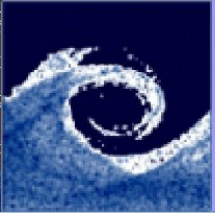


Nonlinear Rock and Roll - Modelling and Control of Parametric Resonance in Wave Energy Devices

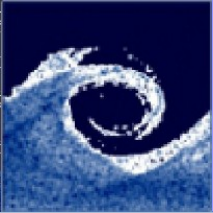
Josh Davidson

Dept of Fluid Mechanics
Budapest University of Technology and Economics



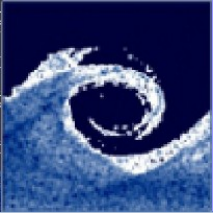
Outline

- Recap of presentation from last workshop
- Parametric resonance in WECs
 - Project background
 - Modelling methods
 - Control



Last Workshop

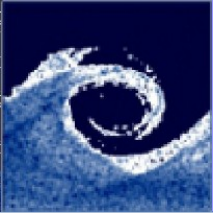
“Evaluation of Energy Maximising Control Systems for WECs using CFD”



Last Workshop

“Evaluation of Energy Maximising Control Systems for WECs using CFD”

- Utilising CFD Numerical Wave Tanks (NWTs) as a high-fidelity test bed for control performance

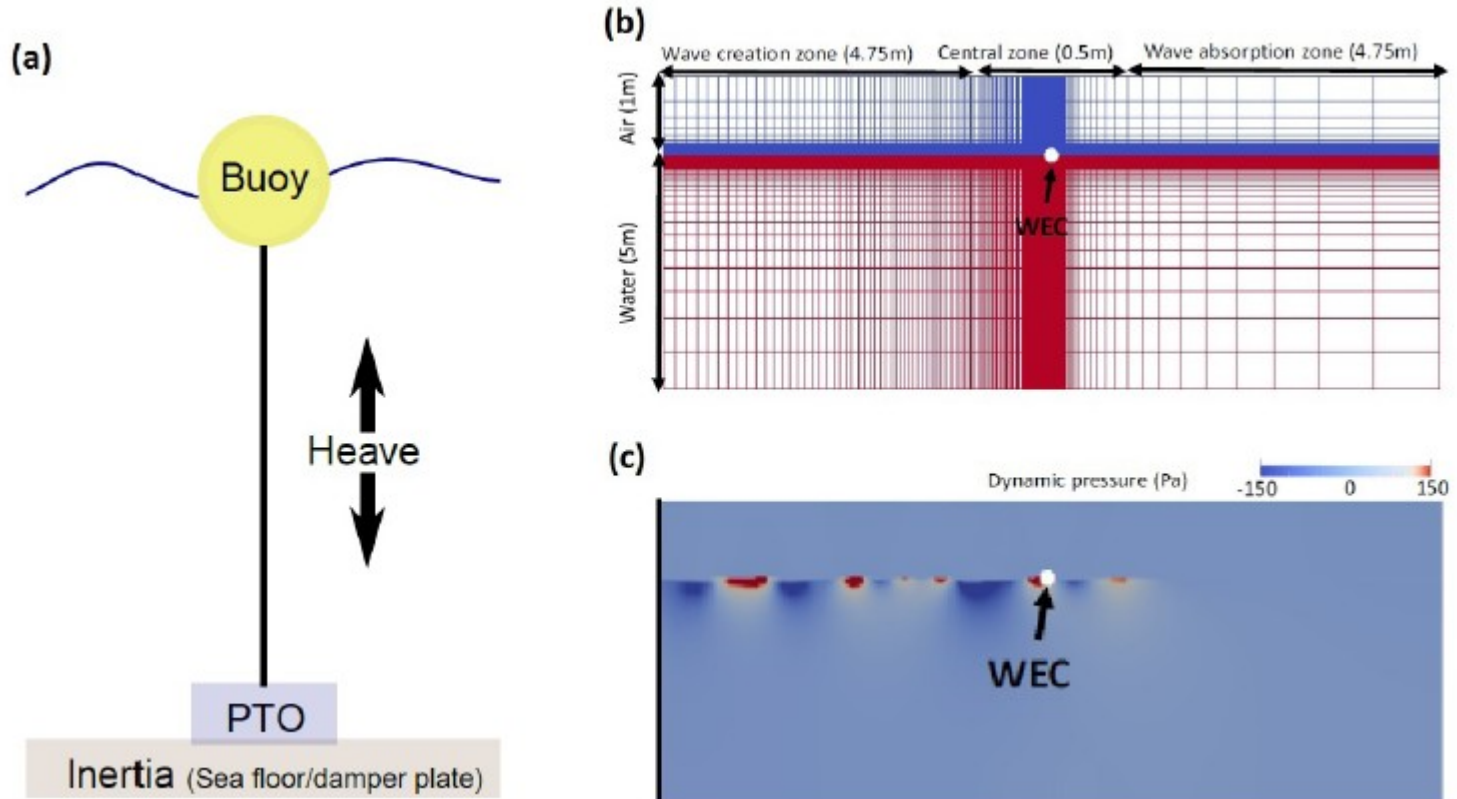


Last Workshop

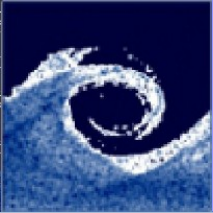
“Evaluation of Energy Maximising Control Systems for WECs using CFD”

- Utilising CFD Numerical Wave Tanks (NWTs) as a high-fidelity test bed for control performance
- System identification of computationally efficient hydrodynamic models from CFD NWT experiments

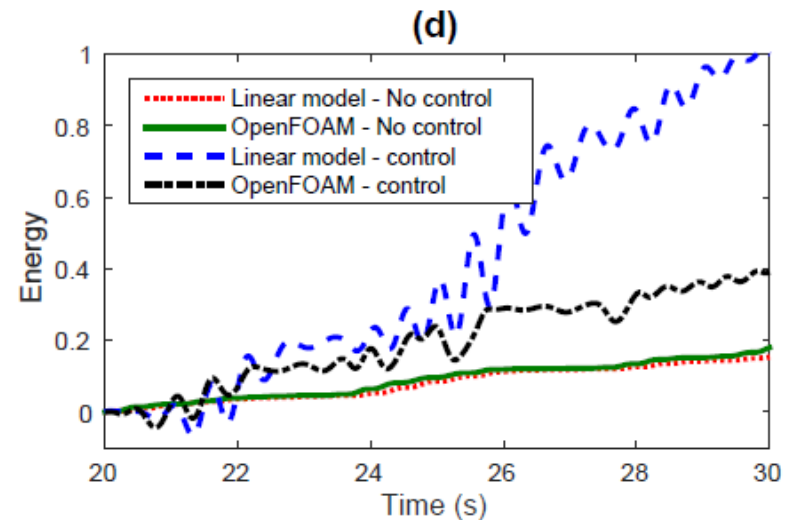
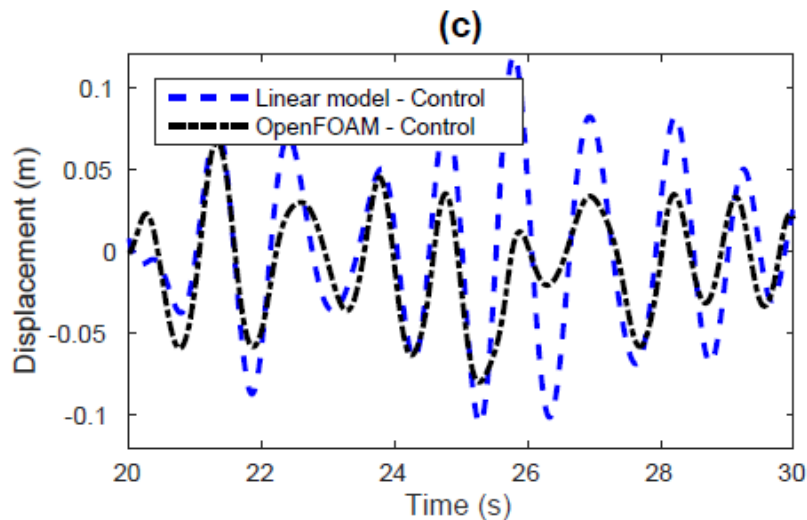
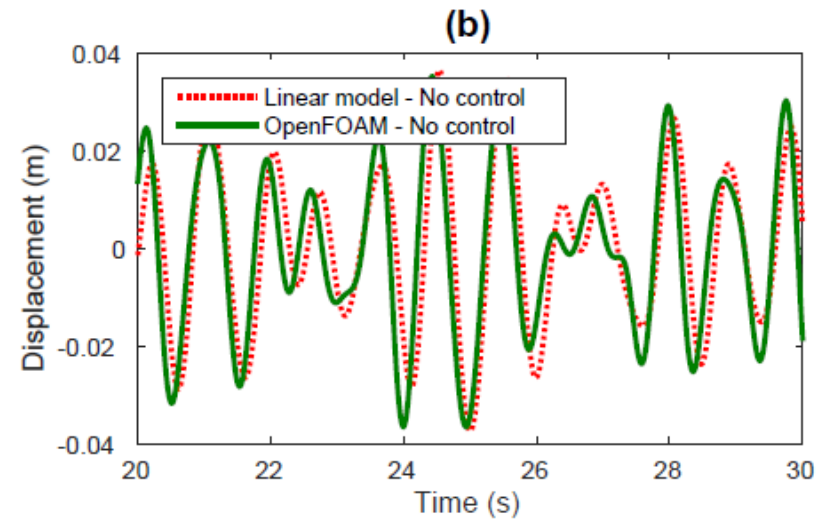
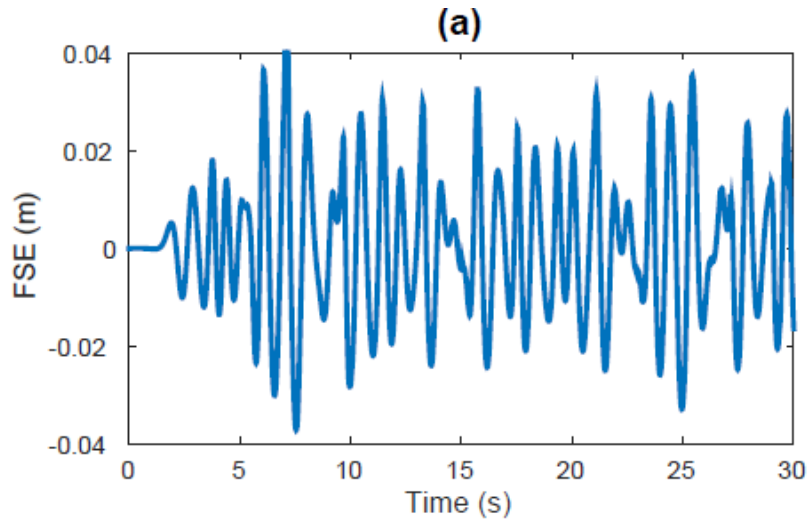
Motivating Example



* Davidson et al, "Evaluation of energy maximising control systems for wave energy converters using OpenFOAM", OpenFOAM – Selected papers from the 11th Workshop, Springer, 2019

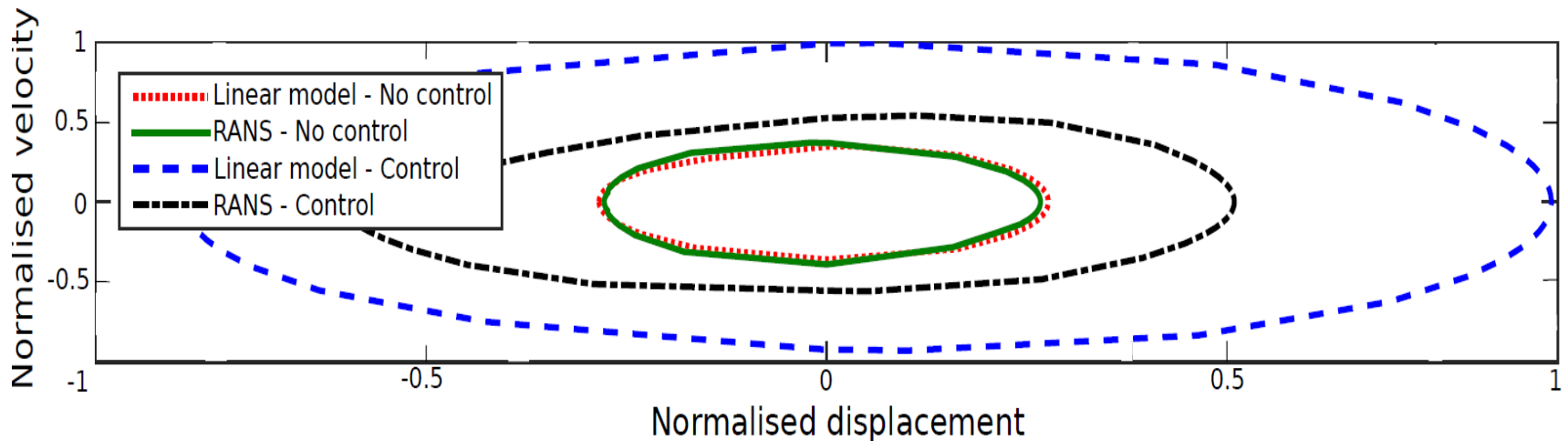


Results

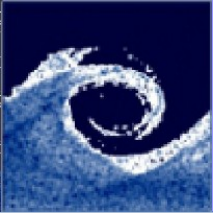


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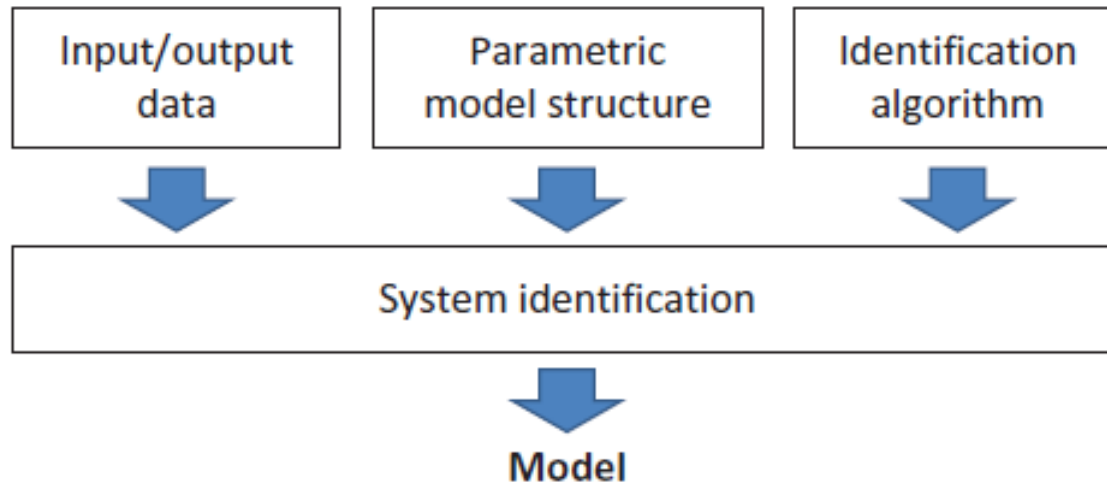
Operational Space



