Politecnico di Torino

Corso di dottorato in Ingegneria Meccanica – XXX Ciclo

Numerical modeling and experimental testing of a Pendulum Wave Energy Converter (PeWEC)

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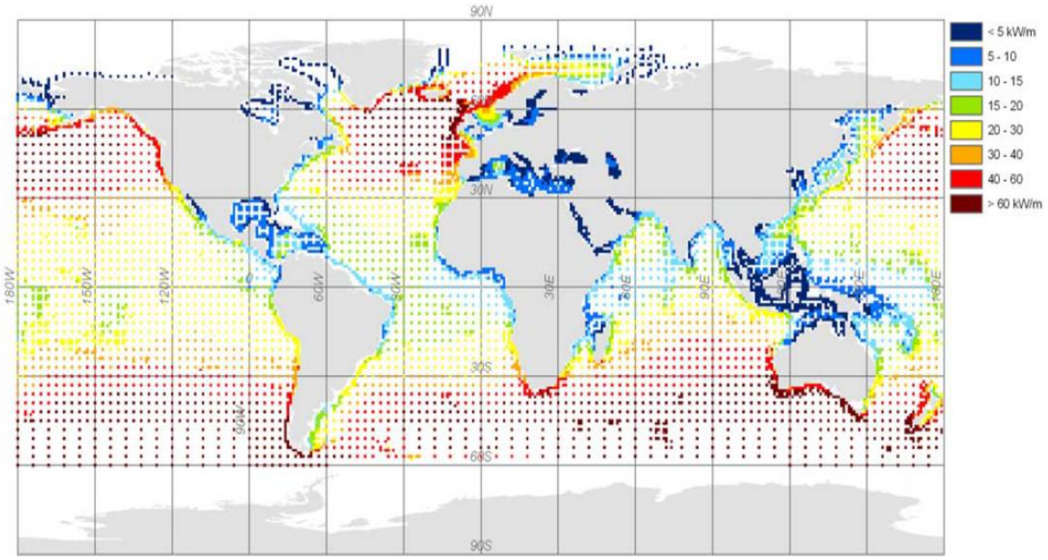
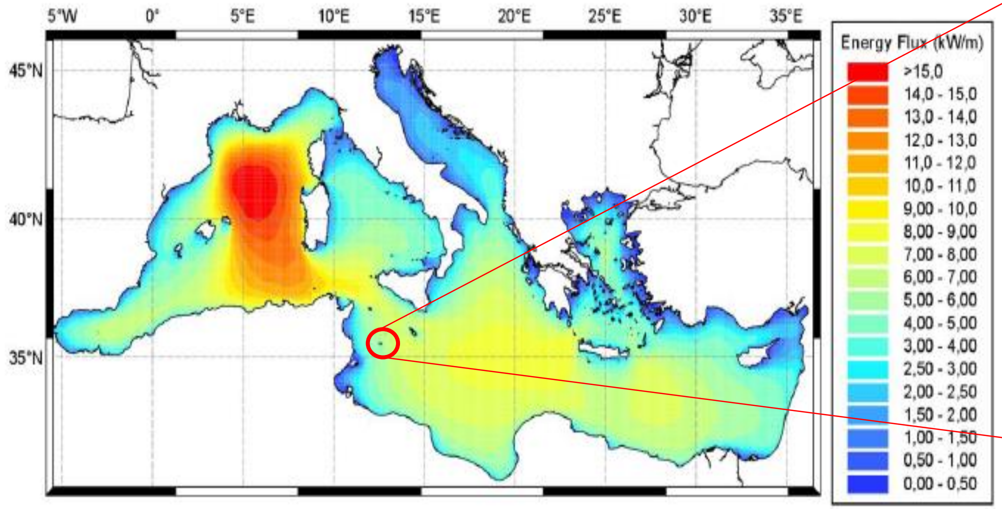
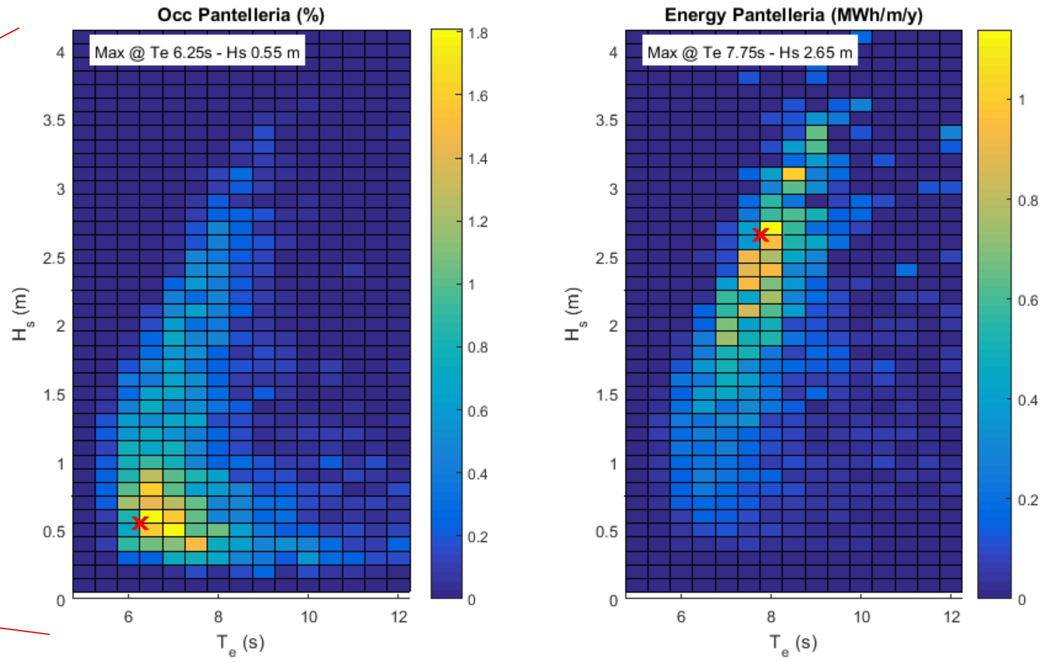
Wave Power overview



Wave Power characteristics:

- High density
- Predictable resource
- Relatively easy access
- Global potential comparable with actual World power demand (~ 10TW) (Panicker, 1976)

