Control of Wave Energy Devices

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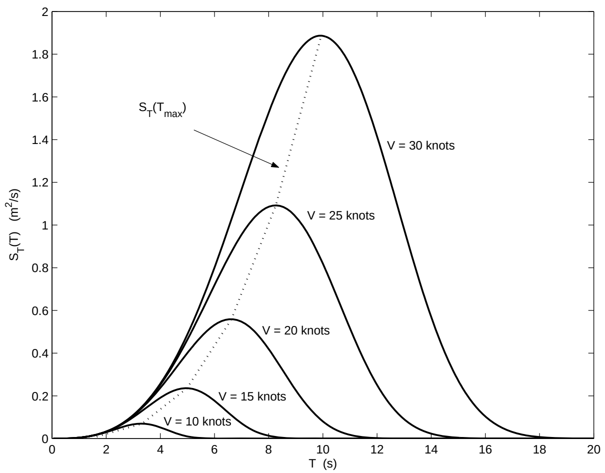
Outline

Outline

Typical P-M Amplitude Spectrum



Discrete frequencies with amplitudes from envelope and random phases used for simulation

Outline

Use of mathematical WEC models

1. Assessment of power production
2. Assessment of loading/forces under extreme sea conditions
3. Simulation of device and array motions,
   - Device geometry optimisation[1] [2]
   - Array layout optimisation[3]
   - Evaluation of effectiveness of control strategies**
4. For use as a basis for model-based control design**

Currently, no 'super' model available[4]

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[1] Garcia Rosa, P.B. and Ringwood, J.V. On the sensitivity of optimal wave energy device geometry to the energy maximising control system. IEEE Trans. on Sustainable Energy, Vol.7, No.1, pp 419-426, 2016

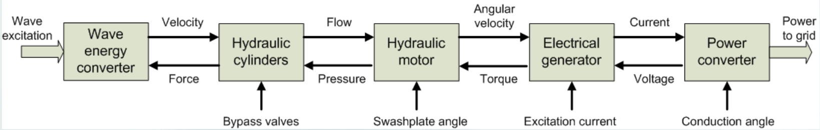
[2] Garcia Rosa, P.B. and Ringwood, J.V. Control-informed geometric optimisation of wave energy converters: The impact of device motion and force constraints, Energies, Vol.8, No.12, pp 13672-13687, 2015

[3] Garcia Rosa, P. B., Bacelli, G. and Ringwood, J.V.. Control-informed optimal layout for wave farms. IEEE Trans. on Sustainable Energy, Vol.6, No.2, pp 575-582, 2015

[4] Penalba, M. and Ringwood, J.V. A review of wave-to-wire models for wave energy converters, Energies, Vol.9, No.7, 506, 2016

Wave-to-wire models

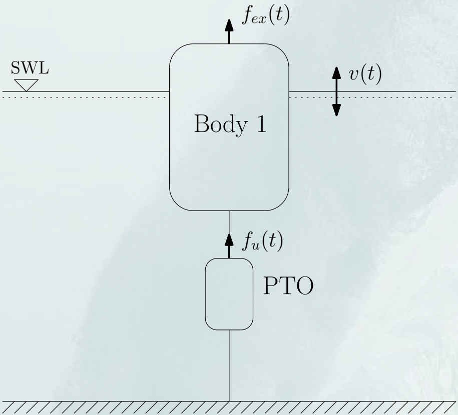
Complete energy flow schematic:



- Multiple changes in form of power (hydrodynamic, mechanical, hydraulic, electrical...)
- Variety of ways to implement torque/force control on PTO
- Ideally, electrical grid should also be modelled
- Bond graphs provide a nice way to model different power/energy forms[5]

[5] Bacelli, G., Gilloteaux, J.-C. and Ringwood, J.V. State space model of a hydraulic power take off unit for wave energy conversion employing bondgraphs, Proc. World Renewable Energy Conference, Glasgow, 2008

Simple heaving buoy



Useful converted power:

$$P_{PTO}(t) = f_u(t)v(t)$$

Basic equation of motion

Following Newton's second law....