* Davidson et al, "Evaluation of energy maximising control systems for wave energy converters using OpenFOAM", OpenFOAM – Selected papers from the 11th Workshop, Springer, 2019

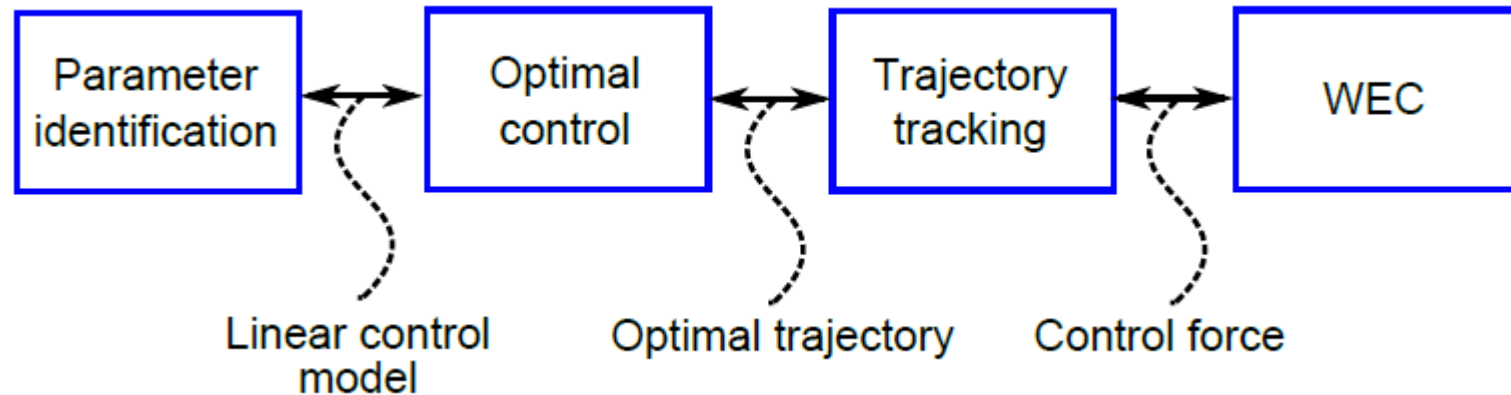


System Identification

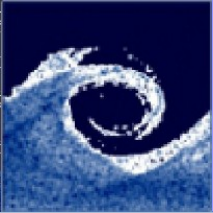


* Ringwood, Davidson and Giorgi, *"Identifying Models Using Recorded Data"*, Numerical Modelling of Wave Energy Converters : State-of-the-art for single devices and arrays, Academic Press, 2016

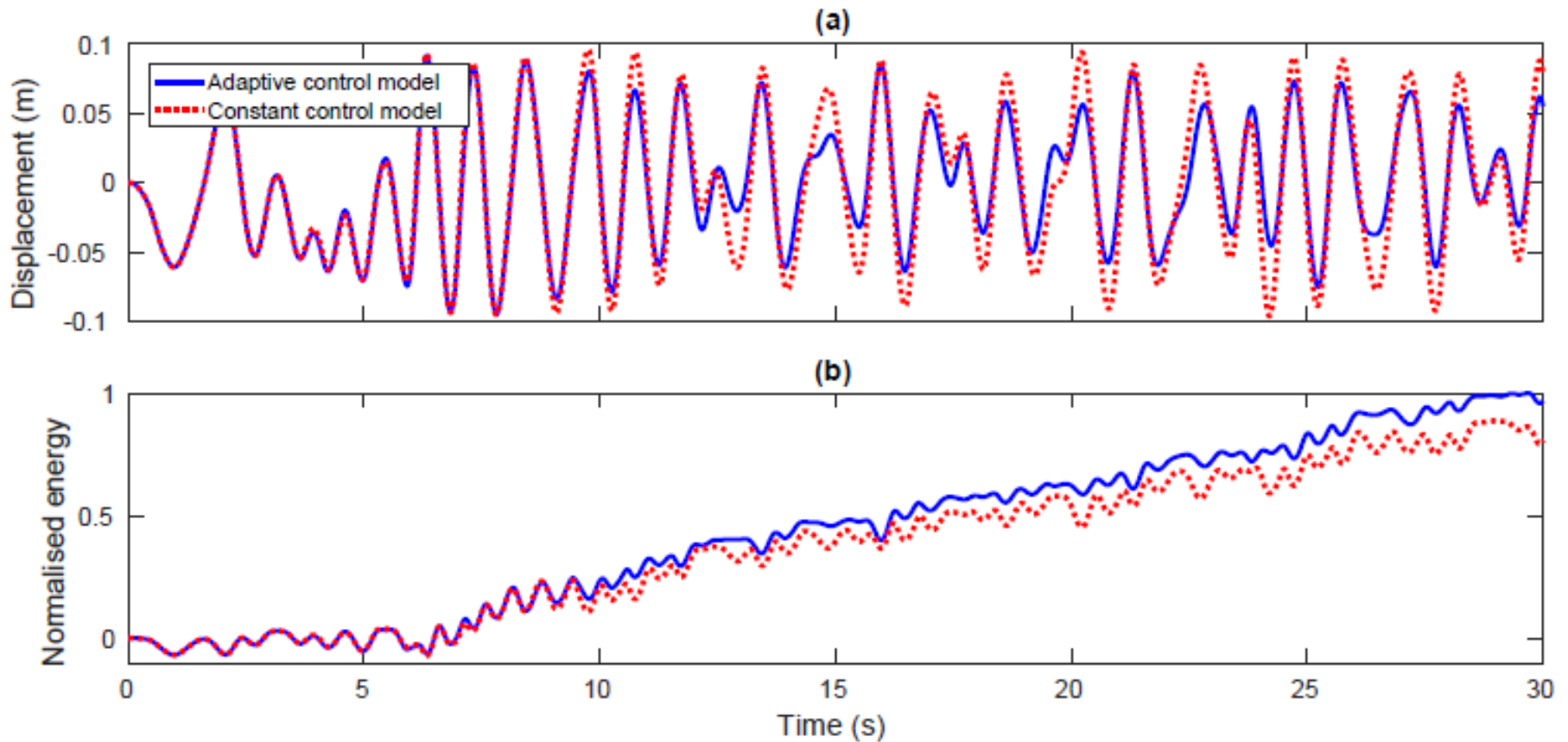
Adaptive Control

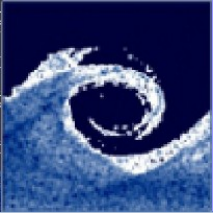


* Davidson, Genest and Ringwood, *"Adaptive control of a WEC simulated in a numerical wave tank"*, EWTEC, 2017

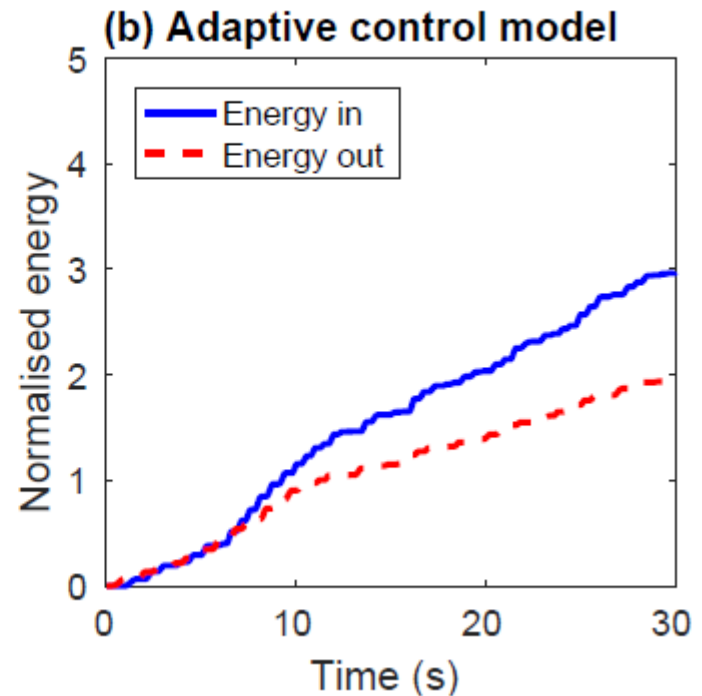
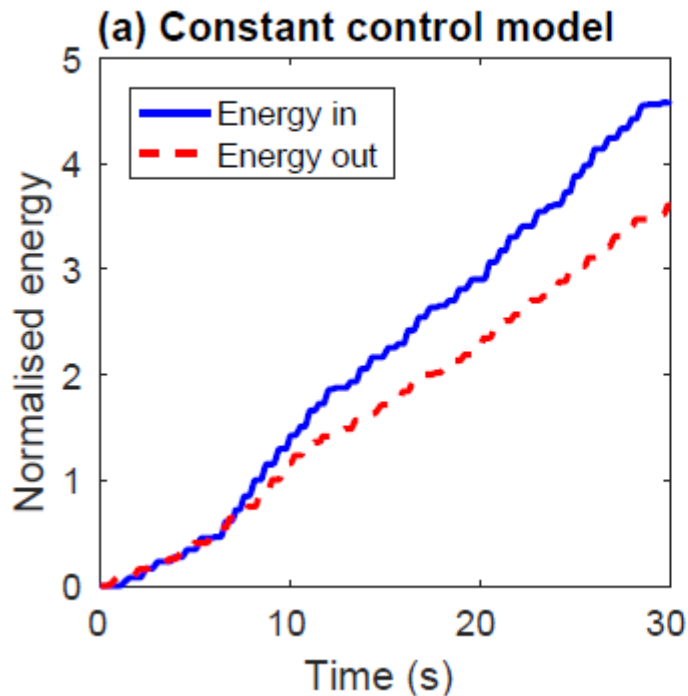