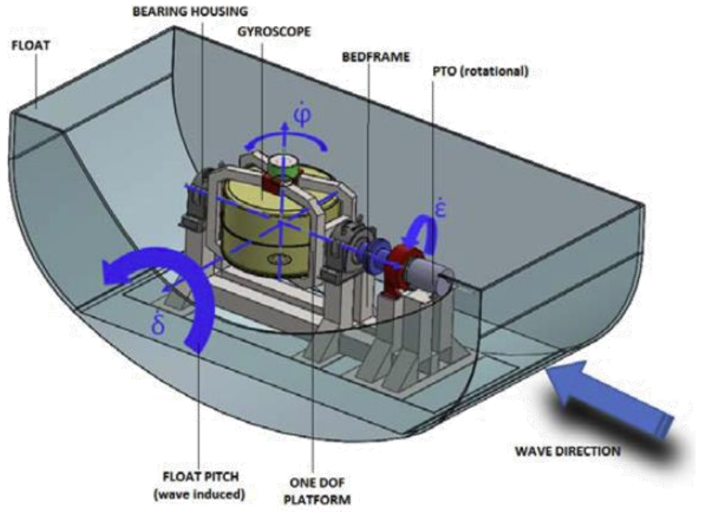




Inertial based Wave Energy Converters

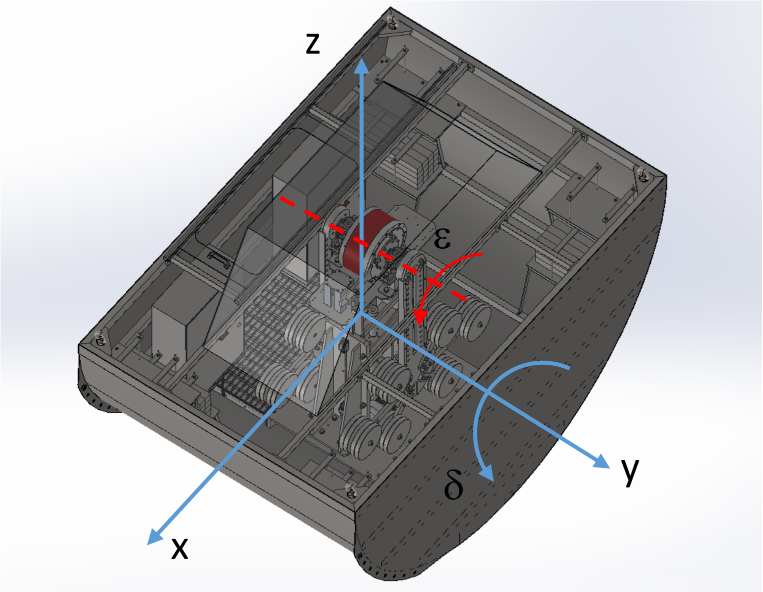
ISWEC

- **Working principle:** gyroscope
- **Active device:** necessity to maintain in rotation mechanical parts (auto-consumption)
- **Tunable with respect to sea state:**
  - PTO control parameters
  - Flywheel speed
- **Mechanics protected against sea environment**
- **Slack mooring line:** low environmental impact



PeWEC

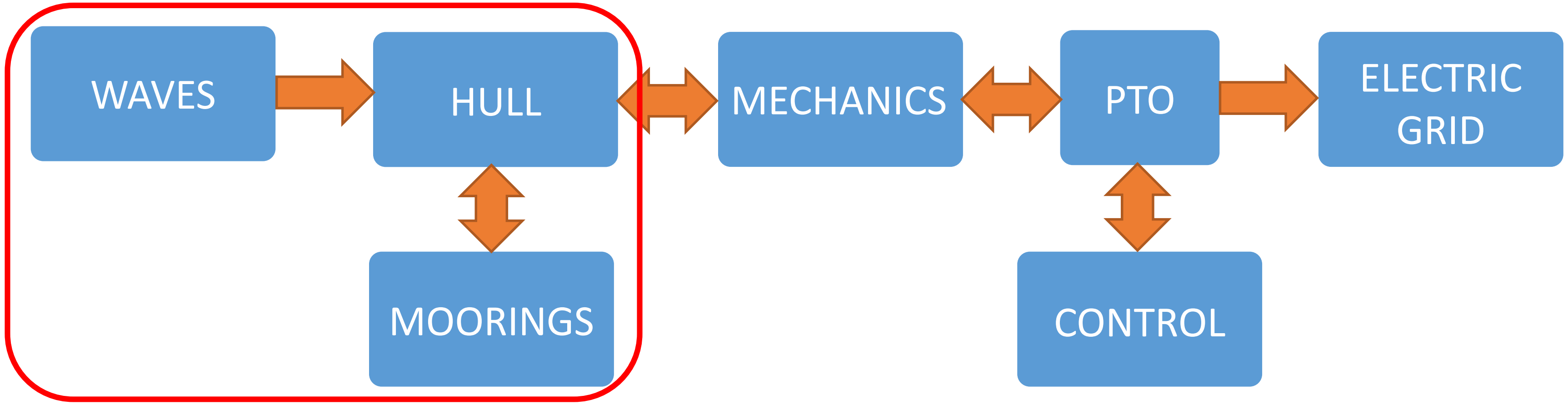
- **Working principle:** oscillating mass
- **Passive device:** no necessity to maintain in rotation mechanical parts
- **Tunable with respect to sea state:**
  - PTO control parameters
- **Mechanics protected against sea environment**
- **Slack mooring line:** low environmental impact



PeWEC numerical modeling activity

Lumped parameters Wave-to-Wire models

- WEC simulation from the waves to the electrical grid
- Includes all the WEC components (hull, moorings, mechanics, PTO, controller)
- Purposes:
  - WEC design and optimization
  - PTO control law design and optimization
  - Productivity analysis in the installation site

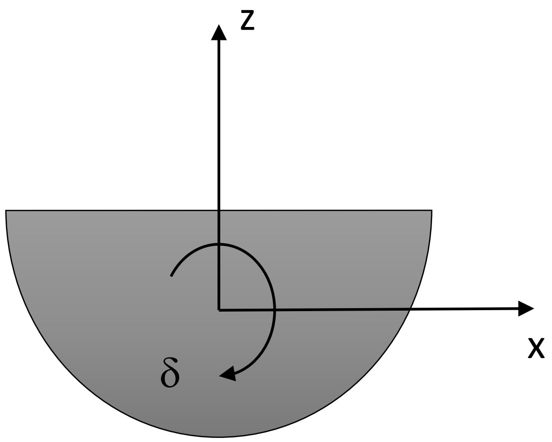


Surge-Pitch couplings

- **ISWEC (1 DOF model)**

$$T_\varepsilon = I_{eq}\ddot{\varepsilon} + J\dot{\varphi}\dot{\delta}\cos\varepsilon$$

- **PeWEC (3 DOFs model)**



$$\boldsymbol{M}\begin{bmatrix}\ddot{x}_G\\ \ddot{z}_G\\ \ddot{\delta}\\ \ddot{\varepsilon}\end{bmatrix} + \boldsymbol{D_{PTO}}\begin{bmatrix}\dot{x}_G\\ \dot{z}_G\\ \dot{\delta}\\ \dot{\varepsilon}\end{bmatrix} + F_{gr} + F_{cor} = 0$$

x-δ link

$$\boldsymbol{M} = \begin{bmatrix} m_p + m_b & 0 & m_p[d\cos\delta - l\cos(\delta+\varepsilon)] & -m_p\, l\cos(\delta+\varepsilon) \\ 0 & m_p + m_b & -m_p[d\sin\delta - l\sin(\delta+\varepsilon)] & m_p\, l\sin(\delta+\varepsilon) \\ m_p[d\cos\delta - l\cos(\delta+\varepsilon)] & -m_p[d\sin\delta - l\sin(\delta+\varepsilon)] & I_b + I_y + m_p(d^2+l^2) - 2\,m\,d\,l\cos\varepsilon & I_y + m_p l^2 - m_p\,d\,l\cos\varepsilon \\ -m_p\, l\cos(\delta+\varepsilon) & m_p\, l\sin(\delta+\varepsilon) & I_y + m_p l^2 - m_p\,d\,l\cos\varepsilon & I_y + m_p l^2 \end{bmatrix}$$