$$M\dot{v}(t) = f_m(t) + f_r(t) + f_d(t) + f_v(t) + f_b(t) + f_{ex}(t) + f_u(t) \quad (1)$$

where $v(t)$ is the heaving velocity and M is the WEC mass and

- f_m is the mooring force
- f_r is the radiation force
- f_d is the diffraction force
- f_v is the viscous damping force
- f_b is the buoyancy/gravity restoring force
- f_{ex} is the wave excitation force
- f_u is opposing PTO (control) force

Linear approximation

With the assumptions of linear potential theory:

1. Irrotational, incompressible and inviscid fluid,
2. Small-body approximation (wave elevation constant across the whole body),
3. Small oscillations (constant wetted surface),

the following simplifying equations apply:

$$f_{ex} + f_d(t) = \int_{-\infty}^{+\infty} h_{ex}(\tau)\eta(t-\tau)d\tau \tag{2}$$

$$f_r(t) = -\int_0^t h_r(\tau)v(t-\tau)d\tau - m_\infty \dot{v}(t) \tag{3}$$

$$f_b(t) = -\rho g S_w \int_0^t v(\tau)d\tau = -K_b x(t) \tag{4}$$

$$f_v(t) = 0. \tag{5}$$

Cummins equation

$$(M + m_\infty)\dot{v}(t) + \int_0^{+\infty} h_r(\tau)v(t-\tau)d\tau + K_b x(t) = \underbrace{\int_{-\infty}^{t} h_{ex}(\tau)\eta(t-\tau)d\tau}_{F_{ex}(t)} + f_u(t) \quad (6)$$

$h_{ex}(t)\,[H_{ex}(\omega)]$ and $h_r(t)\,[H_r(\omega)]$ are typically calculated numerically (non-parametric form) using boundary-element potential methods such as WAMIT, AQUAPLUS, NEMOH, AQWA or ACHIL3D

Radiation damping approximations

Can replace the radiation damping convolution term in (3) by a closed form (finite order) equivalent:

- The integro-differential equation in (6) replaced by a higher-order differential equation, making analysis more straightforward,
- The resulting finite-order dynamical system is faster to simulate, and
- The closed-form dynamical equation can be used as a basis for model-based control design.

Typically, equivalents in the form of:

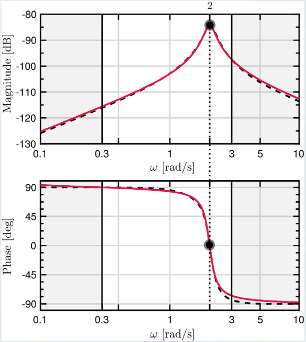
- Transfer function (McCabe et al, 2005)
- State-space (Perez and Fossen, 2009; Faedo et al, 2018[6])
- Impulse response (de Prony, 1795)

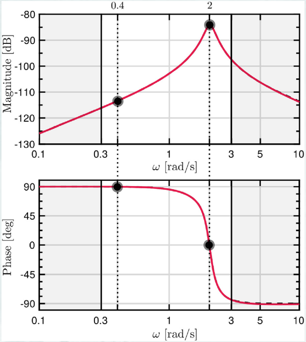
are produced, using time domain (Prony's method) or freq. domain fitting.

[6] Faedo, N., Pena-Sanchez and Ringwood, J.V. Finite-order hydrodynamic model determination for wave energy applications using moment matching, Ocean Engineering, Vol.163, pp 251-263, 2018.

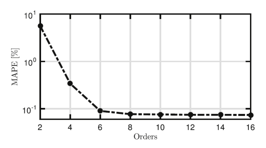
The FOAMM Toolbox

FOAMM - **F**inite **O**rder **A**pproximation using **M**oment **M**atching





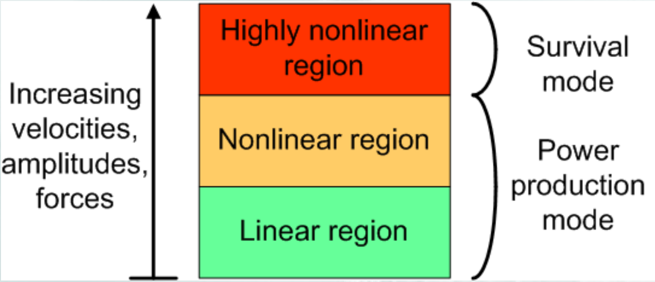
Force-to-velocity frequency response computed with NEMOH (dashed-black) and the reduced order model (solid-red), considering one/two interpolation points.



