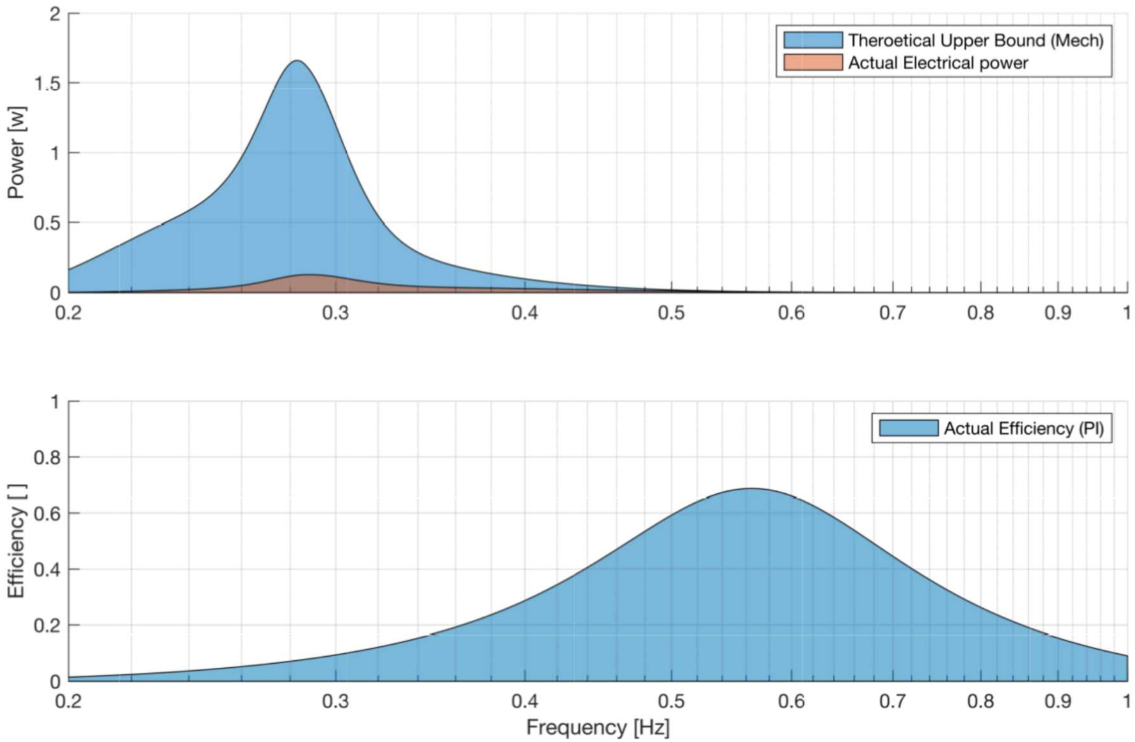
Table 1: Performance improvements with a co-optimized PTO and non-colocated controller

	Non optimized PTO $R_w = 1\text{m}\Omega$		Optimized PTO $R_w = 100\text{m}\Omega$	
	P[W]	η	P[W]	η
Mechanical (CC)	129.3	1	129.3	1
Electrical (CC)	119.7	0.93	117.5	0.91
Electrical (PI)	89.0	0.69	110.0	0.85

Similar overall efficiency with much less efficient (cheaper) generator

Example 4: Fixed load (damping) with tunable PTO

Fixed load ($Z_L = 10\Omega$), Nominal PTO



Fixed load ($Z_L = 10\Omega$), Tuned PTO

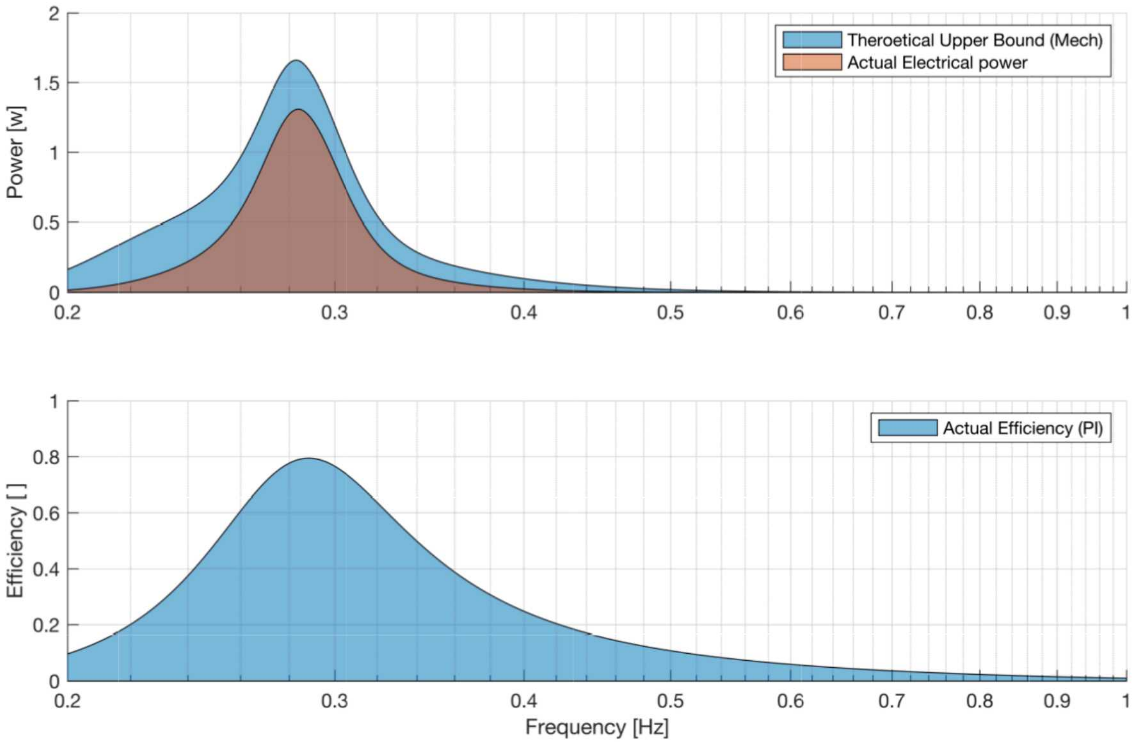


Table 1: Performance improvements of a tuned PTO with a fixed load

	Non Tuned PTO		Tuned PTO	
	P[W]	η	P[W]	η
Theoretical limit ($\bar{P}_m$)	129.3	1	129.3	1
Electrical (P_e)	12.9	0.1	88.0	0.68

$$\Theta = \{I_d, K_d\}$$

Let’s see some examples

https://github.com/SNL-WaterPower/fbWecCntrl/tree/codesign