3 DOF hydrodynamic model

Frequency-domain model → Linear model

$$([M] + [A(\omega)])\ddot{X} + ([B(\omega)] + [B_v(\omega)])\dot{X} + [K]X = F_w(j\omega) + F_m \qquad X = \begin{Bmatrix} x \\ z \\ \delta \end{Bmatrix}$$

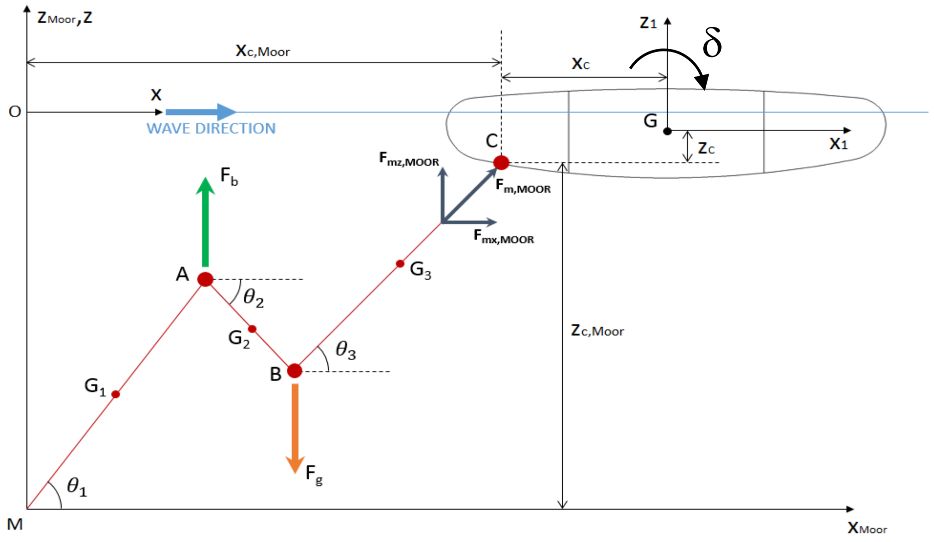
- $[M]$: Body mass matrix
- $[A(\omega)]$: Added-mass matrix
- $[B(\omega)]$: Radiation damping matrix
- $[B_v(\omega)]$: Linearized hydrodynamic viscous damping
- $[K]$: Hydrostatic stiffness
- $F_w(j\omega)$: 1st order incident wave forces
- F_m: Mooring forces

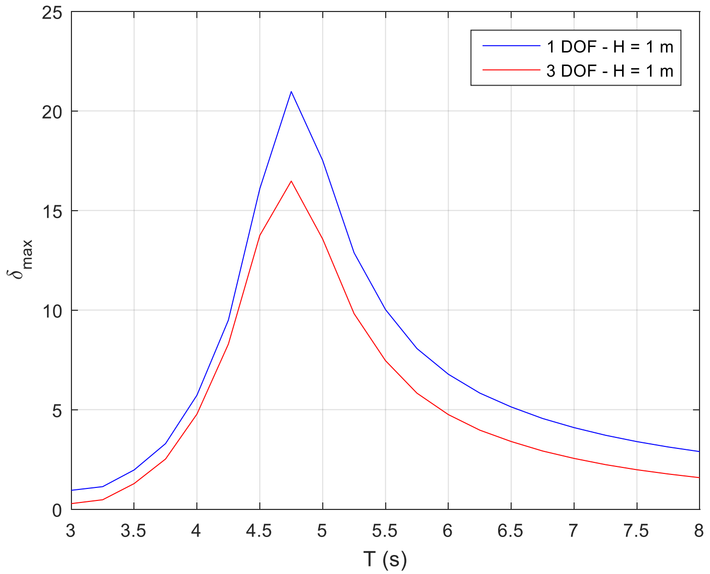
Time-domain model → Non-linear model

$$([M] + [A_\infty])\ddot{X} + \int_0^t [h_r(t - t')]\dot{X}dt' + [\beta]\dot{X}|\dot{X}| + [K]X = F_w(t) + F_D(t) + F_m(t)$$

- $[M]$: Body mass matrix
- $[A_\infty]$: Added-mass matrix for infinite frequency
- $\int_0^t [h_r(t - t')]\dot{X}dt'$: Convolution integral
- $[\beta]\dot{X}|\dot{X}|$: Hydrodynamic viscous damping
- $[K]$: Hydrostatic stiffness
- $F_w(t)$: 1st order incident wave forces
- $F_D(t)$: 2nd order incident wave forces
- $F_m(t)$: Mooring forces