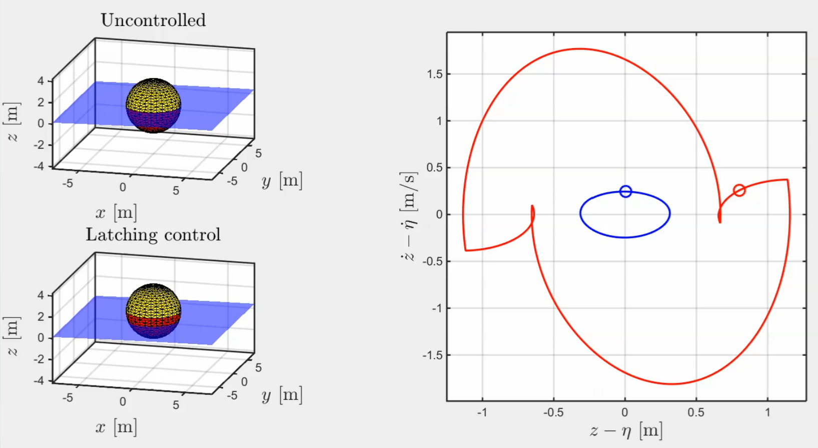
WEC operating regions

Possible nonlinearities:

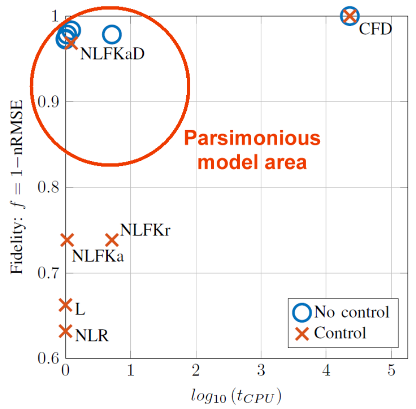
- Nonlinear fluid/structure interactions
- Nonlinear PTO system
- Nonlinear waves



Linearisation ?



Comparison of modelling methodologies[7]



L: A fully linear model, considering the mean wetted surface

NLR: A nonlinear static FK force model, using the instantaneous restoring force

NLFKa: A nonlinear static and dynamic FK forces model, using the algebraic solution of the pressure integral over the instantaneous wetted surface

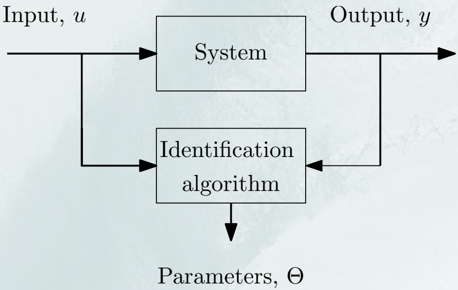
NLFKr: A nonlinear static and dynamic FK forces model, using a discretized geometry and a re-meshing routine to determine the instantaneous wetted surface

NLFKaD: An algebraic nonlinear static and dynamic FK forces model with a viscous drag term

CFD: A fully-nonlinear model, using a computational fluid dynamics software

[7] Giorgi, G. and Ringwood, J.V. Nonlinear hydrodynamic modelling for wave energy devices in the computation/fidelity continuum, Ocean Engineering, Vol.141, pp 164-175, 2017.

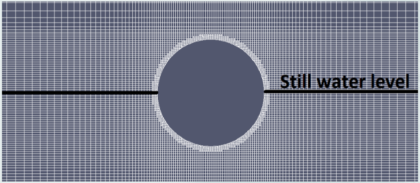
Hydrodynamic models from data

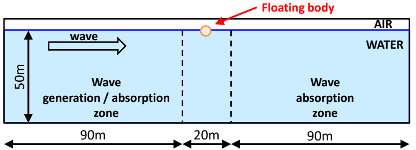


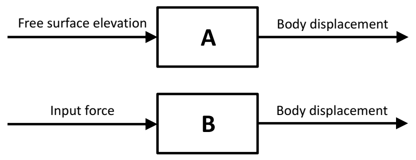
Need to consider:

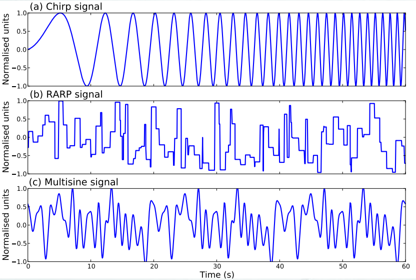
- How the device output/motion is calculated/measured (NWT or tank/ocean)
- What type of excitation should/can be generated
- How the model will be parameterised, and
- How the model parameters will be identified

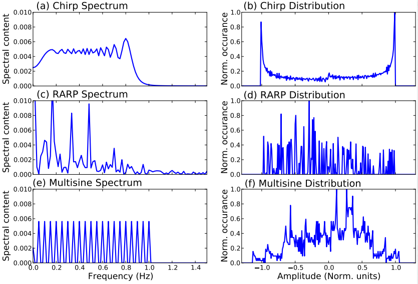
Data from numerical wave tank



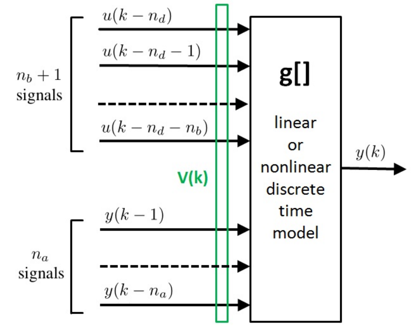








Model parameterisation



Kolmogorov-Gabor polynomial (KGP) model:

$$
\begin{aligned}
y(k) &= \sum_{i=1}^{n_a} a_{i1} y(k-i) + \sum_{i=0}^{n_b} b_{i1} u(k-n_d-i) \\
&+ \dots \\
&+ \sum_{i=1}^{n_a} a_{ip} y^p(k-i) + \sum_{i=0}^{n_b} b_{ip} u^p(k-n_d-i) \\
&+ \sum_{i=1}^{n_a} \sum_{j=0}^{n_b} c_{ij} y(k-i) u(k-n_d-j) \\
&+ \dots
\end{aligned}
\tag{7}
$$

NWT and ID procedures documented in [8] [9]

[8] Davidson, J., Giorgi, S. and Ringwood, J.V. Identification of wave tank models from numerical wave tank data Part 1: NWT identification tests. IEEE Trans. on Sustainable Energy, Vol.7, No.3, pp 1012-1019, 2016

[9] Giorgi, S., Davidson, J. and Ringwood, J.V. Identification of wave tank models from numerical wave tank data Part 2: Data-based model determin. IEEE Trans. on Sustainable Energy, Vol.7, No.3, pp 1020-1027, 2016

Outline

Control problem statement

The real control objective:

Energy cost minimisation

Minimise the Levelised Cost of Energy (LCoE) over the WEC/project lifetime

$$LCoE = \frac{PV(CapEx) + PV(OpEx)}{PV(EP)} \quad , \quad PV(CF) = \sum_{y=y_0}^{Y} \frac{CF(y)}{(1 + R_d/100)^y} \tag{8}$$

usually distilled to:

Energy maximisation

Maximise captured energy:

$$E_c = \int_0^T v(t) F_{PTO}(t) dt \tag{9}$$

subject to:

$$|z(t)| < z_{max} \tag{10}$$

$$|F_{PTO}(t)| < F_{max} \tag{11}$$

$$|v(t)| < v_{max} \tag{12}$$

Control fundamentals

From (6),

$$\frac{V(\omega)}{F_{ex}(\omega) + F_{PTO}(\omega)} = \frac{1}{Z_i(\omega)}, \quad (13)$$

where $Z_i(\omega)$ is the intrinsic WEC impedance:

$$Z_i(\omega) = B_r(\omega) + \jmath\omega \left[M + M_a(\omega) - \frac{k}{\omega^2} \right], \quad (14)$$