Results

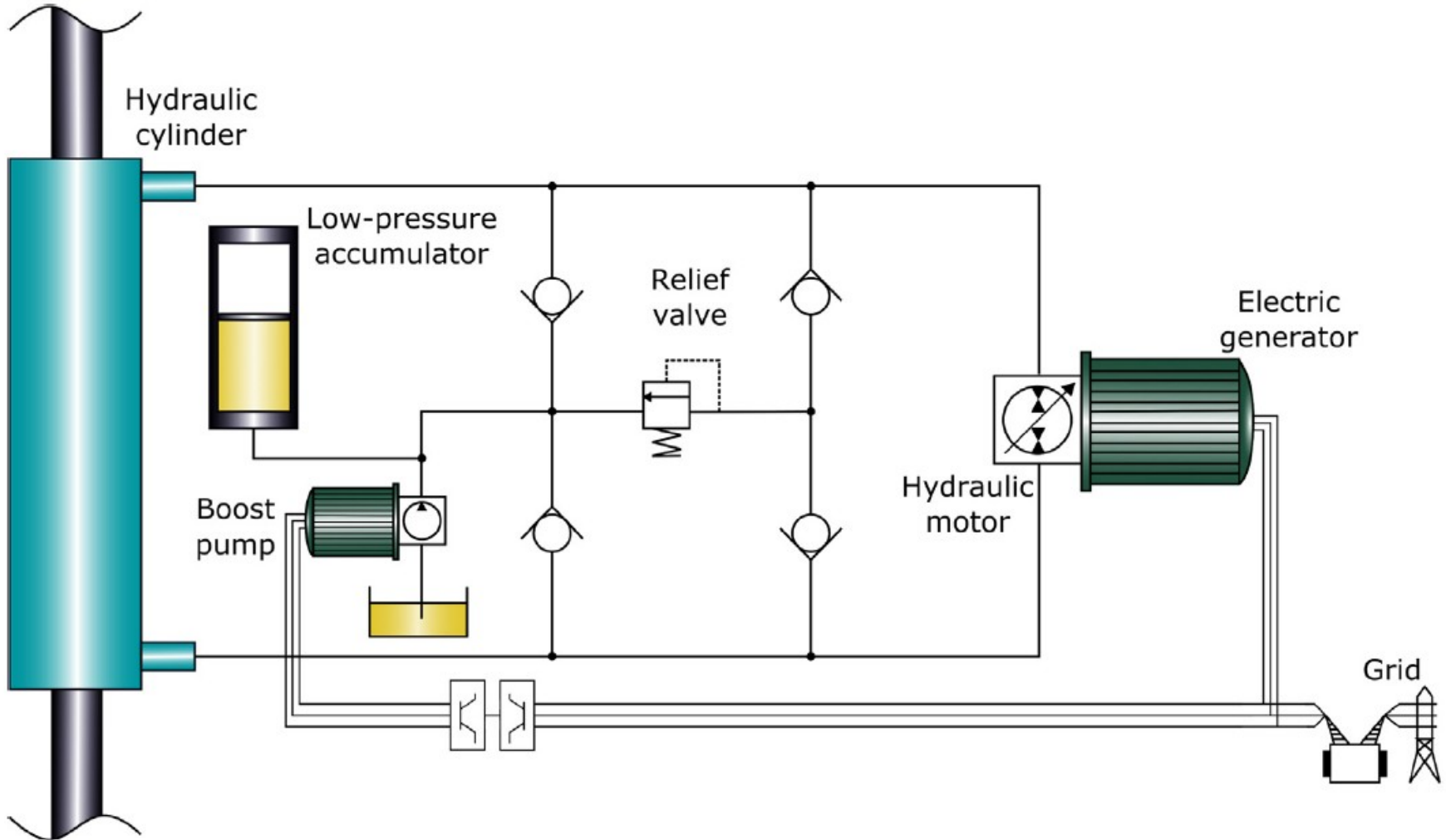




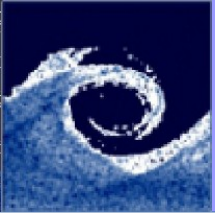
PTO Energy Flow



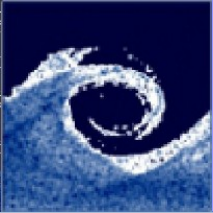
PTO Modelling and Efficiency



* Penalba, Davidson, Windt and Ringwood, "A high-fidelity wave-to-wire simulation platform for wave energy converters: Coupled numerical wave tank and power take-off models", Applied Energy, 2018



Parametric Resonance in WECs



Background

- Open forum discussion at 2017 Maynooth Wave Energy Workshop lead by Prof Alain Clement



2017 Maynooth University Wave Energy Workshop

20/01/2017

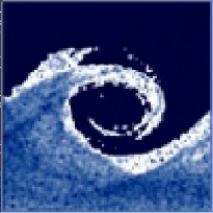


© final: Open Forum discussion

INSTABILITIES of WECs :

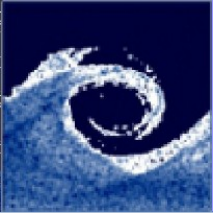
Good news? Bad news?

Alain H. CLEMENT, Senior Researcher , LHEEA Lab, ECN/CNRS , Nantes (FR)



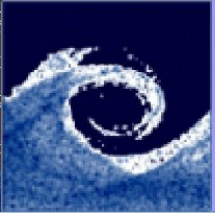
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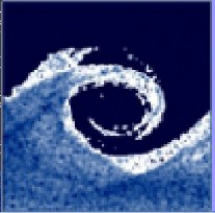
Background

- Open forum discussion at 2017 Maynooth Wave Energy Workshop lead by Prof Alain Clement
- Collaboration with Dr Tamas Kalmar-Nagy from the Dept of Fluid Mechanics, Budapest University of Technology and Economics (BME)
- May 2019 : Commenced 2 year EU funded Research Fellowship, at Dept Fluid Mechanics, BME for project '*Nonlinear Rock and Roll – Modelling and Control of Parametric Resonance in Wave Energy Converters*'
 - Secondments with IST Lisbon, DTU, Wave Venture and Mocean Energy



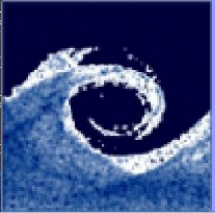
Parametric Resonance

- Parametric resonance is a phenomenon caused by the time-varying changes in the parameters of a system



Parametric Resonance

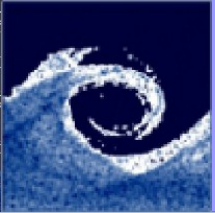
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- Example:



Parametric Resonance

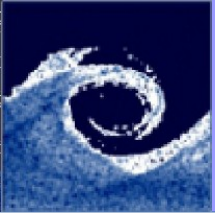
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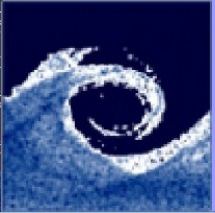
Parametric Resonance in floating bodies

- First observations/studies date back to **Froude** in **1861** who described that large roll motions occur when a ship's roll natural period is twice the heave/pitch natural period.



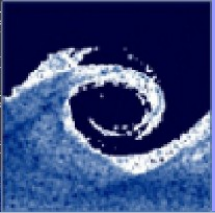
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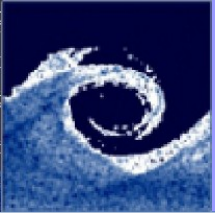
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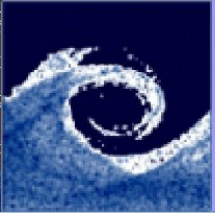
Parametric Resonance in floating bodies

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- Parametric roll is a well known problem in shipping
- Many other studies for parametric pitch/roll of offshore spar platforms
- **BAD NEWS** – Parametric resonance is considered an undesired problem in these fields and research focusses on suppression and stabilisation of parametric pitch/roll



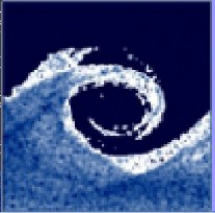
Parametric Resonance in WECs

Resonance	Parametric Resonance



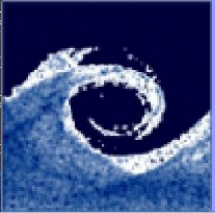
Parametric Resonance in WECs

Resonance	Parametric Resonance
<ul style="list-style-type: none">• Well known in wave energy	<ul style="list-style-type: none">• Very little attention



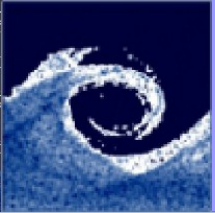
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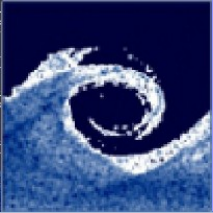
Parametric Resonance in WECs

Resonance	Parametric Resonance
<ul style="list-style-type: none">• Well known in wave energy	<ul style="list-style-type: none">• Very little Much less attention
<ul style="list-style-type: none">• Linear modelling	<ul style="list-style-type: none">• Nonlinear modelling

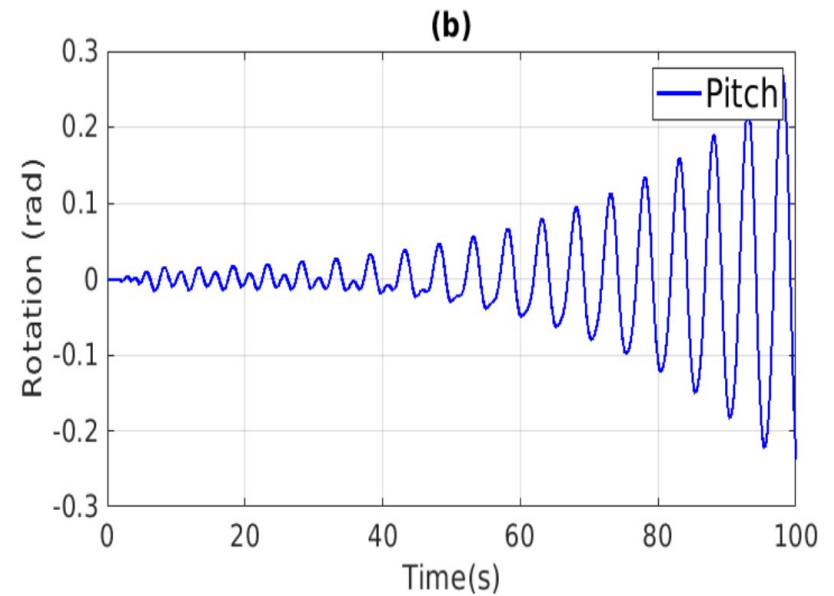
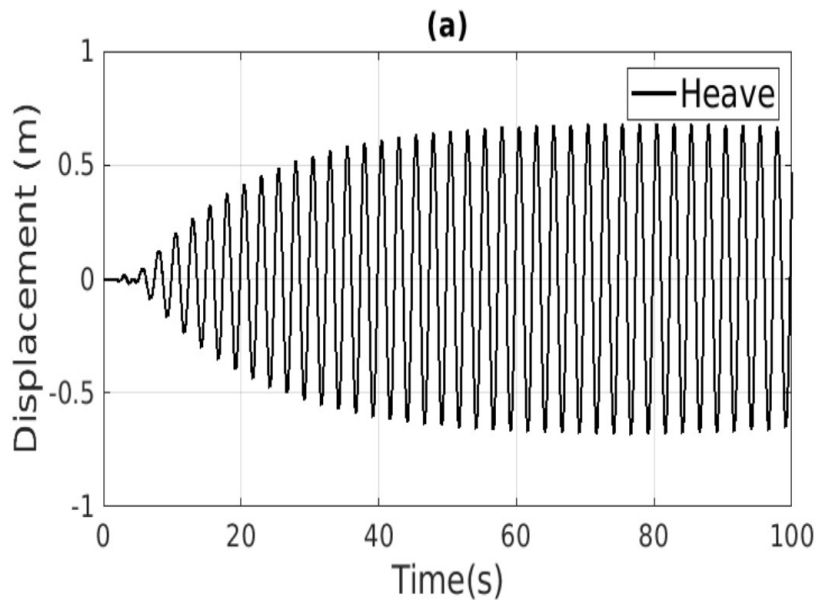


Parametric Resonance in WECs

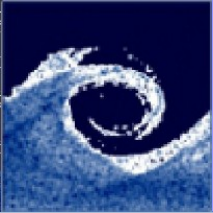
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<ul style="list-style-type: none">• Linear increase in oscillation amplitude	<ul style="list-style-type: none">• Exponential increase in oscillation amplitude



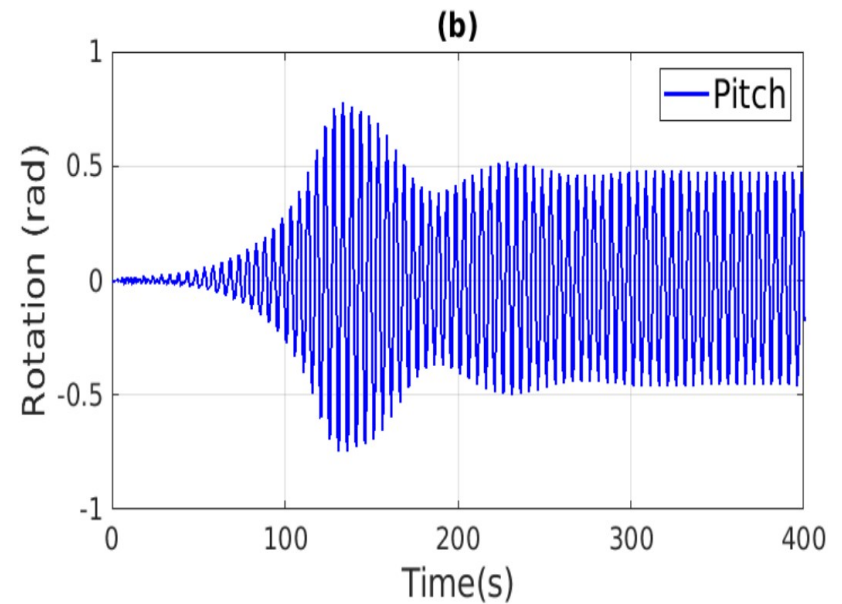
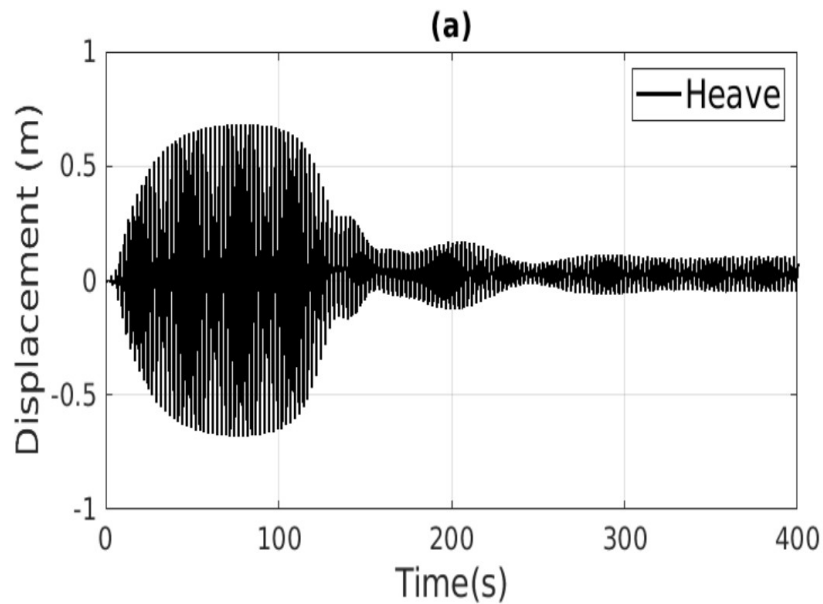
Bad News