Mooring line





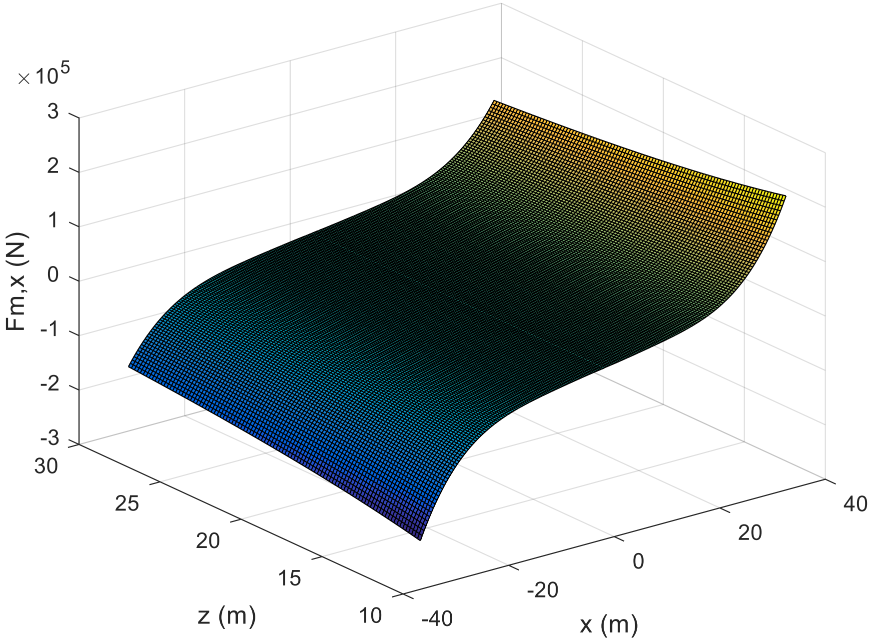
Hypothesis

- Chains assumed as rigid bodies
- Quasi-static behavior

$$F_{mx,Moor} = f(x, z, \delta)$$

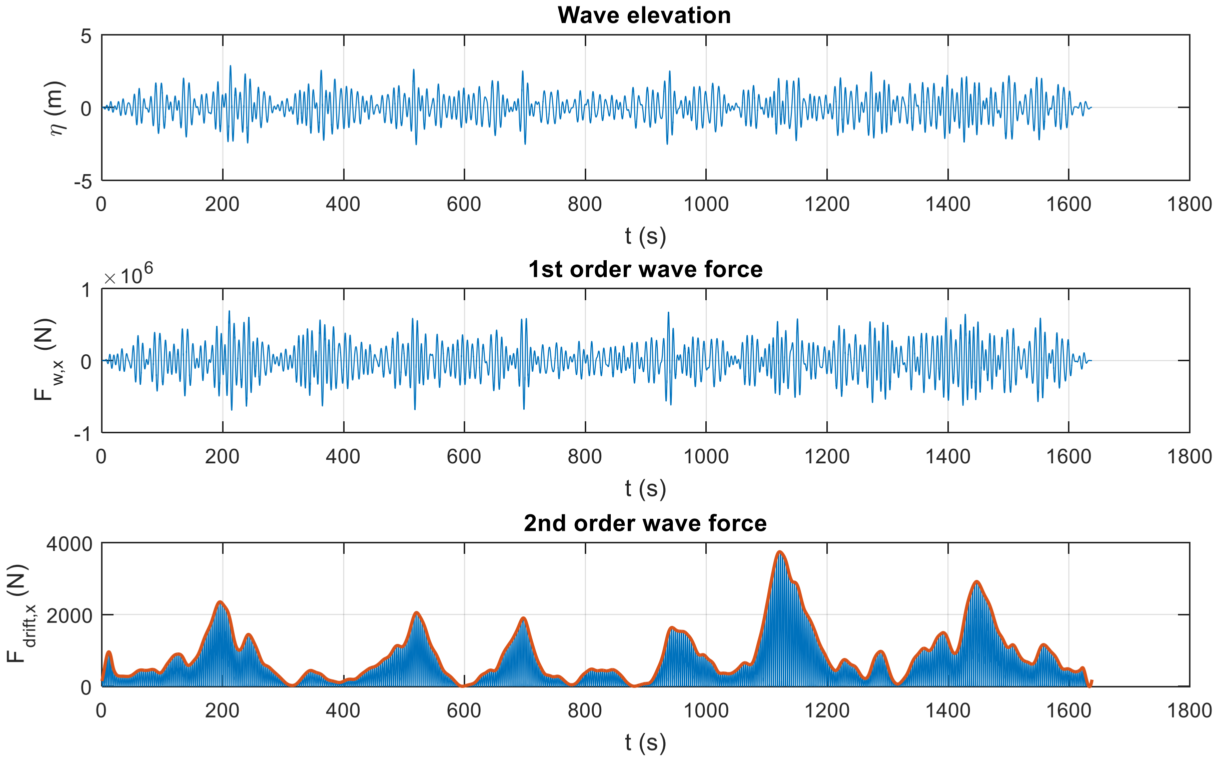
$$F_{mz,Moor} = f(x, z, \delta)$$

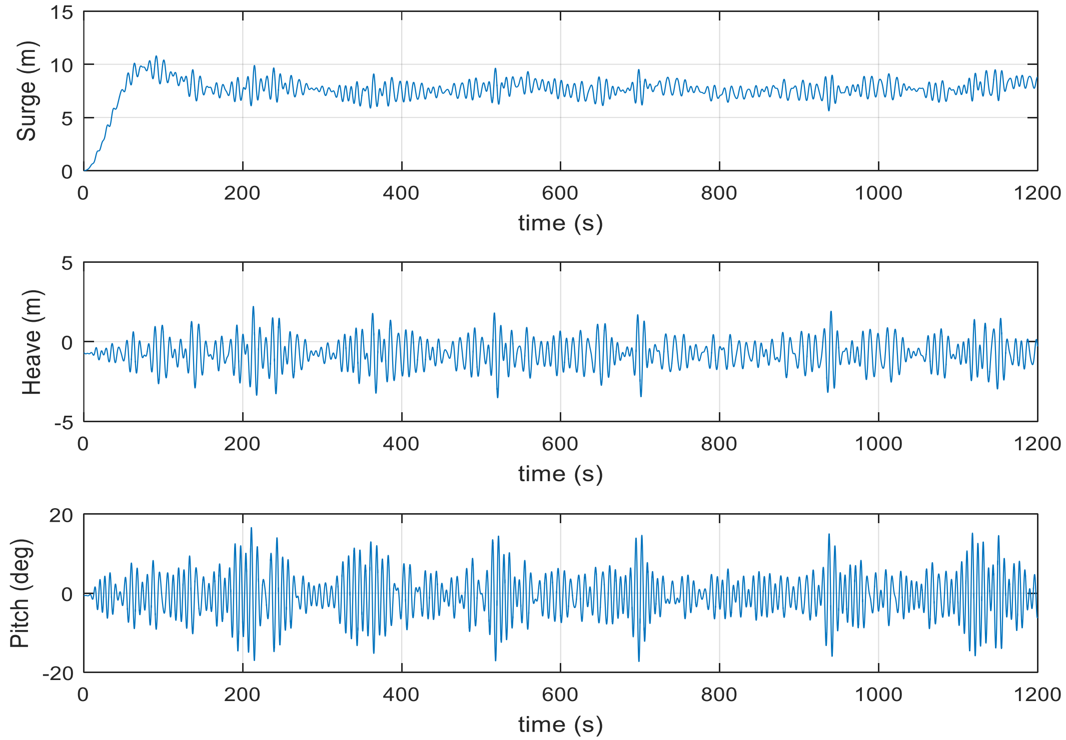
$$F_{mry,Moor} = f\left(x_C, z_C, \delta, F_{mx,Moor}, F_{mz,Moor}\right)$$



Wave Forces

- 1^{st} order wave forces (Froude-Krylov forces)
  - Surge, heave and pitch directions
  - Same frequency content of the wave (5 -10 s)
- 2^{nd} order wave forces (Drift force)
  - Surge only
  - Low frequency (50 -100 s) → resonance with moorings





1:45 PeWEC prototype

Tests at DIATI flume, Politecnico di Torino (July 2014)

- Prototype check ☺
- Data logging software check ☺
- Preliminary numerical models validation 😐
- Performances influenced by the experimental set-up (cables) ☹

Design and execution of the Wi-Fi data logging system

- Battery supplied prototype
- NI cRIO data logging and control system
- Wi-Fi data transmission

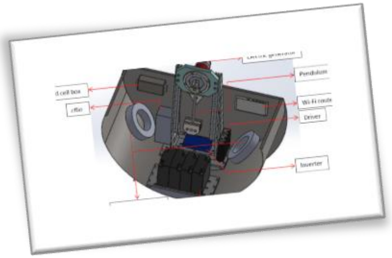
New test campaign at CNR-INSEAN wave basin, Rome (May 2015)