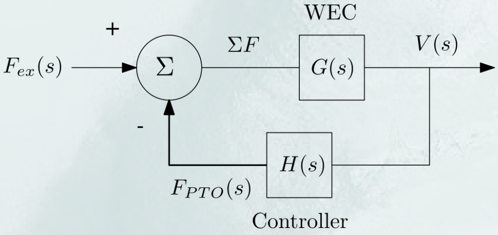
with $M_a(\omega)$ the added mass ($m_\infty = \lim_{\omega\to\infty} M_a(\omega)$) and $B_r(\omega)$ the radiation damping.
For maximum power transfer, we choose a controller 'impedance' $Z_c(\omega)$, ($F_{PTO} = Z_c V$), so that

$$Z_c(\omega) = Z_i^*(\omega), \quad (15)$$

where z^* denotes the complex conjugate of $z \in \mathbb{C}$. Alternatively, an optimal velocity profile $V_{opt}(\omega)$ to follow can be generated:

$$V_{opt}(\omega) = \frac{F_{ex}(\omega)}{2B_r(\omega)} \quad (16)$$

ACC controller



Parameterise the control force as:

$$f_{PTO}(t) = M_c\ddot{x}(t) + B_c\dot{x}(t) + k_c x(t), \tag{17}$$

giving

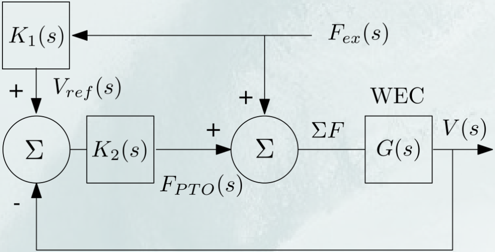
$$Z_c = F_{PTO}/V = B_c + j\left(\omega M_c - \frac{k_c}{\omega}\right) \quad , \quad H(s) \equiv Z_c(\omega) \tag{18}$$

$$G(s) = \frac{s}{(M + M_a^\omega)s^2 + B_r^\omega s + k}, \quad H(s) = \frac{-(M + M_a^\omega)s^2 + B_r^\omega s - k}{s} \tag{19}$$

and

$$T(s) = \frac{G(s)}{1 + G(s)H(s)} = \frac{1}{2B_r^\omega}, \quad \rightarrow V(s) = T(s)F_{ex}(s) = \frac{F_{ex}(s)}{2B_r^\omega} \tag{20}$$

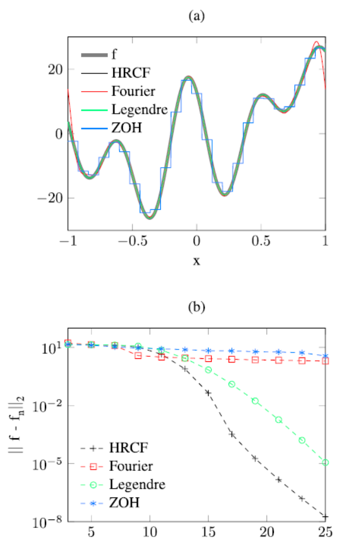
AVT controller

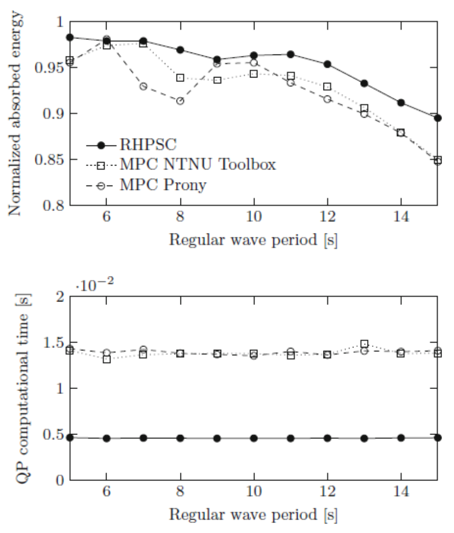


- Effectively implements a version of $V_{opt}(\omega) = \dfrac{F_{ex}(\omega)}{2B_r(\omega)}$ i.e. (16)
- $v_{ref}(t)$ is usually evaluated as the solution of a numerical optimisation problem[10] for panchromatic case
- Since K_1 is, in general, anticausal, future knowledge of $f_{ex}(t)$ is required
- Can include physical constraints in optimisation problem
- Can apply robust synthesis to velocity tracking loop

[10] Faedo, N., Olaya, S., and Ringwood, J.V. (2017). Optimal control, MPC and MPC-like algorithms for wave energy systems: An overview. IFAC Journal of Systems and Control, Vol.1, pp 37-56