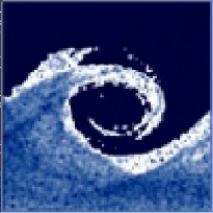
* Davidson, Karimov, Habib and Kalmar-Nagy, *“Parametric excitation suppression in a floating cylinder via dynamic vibration absorbers : A comparative analysis”*, Nonlinear Dynamics, (In preparation)



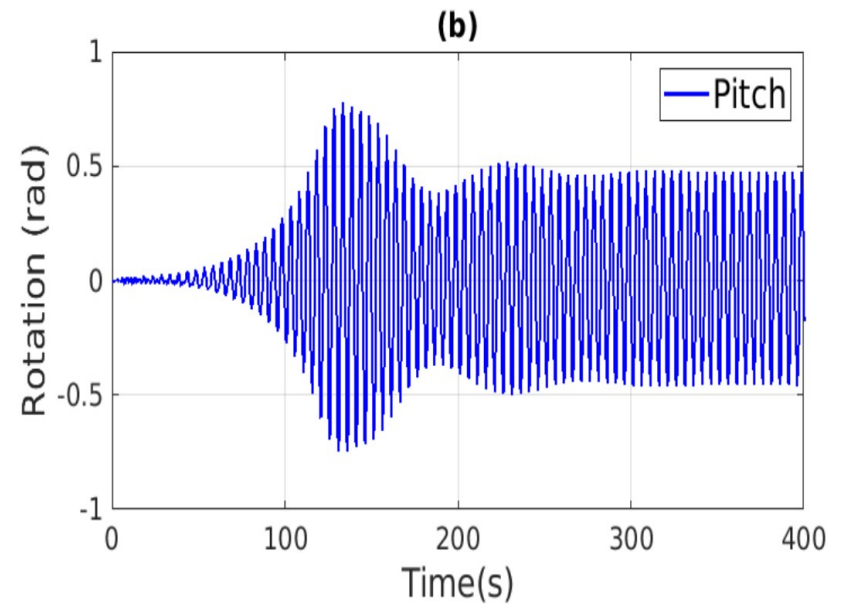
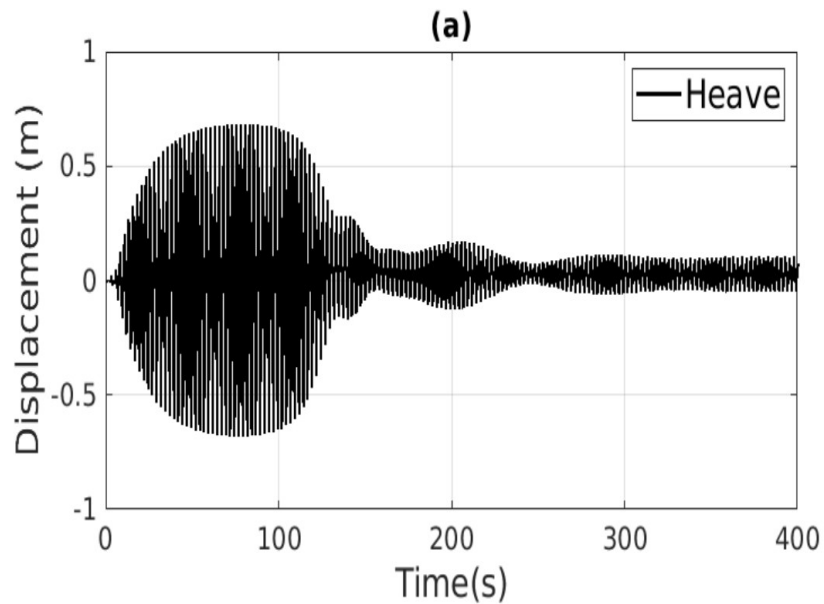
Bad News



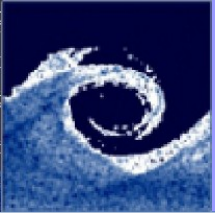
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Bad News



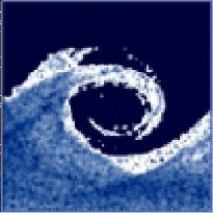
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Good News



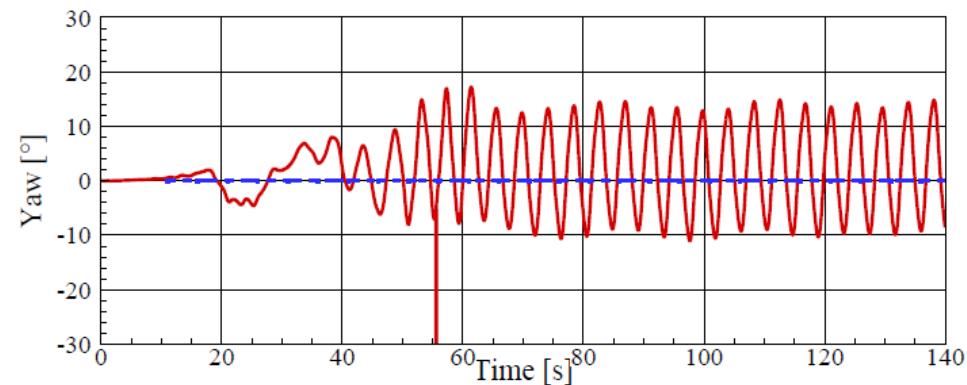
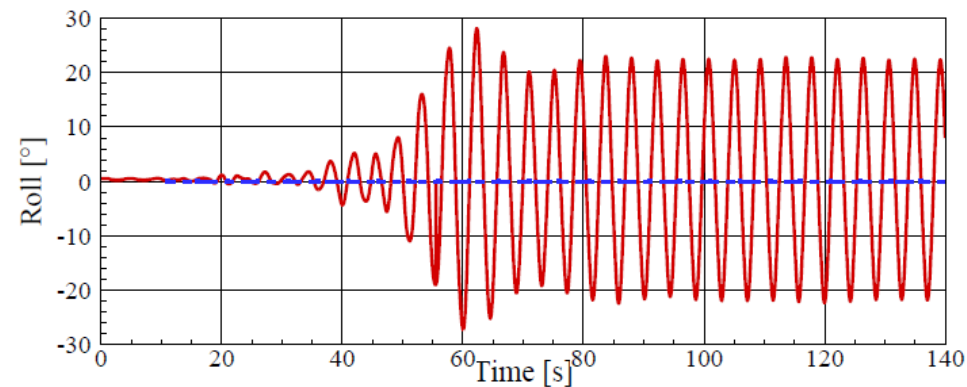
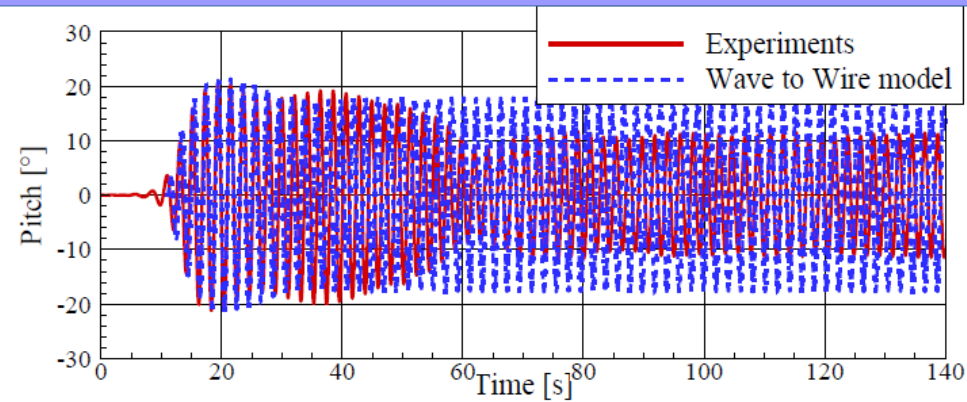
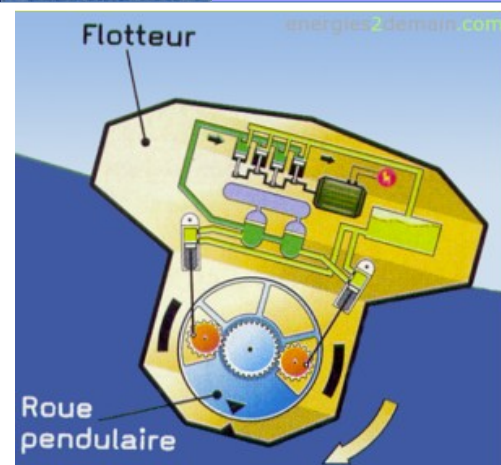
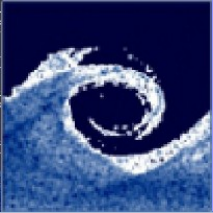
* Image credit – Google Images.
Idea – Prof Ringwood's Seminars



Modelling methods

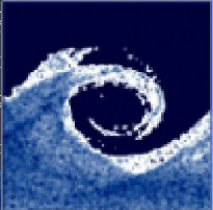
- Linear models
- Nonlinear potential flow
- CFD
- Nonlinear parametric models
- Moorings

Linear hydrodynamic model

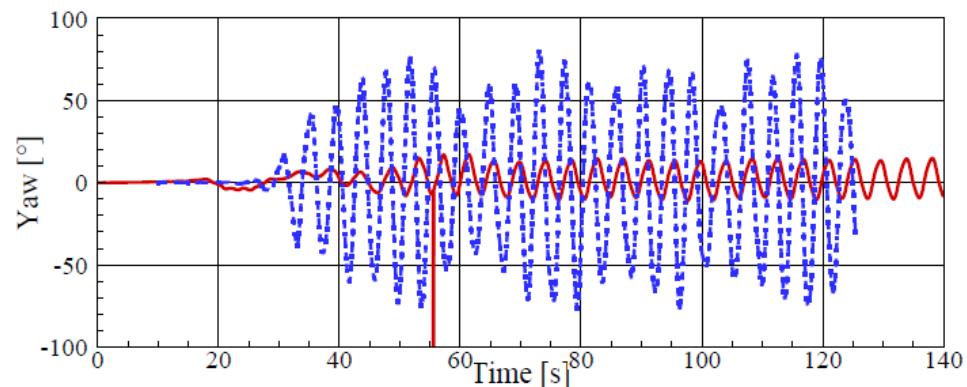
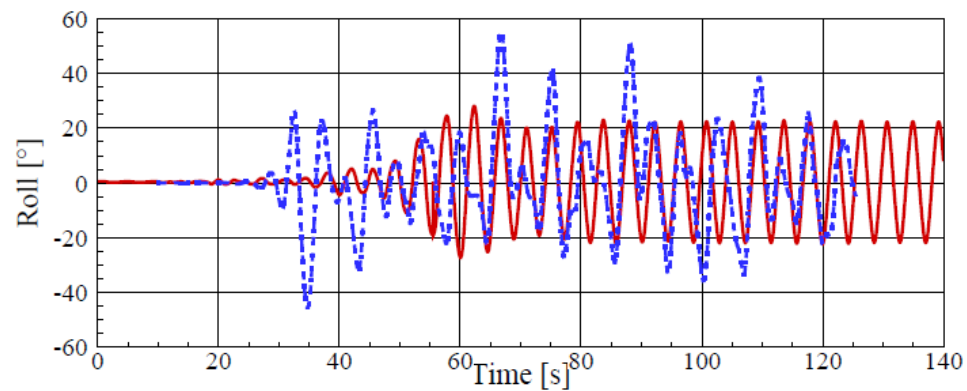
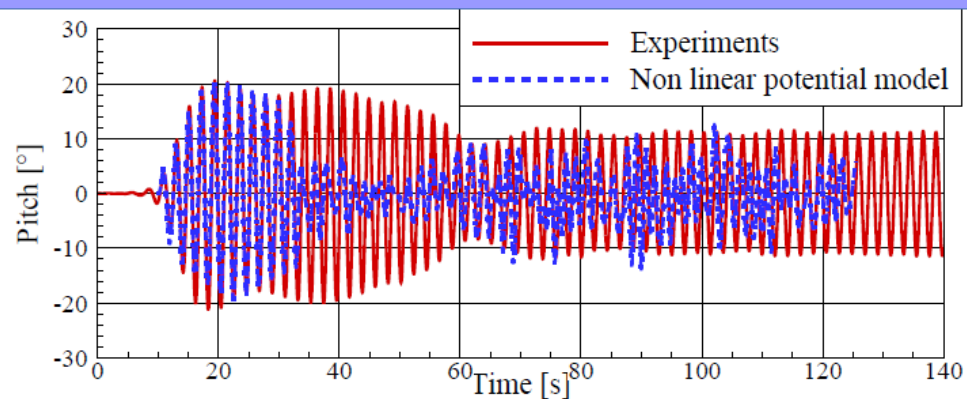
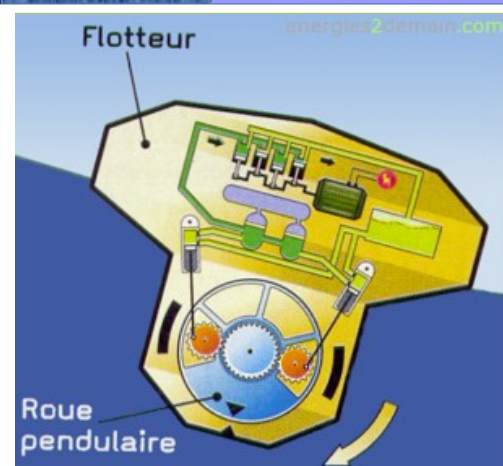


Babarit, A., Mouslim, H., Clément, A., and Laporte-Weywada, P.
On the numerical modelling of the nonlinear behaviour of a wave energy converter.