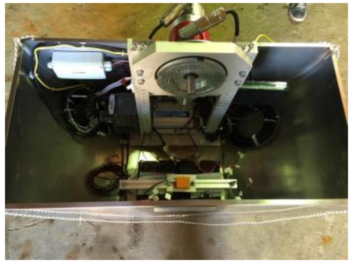
- Check of the new experimental layout
- Regular wave tests
- Irregular wave test
- Numerical model validation

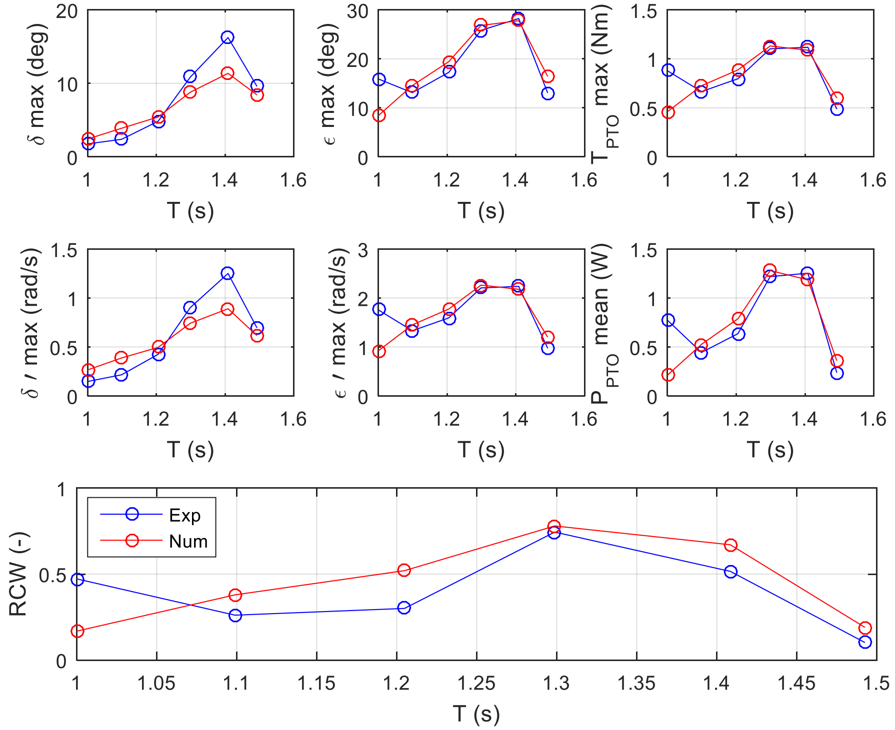
Tests at DIATI flume, Politecnico di Torino

(July 2014)

Design and execution of the Wi-Fi data logging system



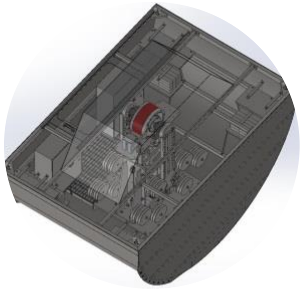




New test campaign at CNR-INSEAN wave basin, Rome

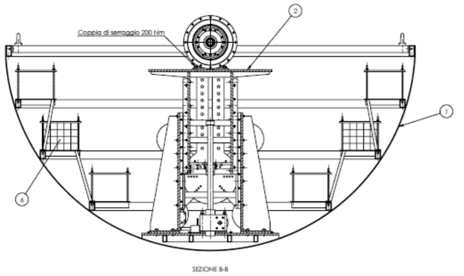
(May 2015)

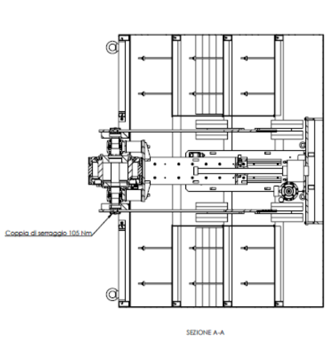
1:12 PeWEC prototype

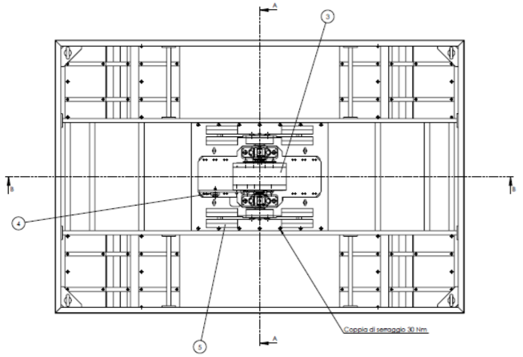


Design

- ***Hull***
- ***Pendulum***
- ***PTO***
- ***Electrical systems***
- ***Control and sensors***
- ***Mooring line***



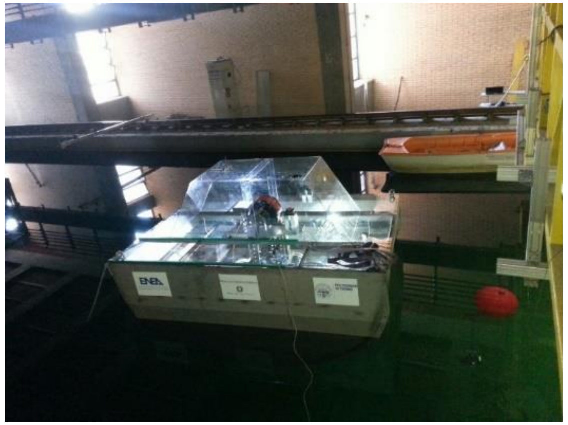




Prototype manufacturing

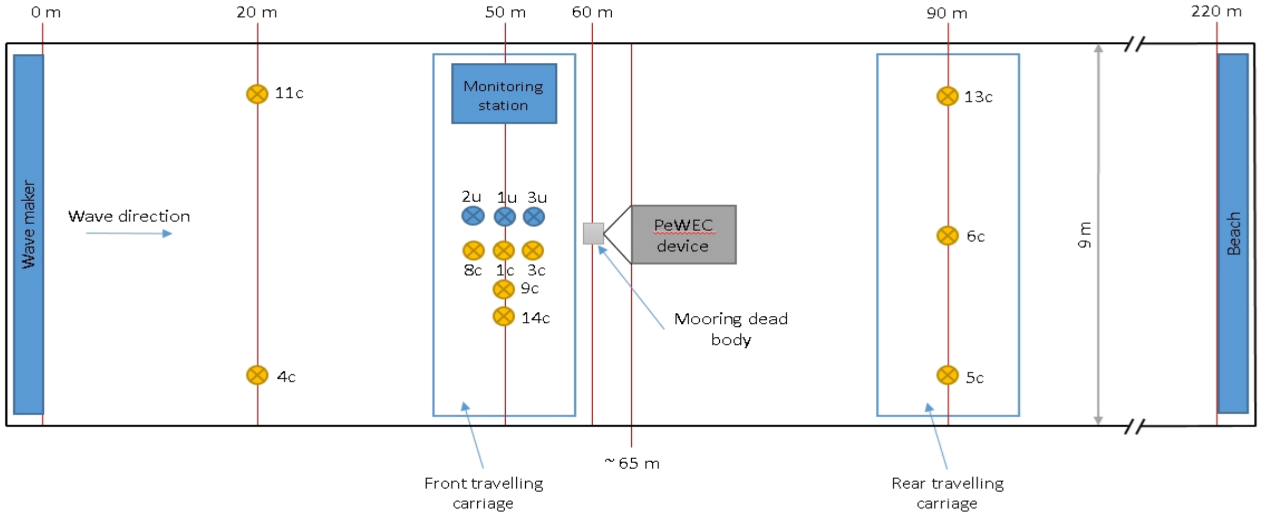
Tank testing @ CNR-INSEAN

(July, August and September 2015)