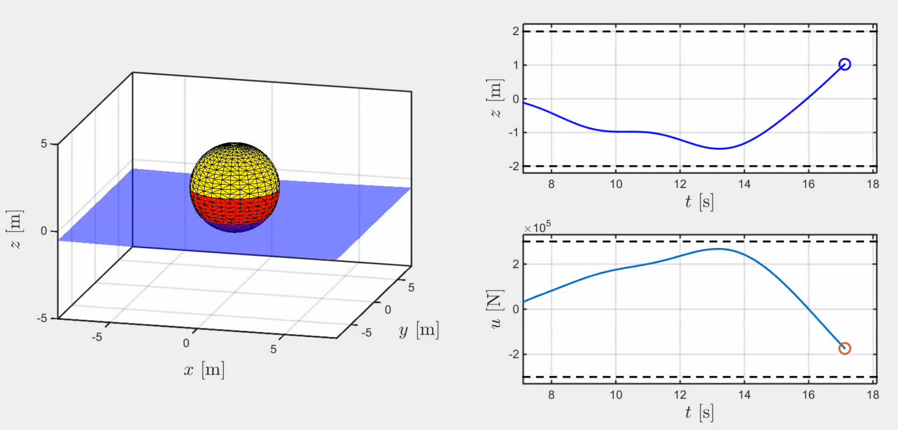
Signal parameterisation[11]





[11] Genest, R. and Ringwood, J.V. Receding horizon pseudospectral control for energy maximisation with application to wave energy devices, IEEE Trans. on Control Systems Technology, Vol.25, No.1, pp 29-38, 2017

WEC control using moment matching[12]



[12] Faedo, N., Scarciotti, G., Astolfi, A. and Ringwood, J.V. Energy maximising control of wave energy devices using a moment-domain representation, Control Engineering Practice, Vol.81, pp 85-96, 2018

Outline

ACC controller calculations[13]

$$S_G^T(s) = \frac{dT(s)}{dG(s)}\frac{G(s)}{T(s)} = \frac{1}{1+G(s)H(s)} = S_G^T(s) = \frac{(M+M_a^\omega)s^2 + B_r^\omega s + k}{2B_r^\omega s} \quad (21)$$

Also, since, in general, $S_\alpha^T(s) = \frac{\alpha}{T(s)}\frac{dT(s)}{d\alpha} = S_G^T(s)S_\alpha^G(s)$,

$$S_{M*}^G(s) = -\frac{M^* s^2}{M^* s^2 + B_r^\omega s + k} \quad (22)$$

$$S_B^G(s) = -\frac{B_r^\omega s}{M^* s^2 + B_r^\omega s + k} \quad (23)$$

$$S_k^G(s) = -\frac{k}{M^* s^2 + B_r^\omega s + k} \quad (24)$$

$$S_{M*}^T(s) = S_G^T(s)S_{M*}^G(s) = -\frac{M^* s^2}{2B_r^\omega} \quad (25)$$

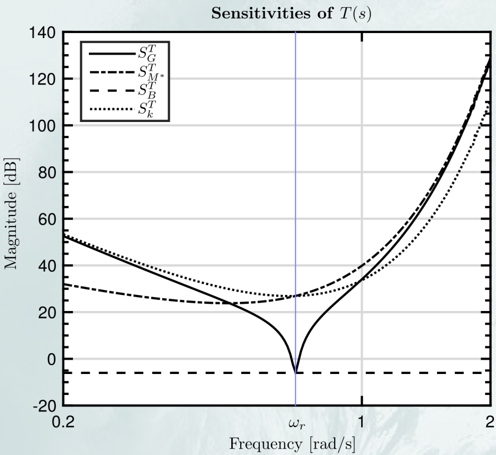
$$S_B^T(s) = S_G^T(s)S_B^G(s) = -\frac{1}{2} \quad (26)$$

$$S_K^T(s) = S_G^T(s)S_K^G(s) = -\frac{k}{2B_r^\omega s} \quad (27)$$

Note that $M^* = M + M_a^\omega$

[13] Ringwood, J.V., Merigaud, A., Faedo, N. and Fusco, F. Wave energy control systems: Robustness issues, Proc. 11th IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles (CAMS), Opatija, Croatia, Sept. 2018, pp 62-67

ACC controller results



Power sensitivity[14]

Define:

- $\rho_{\Re} := \frac{\Re\{\epsilon_Z\}}{\Re\{Z_i\}}$ as the relative error in the radiation damping
- $\rho_{\Im} = \frac{\Im\{\epsilon_Z\}}{\Im\{Z_i\}}$ represents relative errors in either inertial or stiffness terms

Then, can evaluate P_{act}/P^o, to different error types, where

- P^o is power converted for the nominal system, and
- P_{act} the actual power converted under perturbed conditions.