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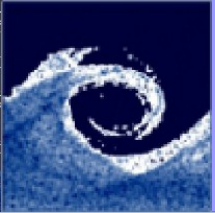
Nonlinear Froude Krylov



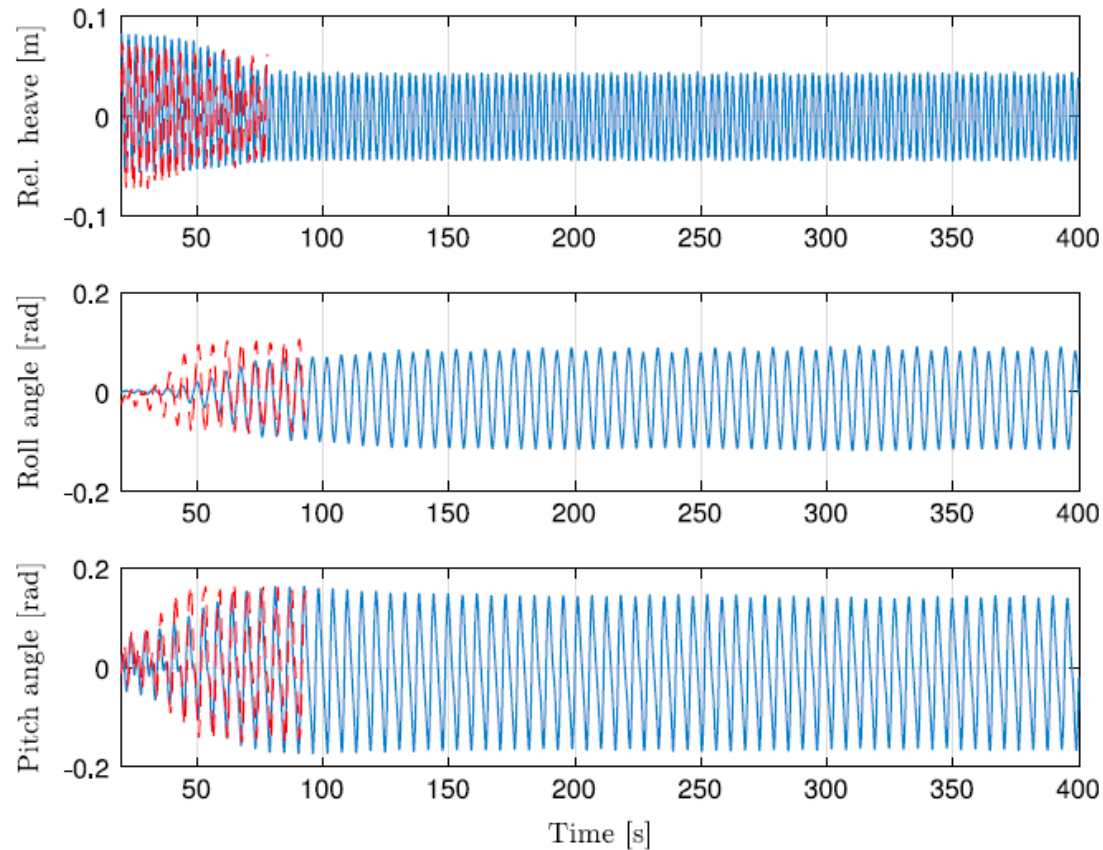
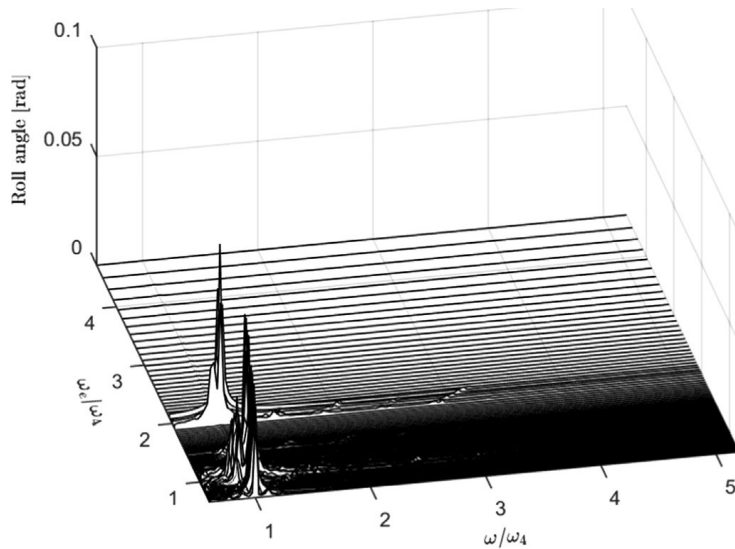
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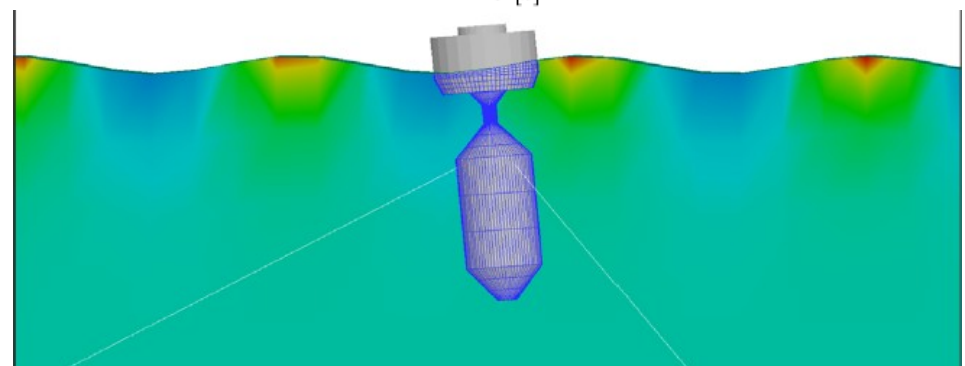


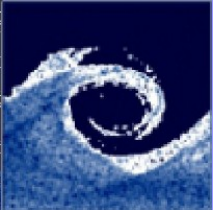
Nonlinear Froude Krylov + Drag



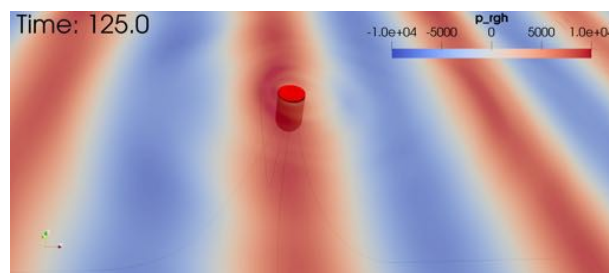
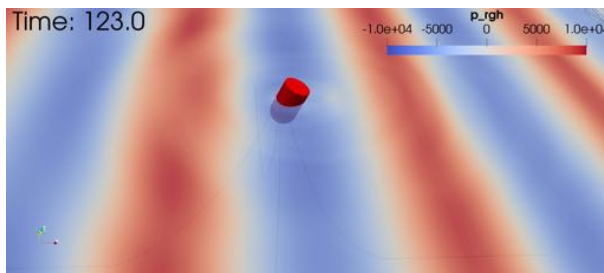
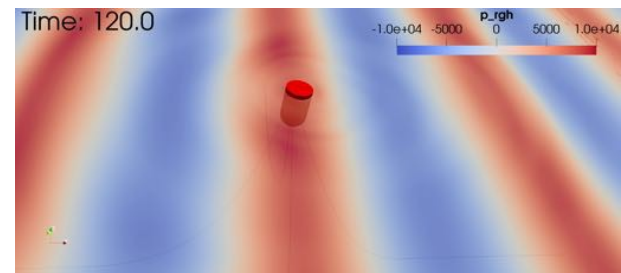
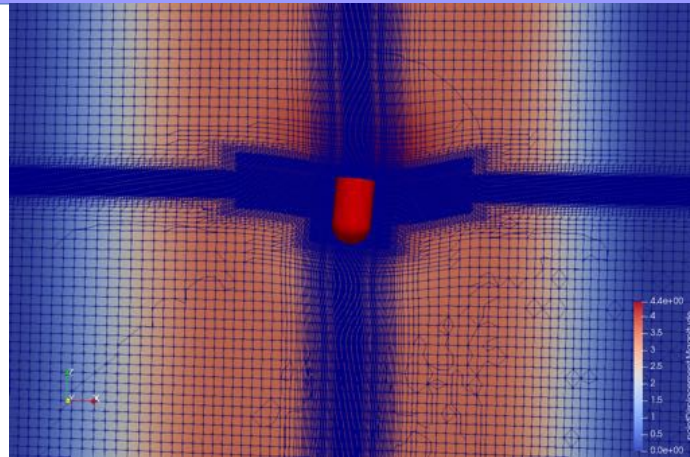
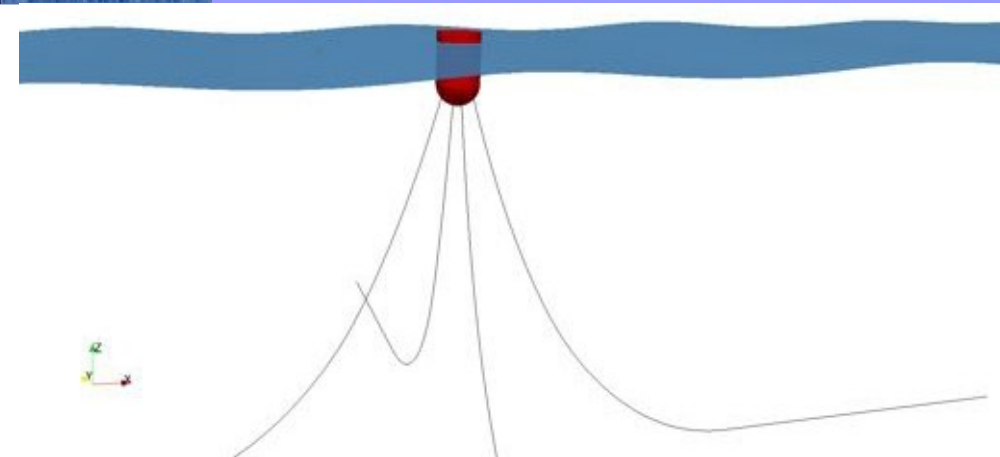
Tarrant, K.R.
*Numerical Modelling of
Parametric
Resonance of a Heaving Point
Absorber Wave Energy
Converter.*

Ph.D. thesis, Trinity College
Dublin. 2015

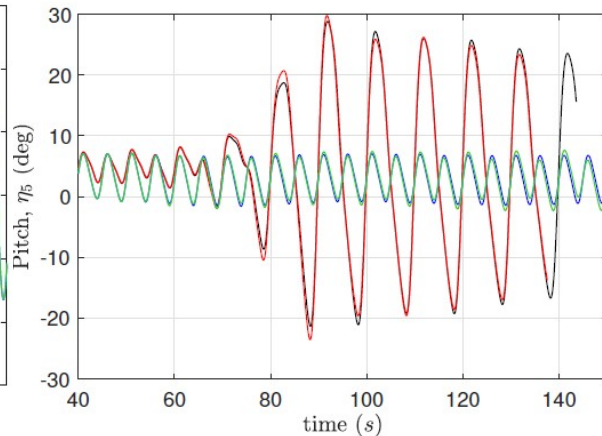
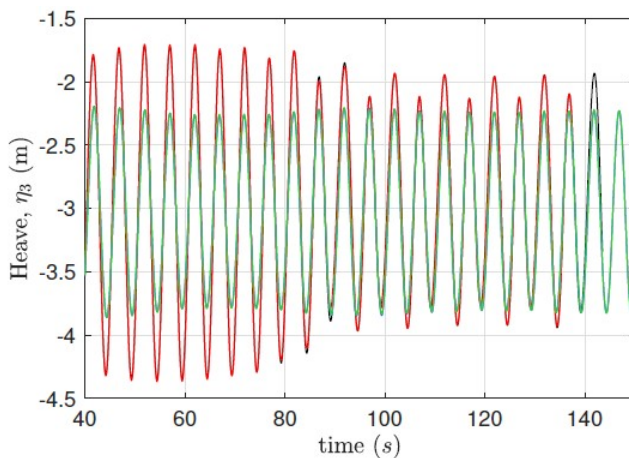


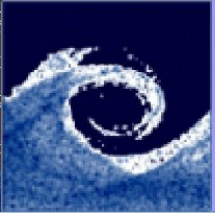


CFD

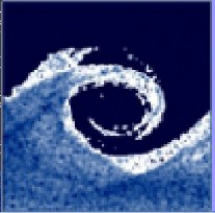


Palm, Bergdahl and Eskilsson
*Parametric excitation of
moored wave energy
converters using viscous and
non-viscous CFD simulations,*
RENEW, 2018