1:12 PeWEC prototype tank testing

- **4 weeks of experimental testing**
- **INSEAN wave basin, Rome**
- **126 tests:**
  - 74 regular waves tests
  - 52 irregular waves tests based on real Pantelleria Island wave climate
- **Data logging of the main physical variables**
  - Hull and pendulum motions
  - PTO torque and power
  - Wave field monitoring



Regular waves properties and experimental verification in the free wave basin

Symbol	Theoretical wave			Measured wave			Error		
–	H (m)	T (s)	P_w (W/m)	H (m)	T (s)	P_w (W/m)	H $(\%)$	T $(\%)$	P_w $(\%)$
A	0.15	1.90	42.75	0.151	1.89	43.09	0.67	-0.53	0.80
B	0.15	2.00	45.00	0.147	2.00	43.22	-2.00	0.00	-3.96
C	0.15	2.10	47.25	0.149	2.09	46.40	-0.67	-0.48	-1.80
D	0.15	2.20	49.50	0.150	2.20	49.50	0.00	0.00	0.00
E	0.15	2.30	51.75	0.149	2.29	50.84	-0.67	-0.43	-1.76
F	0.15	2.40	54.00	0.152	2.39	55.22	1.33	-0.42	2.26
G	0.15	2.50	56.25	0.148	2.50	54.76	-1.33	0.00	-2.65
H	0.15	2.60	58.50	0.147	2.59	55.97	-2.00	-0.38	-4.33
I	0.15	2.70	60.75	0.151	2.69	61.33	0.67	-0.37	0.96
L	0.15	2.80	63.00	0.156	2.80	68.14	4.00	0.00	8.16

Irregular waves properties and experimental verification in the free wave basin

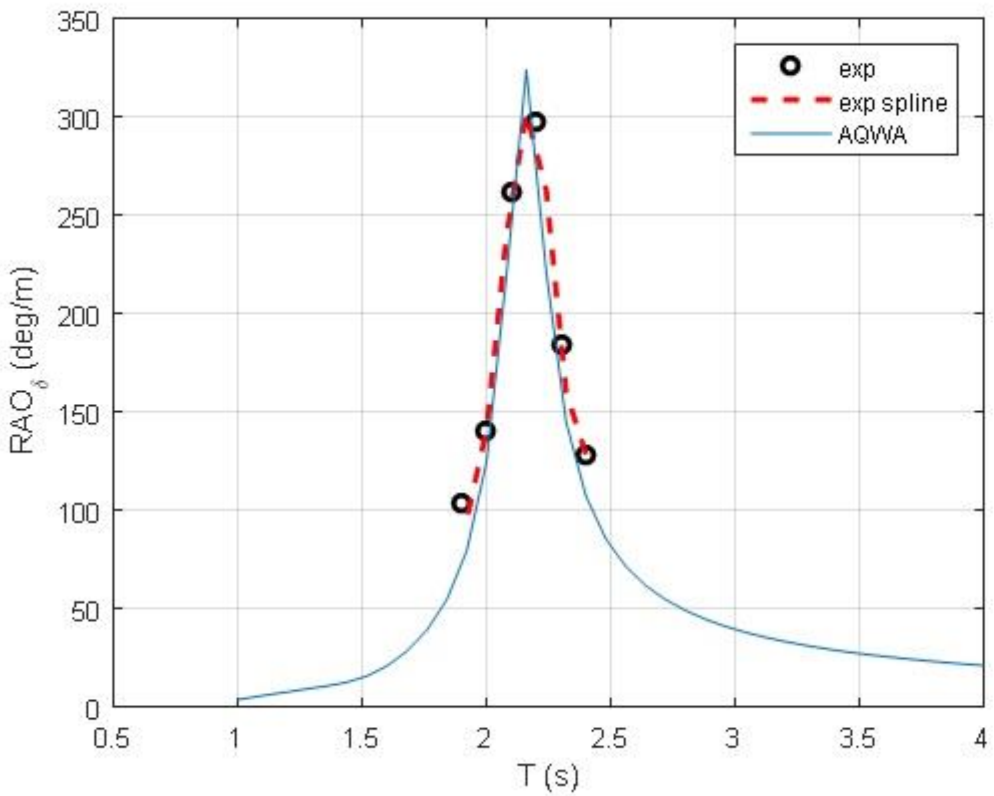
Symbol	Theoretical wave			Measured wave			Error		
–	H_s (m)	T_e (s)	P_w (W/m)	H_s (m)	T_e (s)	P_w (W/m)	H_s $(\%)$	T_e $(\%)$	P_w $(\%)$
U	0.221	2.23	54.46	0.226	2.12	54.30	2.26	-4.93	-0.29
W	0.139	1.94	18.74	0.142	1.92	19.30	2.16	-1.19	2.99

Pitch RAO validation

Response Amplitude Operator (RAO): ratio between the *i-th* floater motion amplitude and the wave amplitude