[14] Ringwood, J.V., Merigaud, A., Faedo, N. and Fusco, F. An analytical and numerical sensitivity and ribustness analysis of wave energy control systems, IEEE Trans. on Control Systems Technology, in press (available online)

Damping term errors

With modelling errors on damping terms only, i.e. errors in $\Re\{Z_i\}$, get:

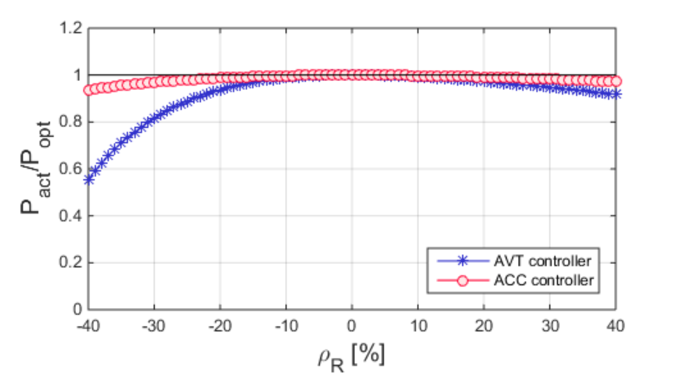
ACC

$$S_{\Re}(\rho_{\Re}) = \frac{1+\rho_{\Re}}{1+\rho_{\Re}+\frac{1}{4}\rho_{\Re}^2} \quad (28)$$

AVT

$$S_{\Re}(\rho_{\Re}) = \frac{1+2\rho_{\Re}}{(1+\rho_{\Re})^2} \quad (29)$$

If $\rho_{\Re} \ll 1$, $S_{\Re}(\rho_{\Re}) \approx 1 - \frac{1}{4}\rho_{\Re}^2, \Rightarrow 10\% \rightarrow 0.25\%$ $\quad S_{\Re}(\rho_{\Re}) \approx 1 - \rho_{\Re}^2, \quad \Rightarrow 10\% \rightarrow 1\%$



Inertial or stiffness errors

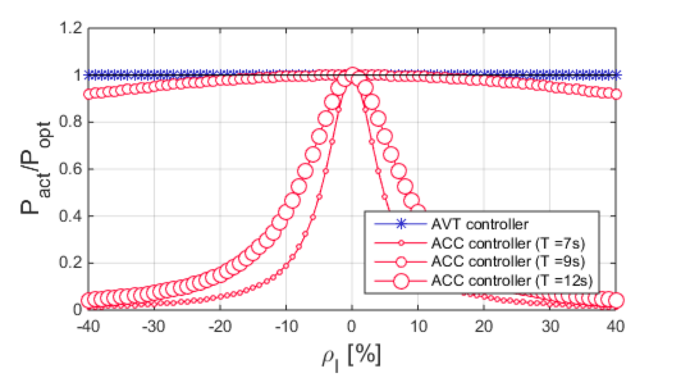
With modelling errors on inertial or stiffness terms only, i.e. errors in $\Im\{Z_i\}$, get:

ACC

$$S_{\Im}(\rho_{\Im}) = \frac{1}{1 + \frac{1}{4}\frac{\Im\{Z_i\}^2}{\Re\{Z_i\}^2}\rho_{\Im}^2} \quad (30)$$

AVT

$$S_{\Re}(\rho_{\Re}) = 1 \quad (31)$$



Note that $Tres \approx 9s$

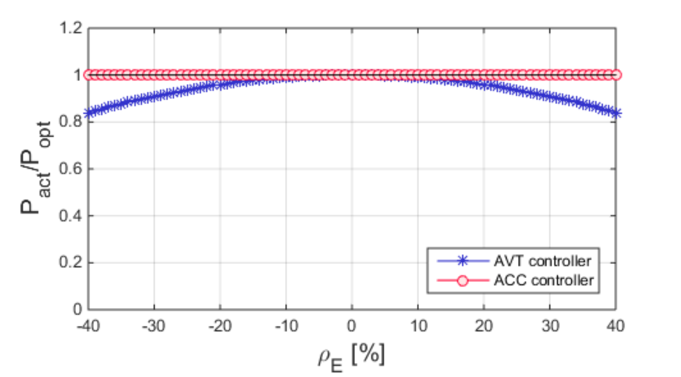
Excitation force errors

ACC

$$S_E(\rho_E) = 1 \quad (32)$$

AVT

$$S_E(\rho_E) = 1 - |\rho_E|^2. \quad (33)$$



Note that ϵ_E and F_{ex} are assumed to have the same phase over $[0; \pi]$
i.e. ρ_E takes positive and negative real values