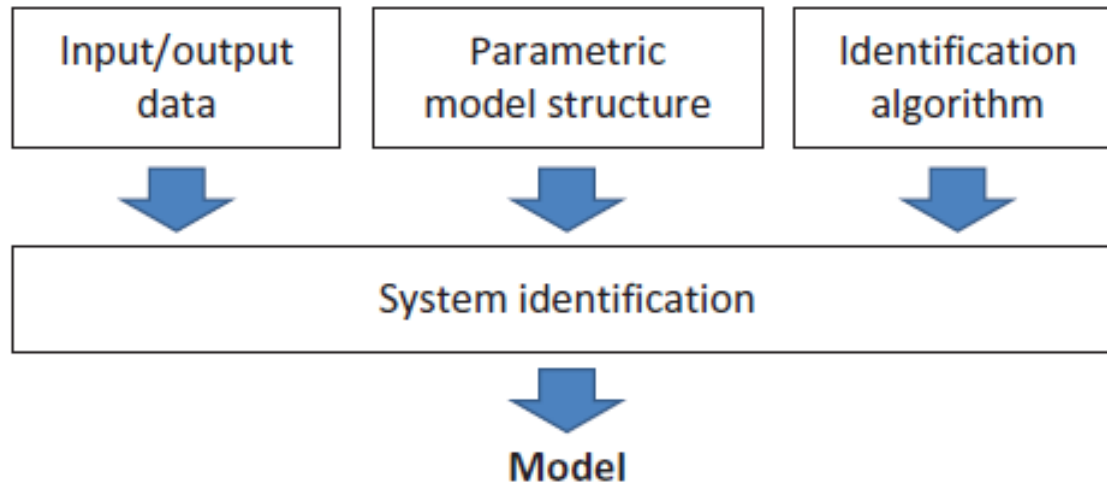


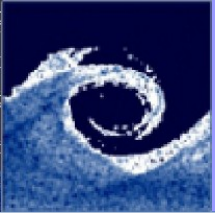


Nonlinear Parametric Models



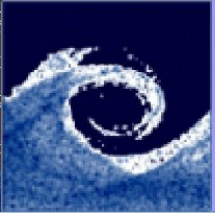
Nonlinear Parametric Models





Example – Mathieu Equation

$$\ddot{x}_4(t) + b\dot{x}_4(t) + a(t)x_4(t) = 0.$$

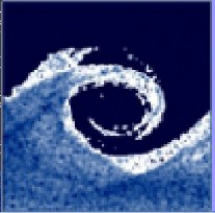


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Time-varying hydrostatic restoring torque

$$a(t) = S_h(t)/(M + m_\infty)$$



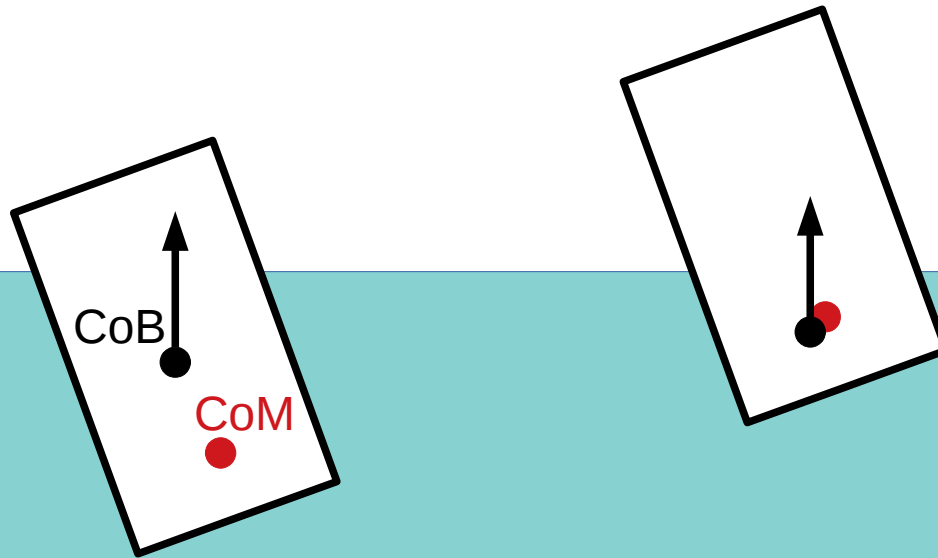
Example – Mathieu Equation

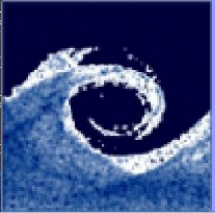
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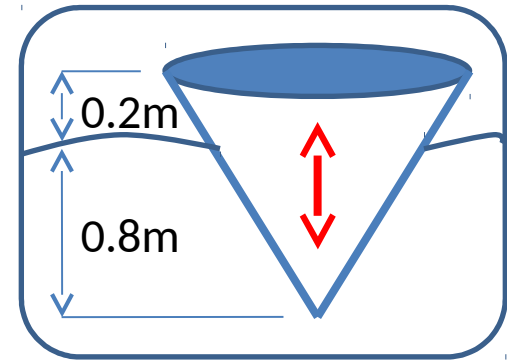
...caused by heave motion oscillations





CFD System Identification

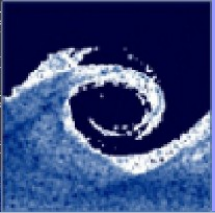
Nonlinear heave restoring force



$$(m + \mu_{\infty})\ddot{x}_3(t) + \int_0^t K_r(t - \tau)\dot{x}_3(\tau)d\tau + f_s(x_3, t) = f_e(t)$$

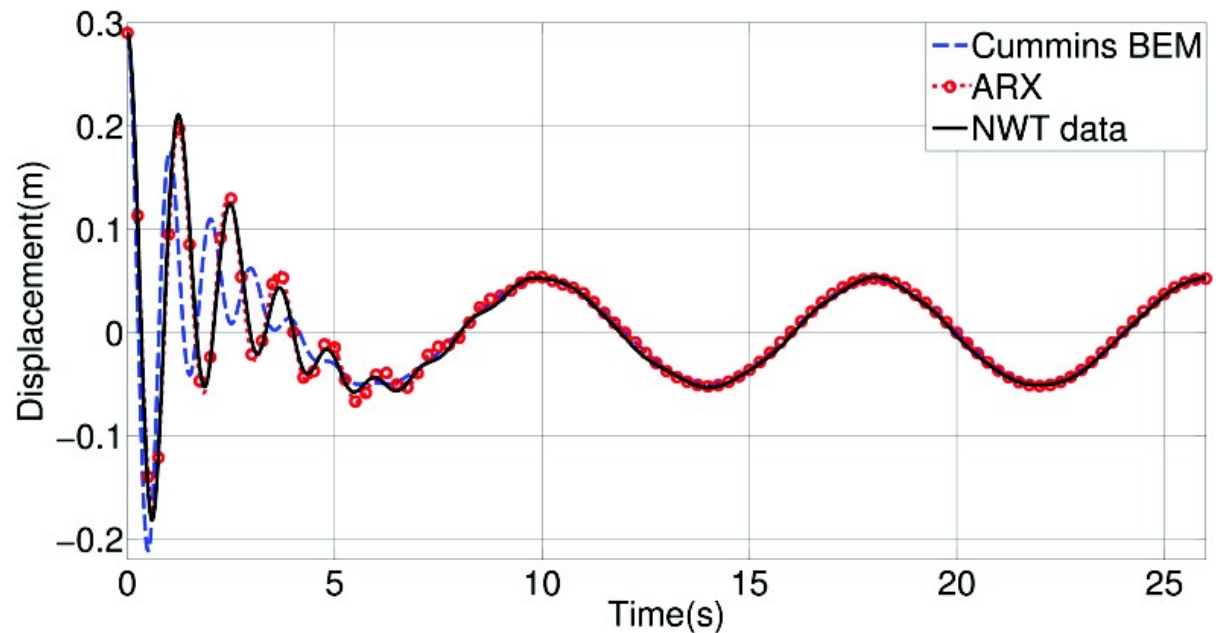
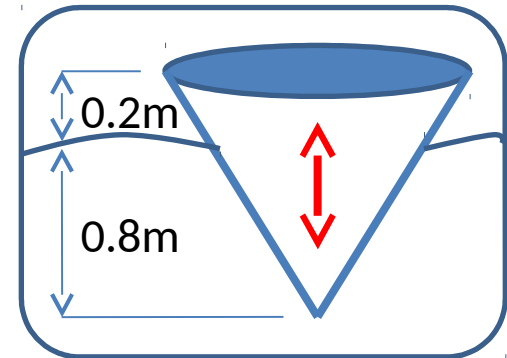
* Davidson, Giorgi and Ringwood, *Numerical wave tank identification of nonlinear discrete time hydrodynamic models*, RENEW, 2014

CFD System Identification



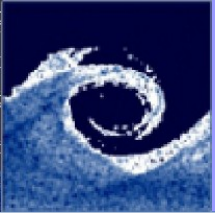
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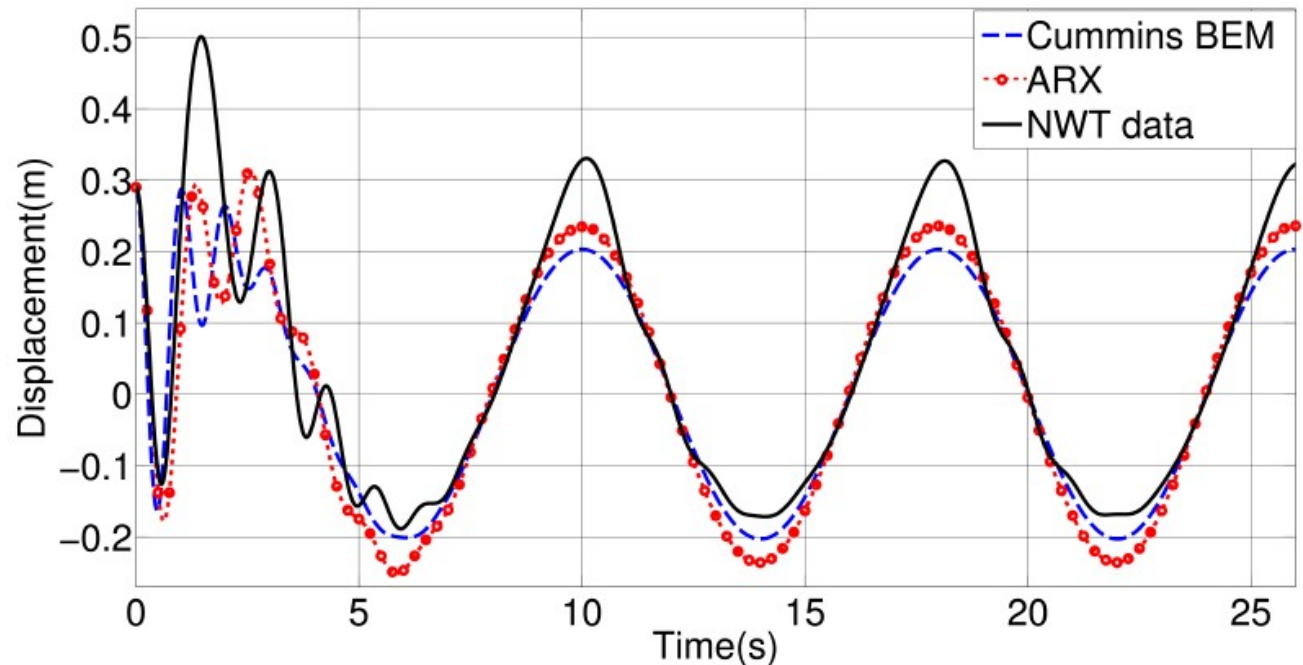
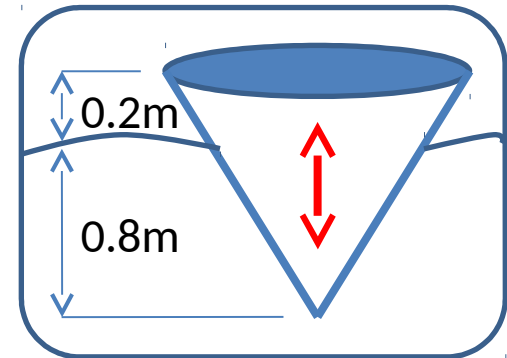
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CFD System Identification



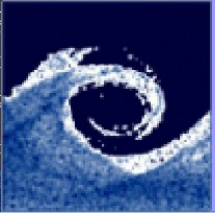
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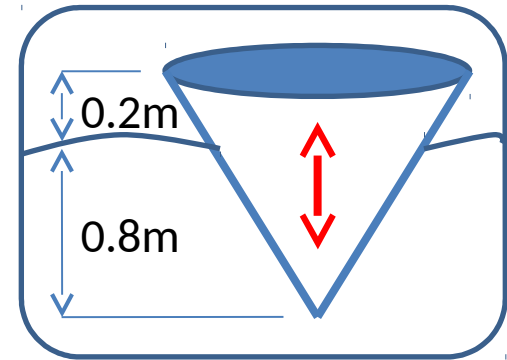


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CFD System Identification



Nonlinear heave restoring force



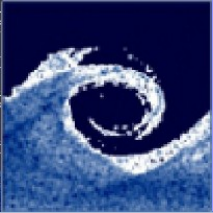
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$$(m + \mu_\infty)\ddot{x}_3(t) + \int_0^t K_r(t - \tau)\dot{x}_3(\tau)d\tau + \sum_1^n a_n x_3^n(t) = f_e(t)$$