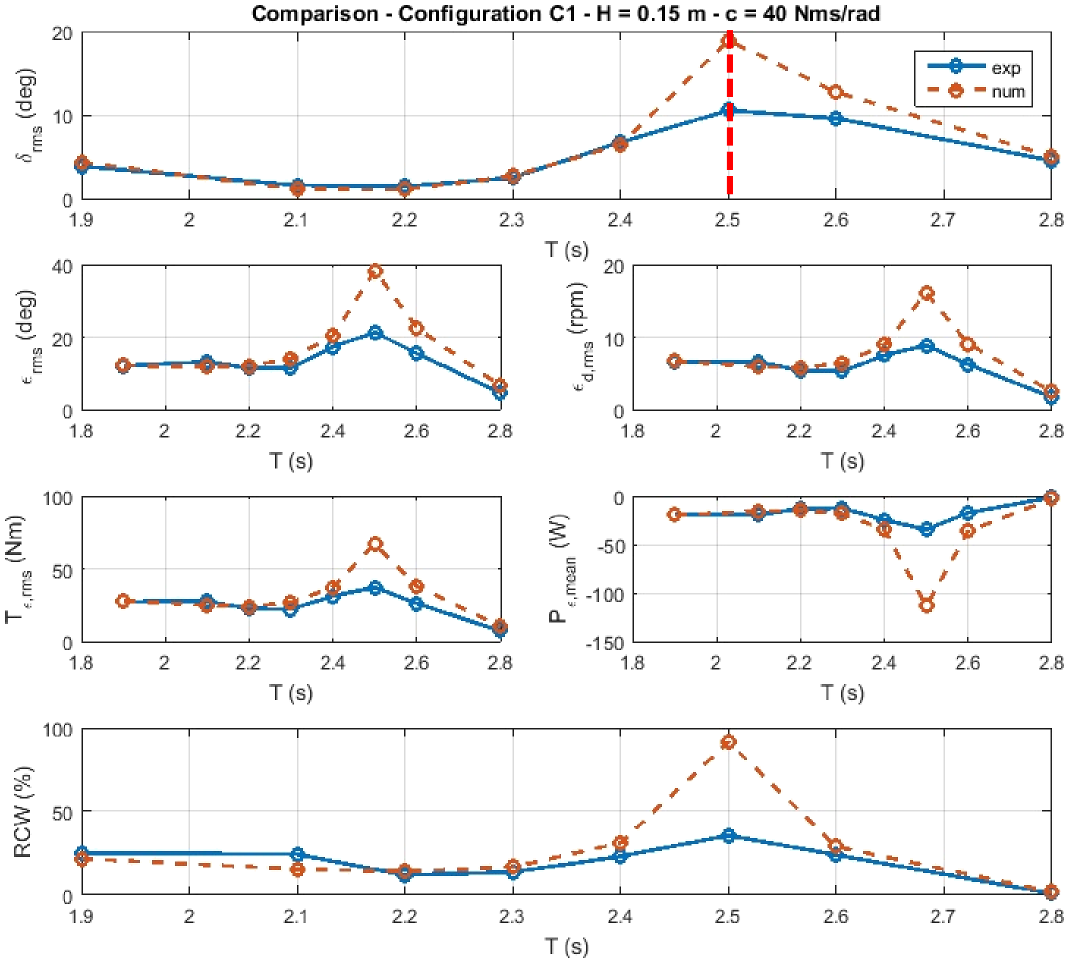
$$RAO = \frac{X_i}{\left(\frac{H}{2}\right)} = \frac{f_{i,w}}{-\omega^2\left(M_{ii} + A_{ii}(\omega)\right) + j\omega B_{ii}(\omega) + K}$$

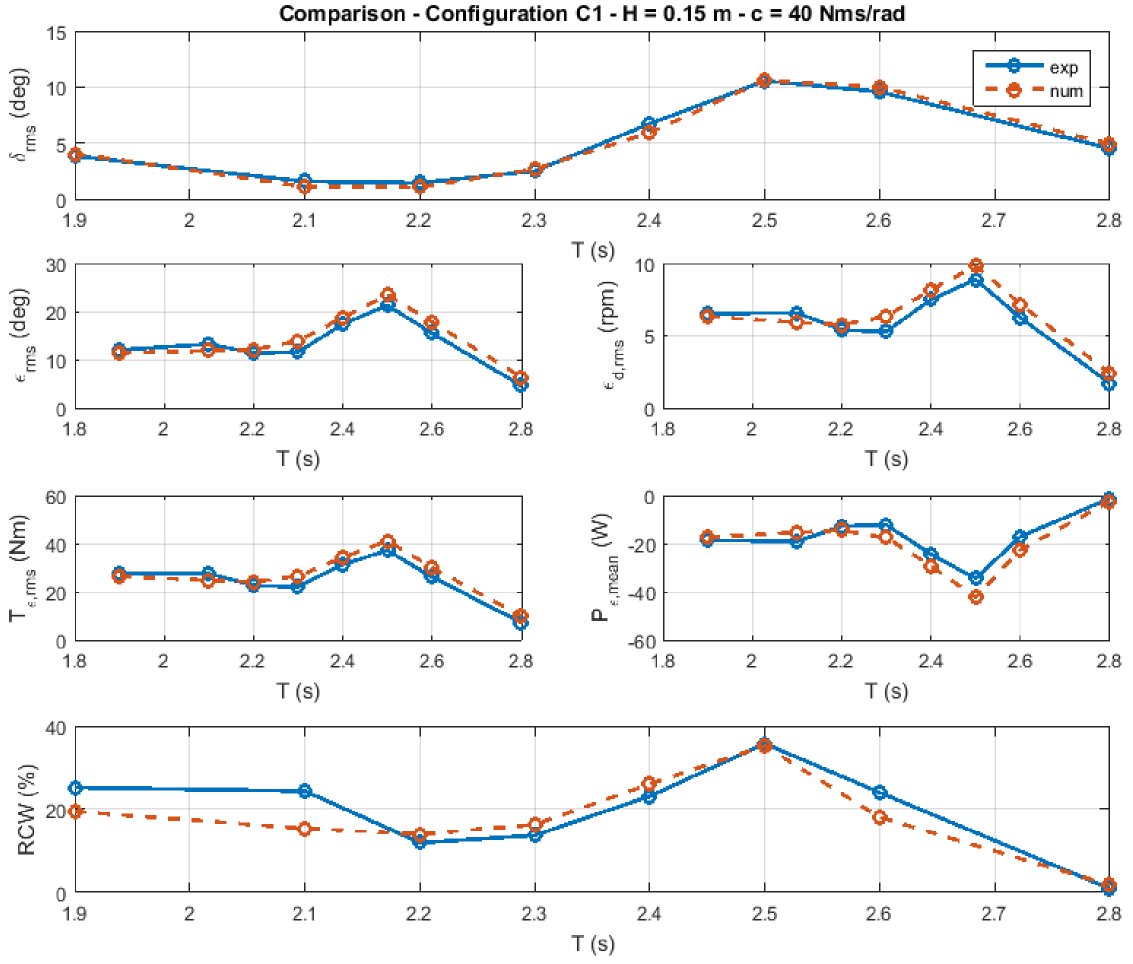
- **Regular wave tests**
  - Fixes wave height → 0,15 m
  - Variable wave period → 1,9 – 2,4 s
- **Locked pendulum**



Model validation (1)