Outline

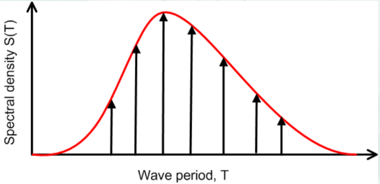
Estimation of F_{ex}

$$\begin{bmatrix} \dot{z} \\ \dot{v} \\ \dot{\hat{F}}_e \\ \ddot{\hat{F}}_e \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{-K_h}{m+A_\infty} & \frac{bh}{m+A_\infty} & \frac{1}{m+A_\infty} & 0 \\ 0 & 0 & 0 & I \\ 0 & 0 & -\Omega^2 & 0 \end{bmatrix} \begin{bmatrix} z \\ v \\ \hat{F}_e \\ \dot{\hat{F}}_e \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} w \quad (34)$$

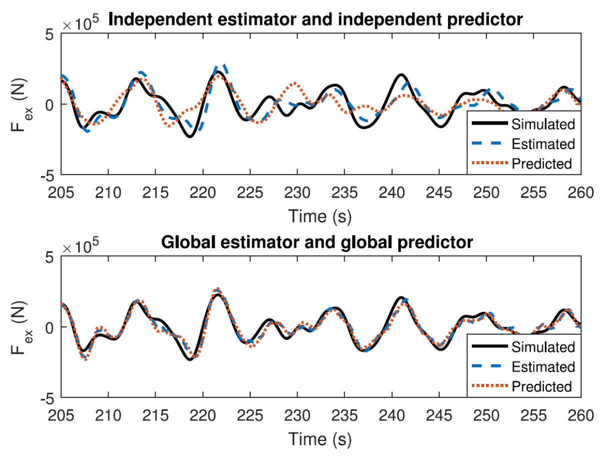
$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} z \\ v \\ \hat{F}_e \\ \dot{\hat{F}}_e \end{bmatrix} + v \quad (35)$$

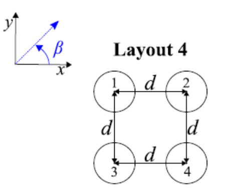
where

$$\Omega = \begin{bmatrix} \omega_1 & 0 & \dots & 0 \\ 0 & \omega_2 & \dots & 0 \\ & & & \\ 0 & 0 & \ddots & \dots \\ 0 & 0 & \dots & \omega_N \end{bmatrix} \quad (36)$$



Estimation and forecasting in arrays[15]





7 frequencies in estimator

AR model for forecasting (4 s)

[15] Pena, Y. Garcia-Abril, M., Paparella, F. and Ringwood, J.V. Estimation and forecasting of excitation force for arrays of wave energy devices, IEEE Trans. on Sustainable Energy, Vol.9, No.4, pp 1672-1680, Oct. 2018

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Conclusions

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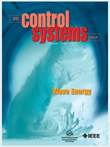
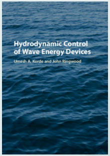
- System identification straightforwardly applied, but limitations on wave excitation signal
- Unknown input, rather than state estimation
- Forecasting necessary for non-causal control strategy
- Some rather spectacular sensitivity functions - nonlinear models required
- WEC arrays present both challenge and opportunity (measurement array)

More info, and a few plugs!



Ringwood, J.V., Bacelli, G. and Fusco, F. Energy-maximising control of wave energy converters: The development of control system technology to optimise their operation, *IEEE Control Systems Magazine*, Vol.34, No.5, pp 30-55, Oct. 2014.



Korde, U.A. and Ringwood, J.V. *Hydrodynamic Control of Wave Energy Devices*, Cambridge University Press, 2016.

See also:

http://www.eeng.nuim.ie/coer/publications/

Thank You !