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CFD System Identification

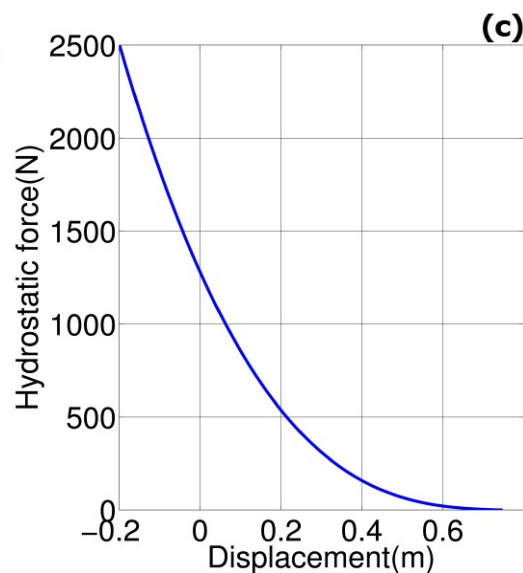
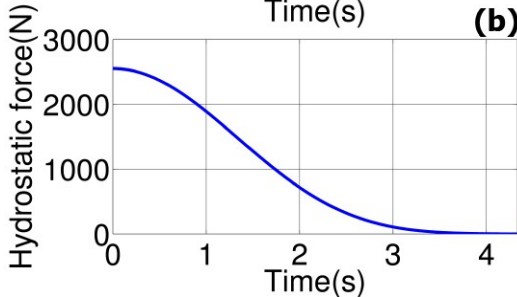
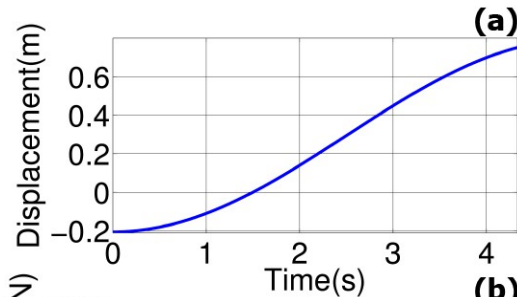
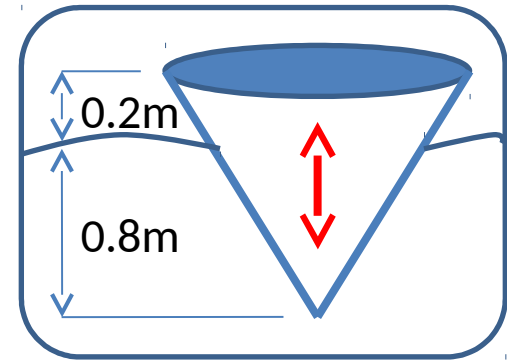


Nonlinear heave restoring force

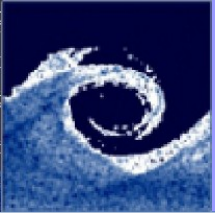
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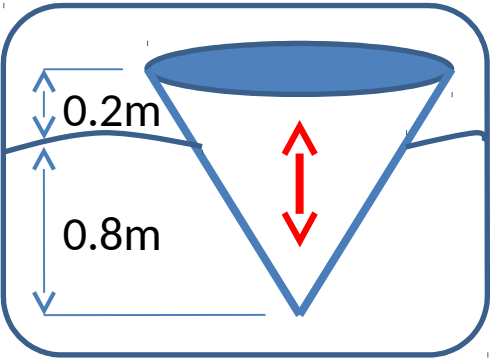


* Davidson, Giorgi and Ringwood, *Numerical wave tank identification of nonlinear discrete time hydrodynamic models*, RENEW, 2014



CFD System Identification

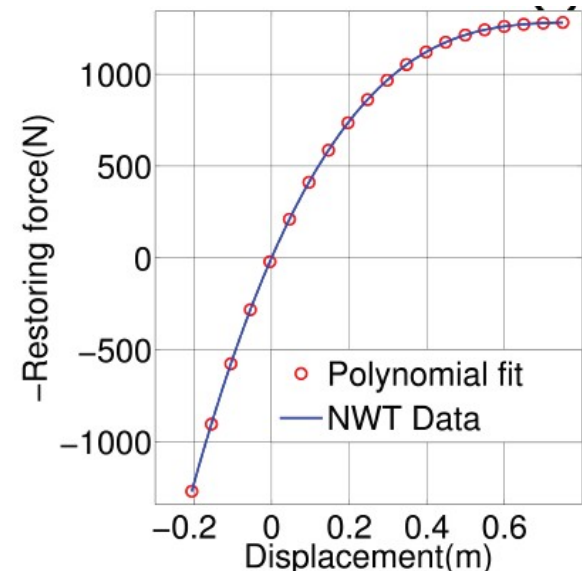
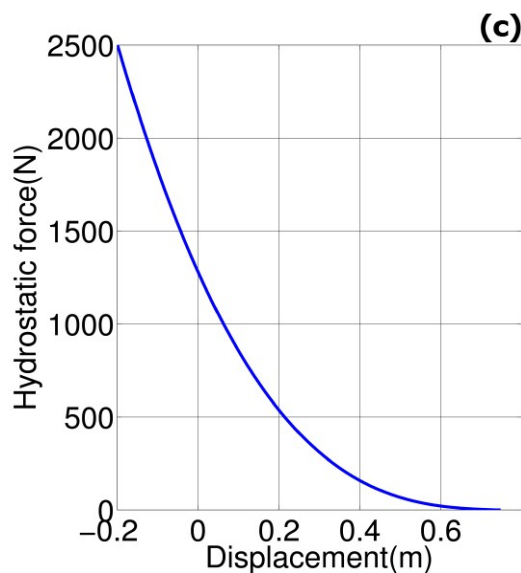
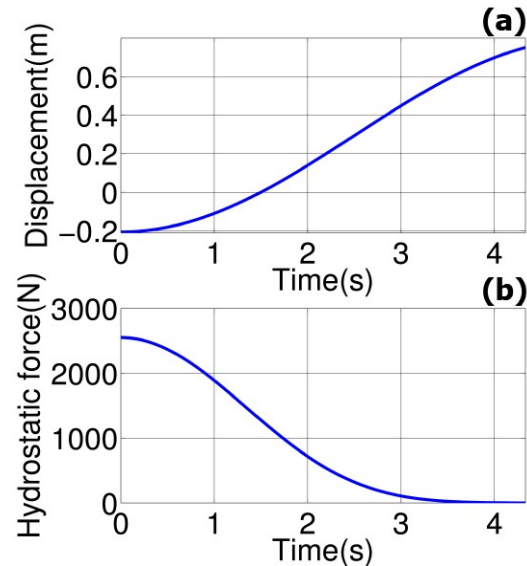
Nonlinear heave restoring force



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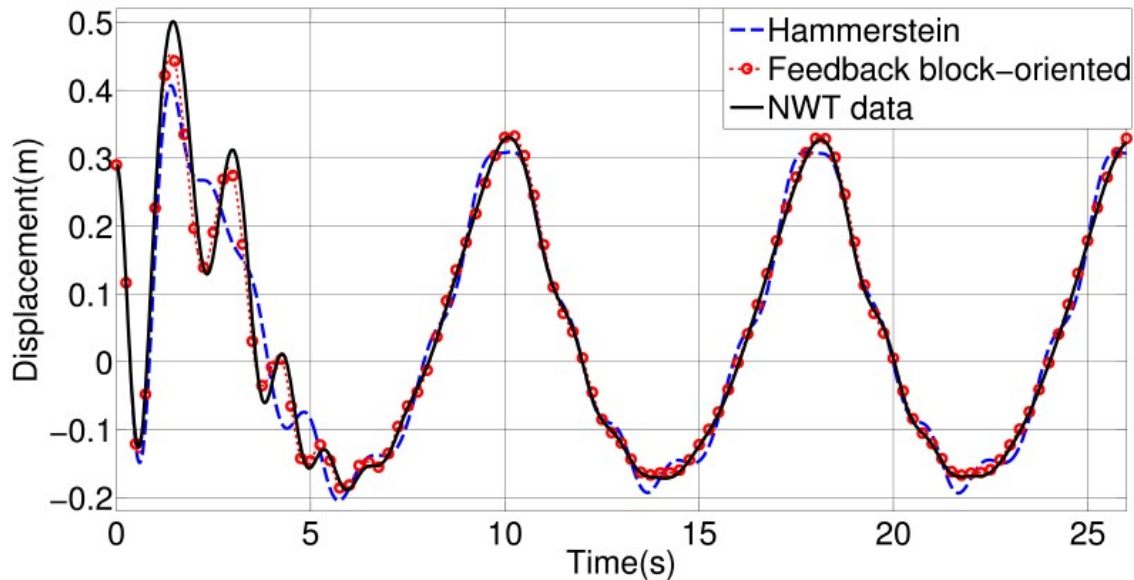
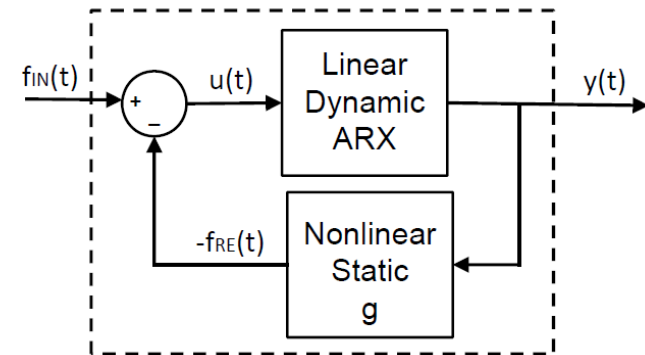
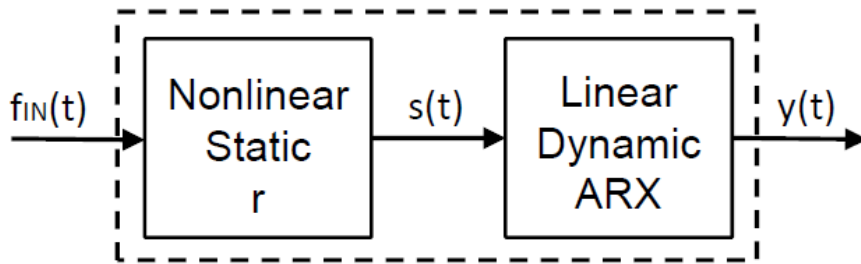


$$(m + \mu_\infty)\ddot{x}_3(t) + \int_0^t K_r(t - \tau)\dot{x}_3(\tau)d\tau + \sum_1^n a_n x_3^n(t) = f_e(t)$$

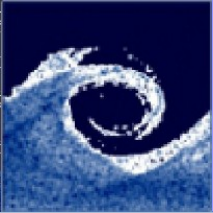


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CFD System Identification



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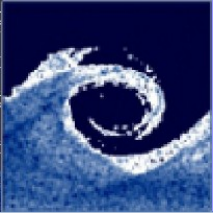


CFD System Identification

Nonlinear heave restoring torque for parametric resonance

$$(m + \mu_{\infty})\ddot{x}_5(t) + \int_0^t K_r(t - \tau)\dot{x}_5(\tau)d\tau + f_s(x_5, x_3, t) = f_e(t)$$

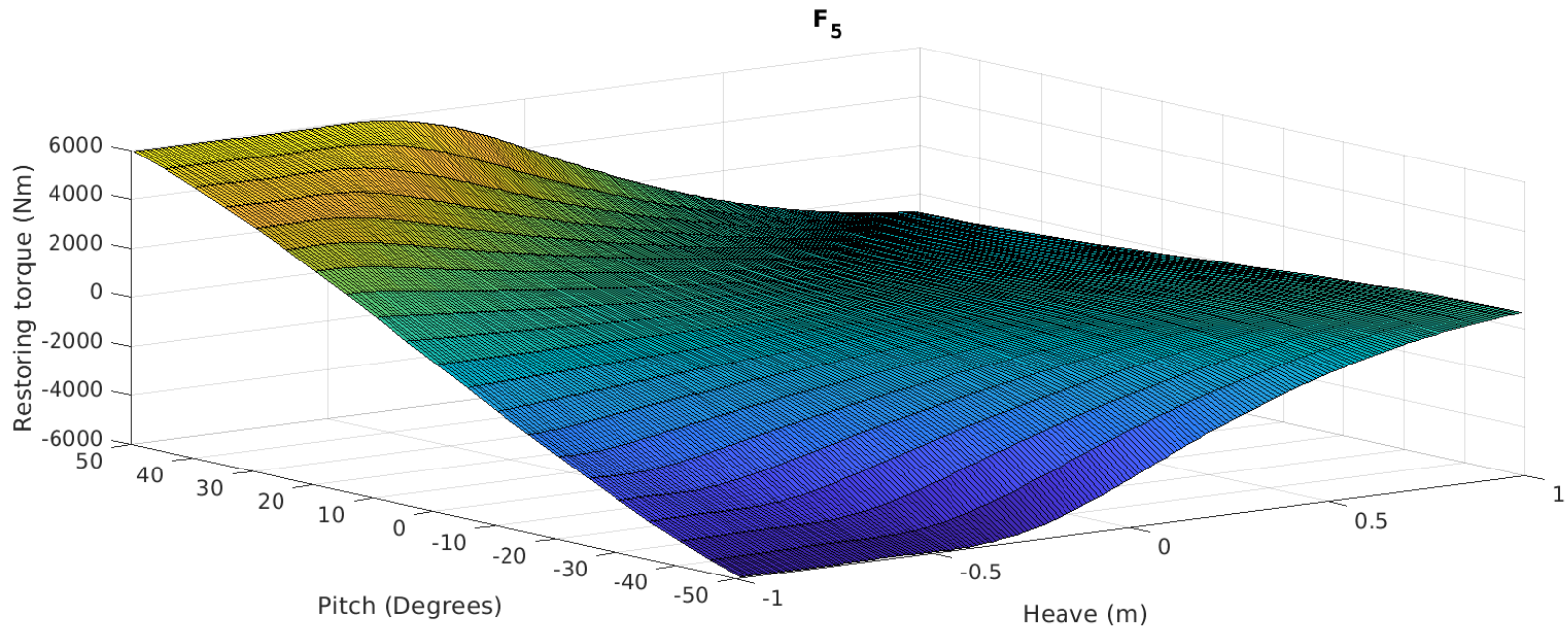
* Davidson, Karimov, Habib and Kalmar-Nagy, “*Parametric excitation suppression in a floating cylinder via dynamic vibration absorbers : A comparative analysis*”, Nonlinear Dynamics, (In preparation)



CFD System Identification

Nonlinear heave restoring torque for parametric resonance

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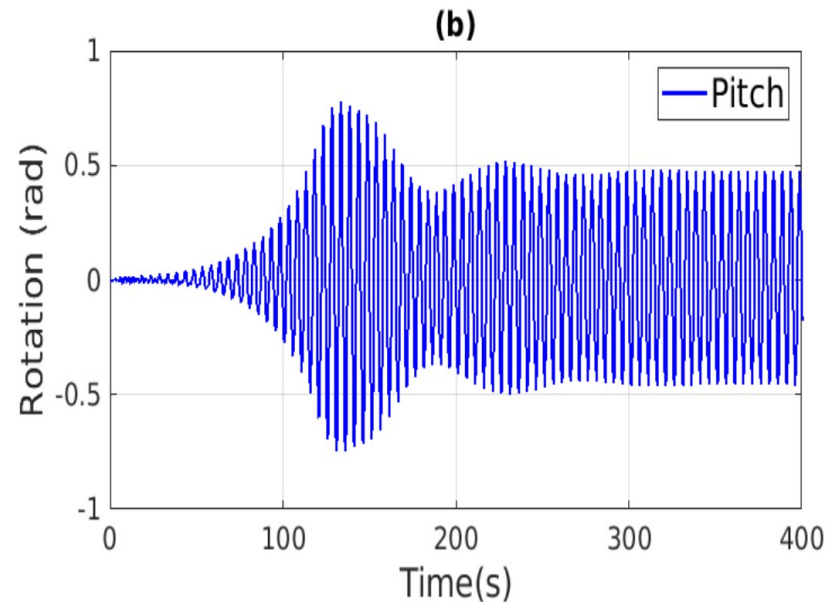
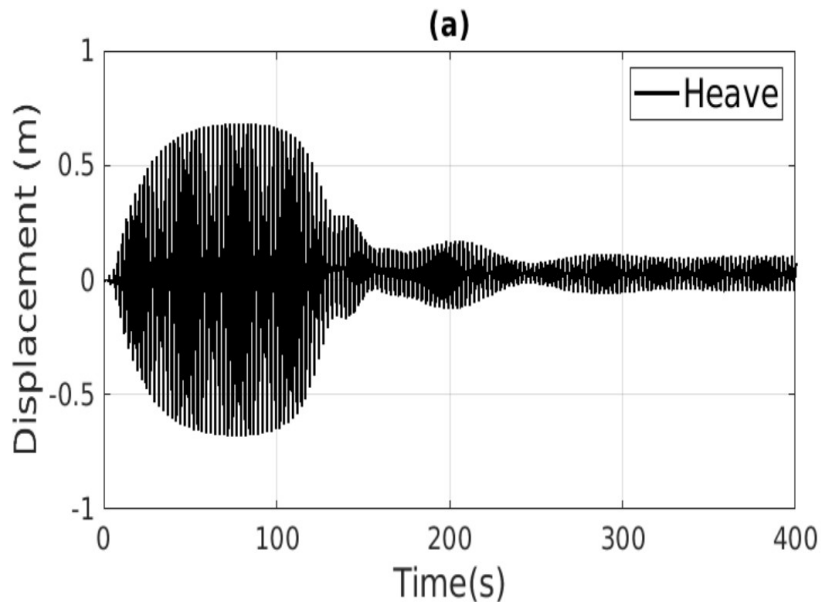


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CFD System Identification

Nonlinear heave restoring torque for parametric resonance

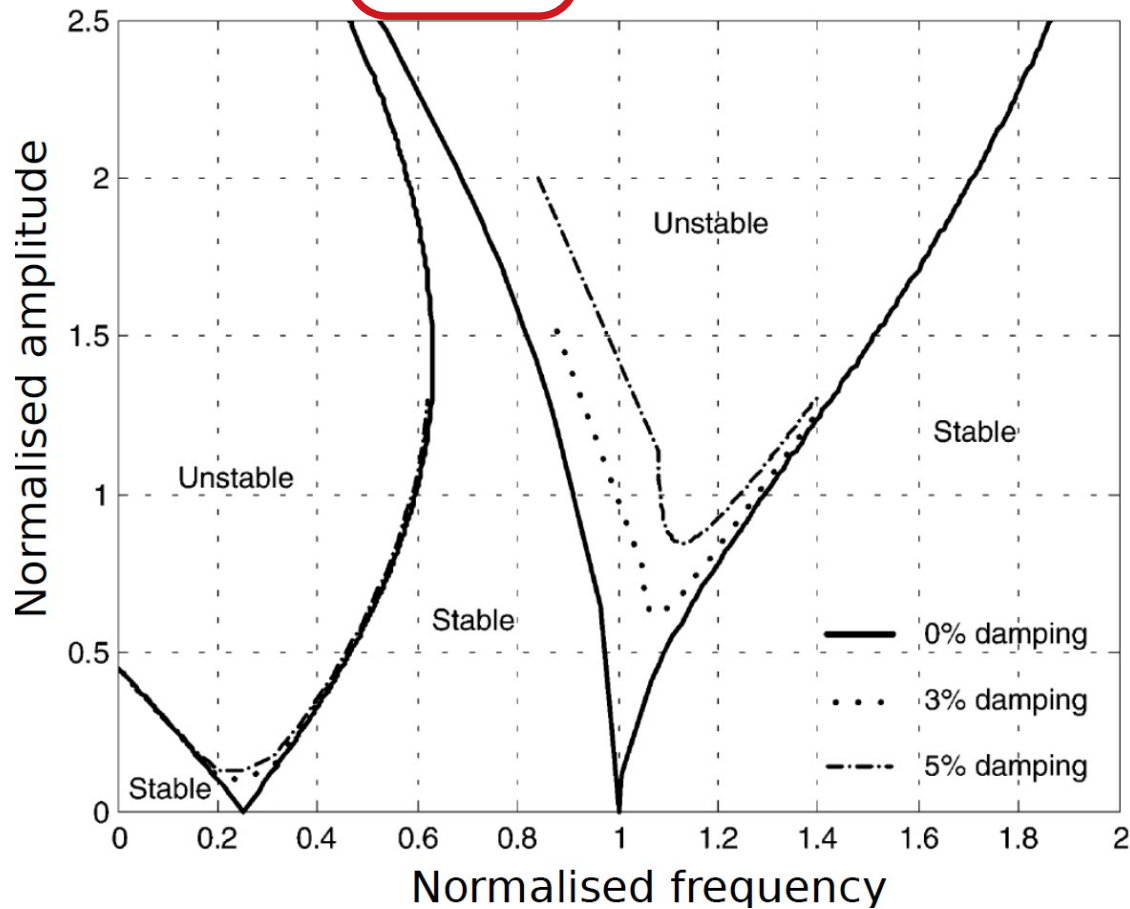
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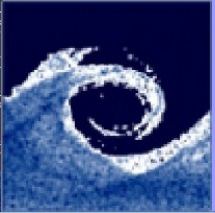
* Davidson, Karimov, Habib and Kalmar-Nagy, "Parametric excitation suppression in a floating cylinder via dynamic vibration absorbers : A comparative analysis", Nonlinear Dynamics, (In preparation)

CFD System ID of Damping

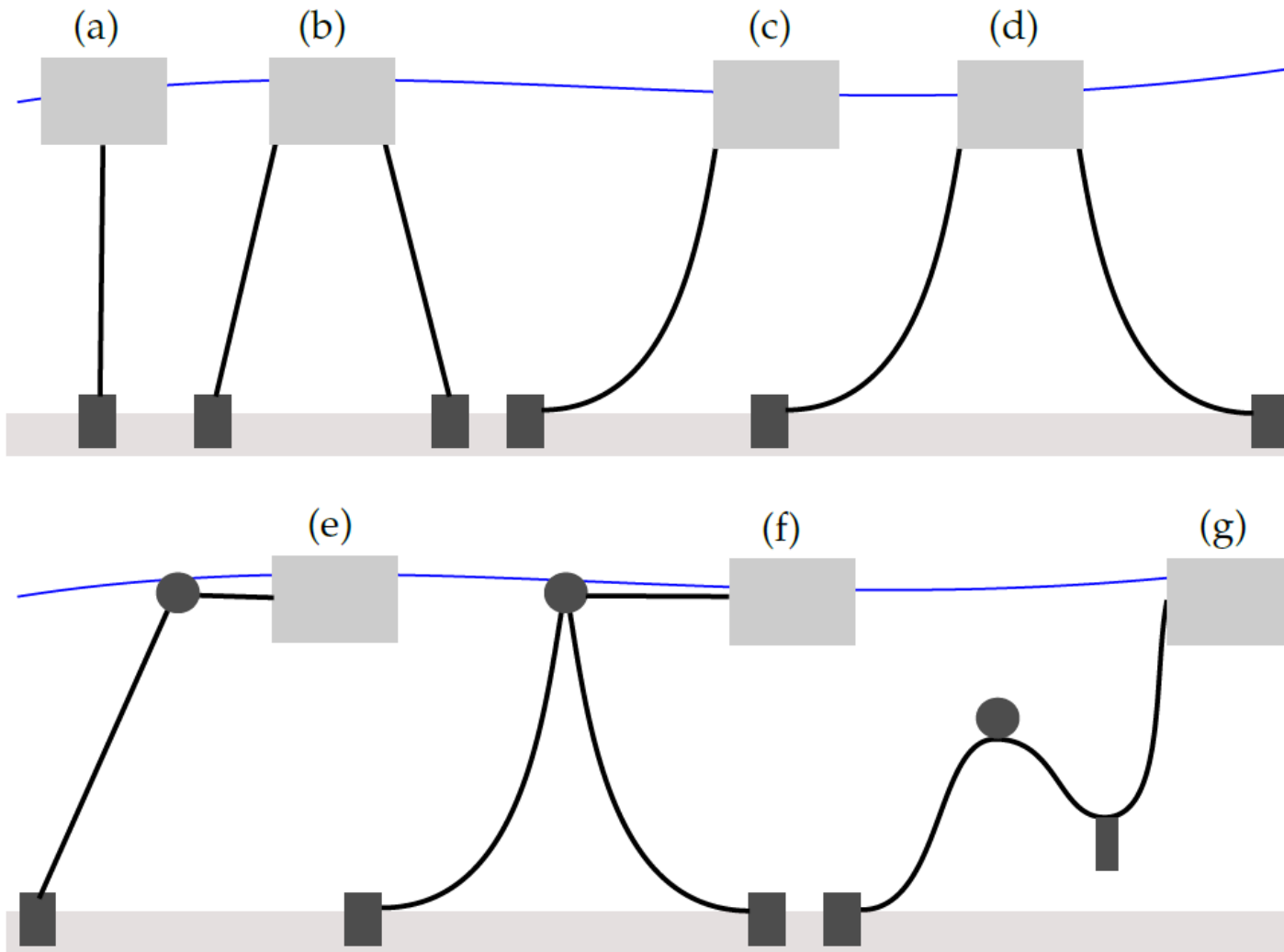
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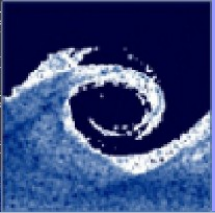
* Koo, Kim and Randall, *Mathieu instability of a spar platform with mooring and risers*, Ocean engineering, 2004



Moorings

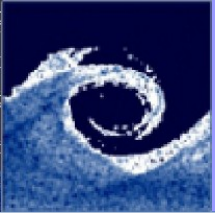


* Davidson and Ringwood, *Mathematical modelling of mooring systems for wave energy converters – A review*, *Energies*, 2017



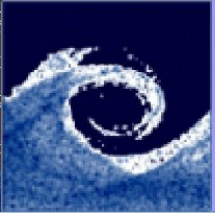
Controlling Parametric Resonance in WECs

- The exponential increase in oscillation amplitude caused by PR can be either detrimental or beneficial for different types of WECs.



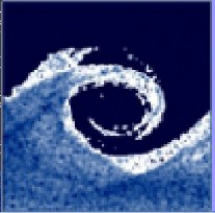
Controlling Parametric Resonance in WECs

- The exponential increase in oscillation amplitude caused by PR can be either detrimental or beneficial for different types of WECs.
- Correspondingly, control systems should be designed to mitigate or induce this effect.

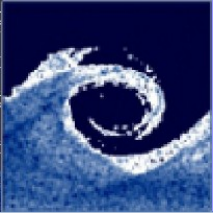


Controlling Parametric Resonance in WECs

- The exponential increase in oscillation amplitude caused by PR can be either detrimental or beneficial for different types of WECs.
- Correspondingly, control systems should be designed to mitigate or induce this effect.
- The modelling methods discussed in this presentation will be used to investigate control techniques to:
 - Suppress parametric resonance in certain classes of WECs, and
 - Harness parametric resonance in other types of WECs



Questions / Discussion



Acknowledgement



This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 867453