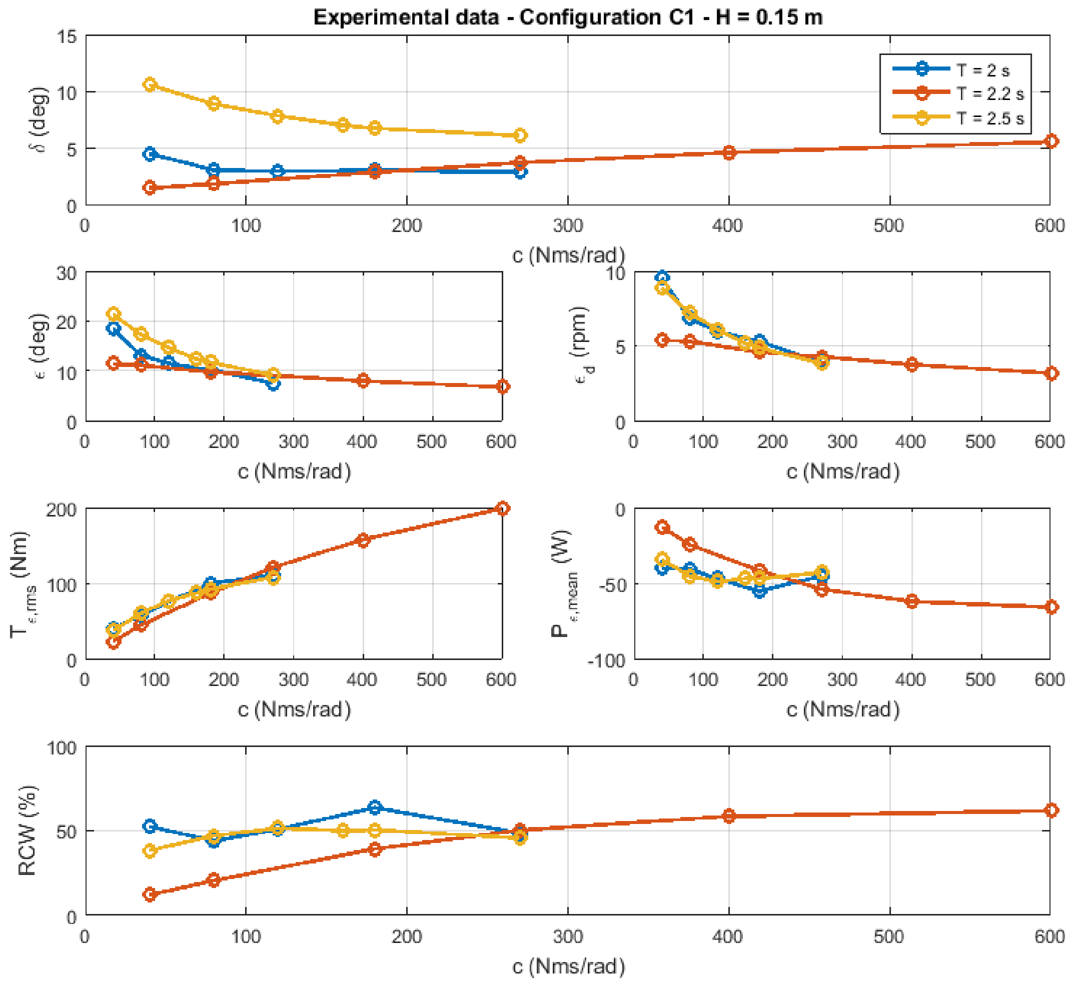
Regular waves tests – Frequency sweep → hydrodynamic viscous damping identification

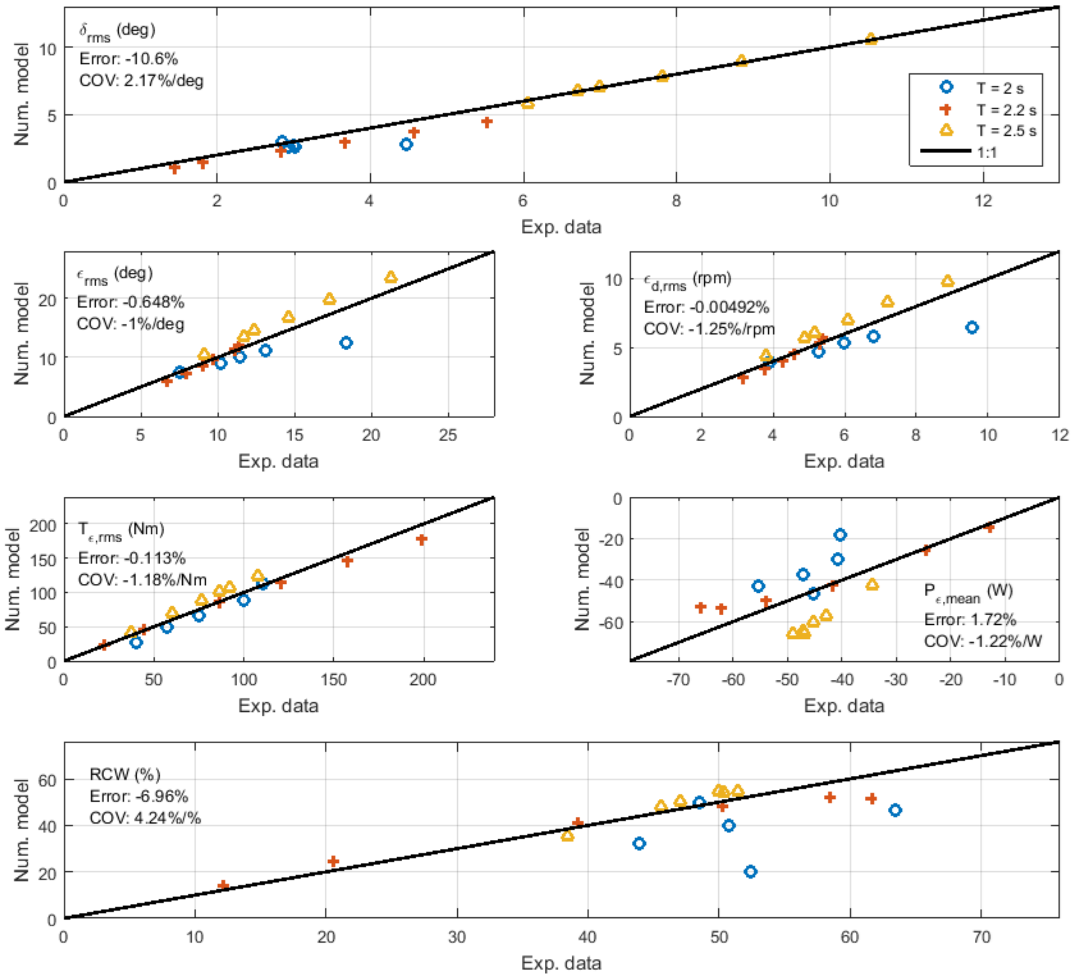




Model validation (2)

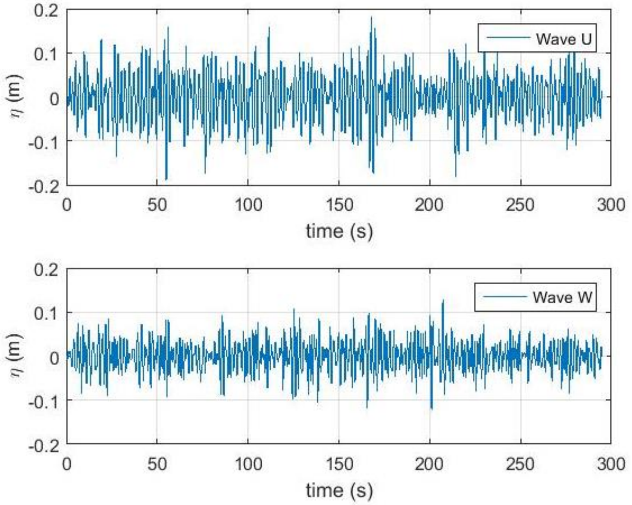
Regular waves tests – PTO control analysis

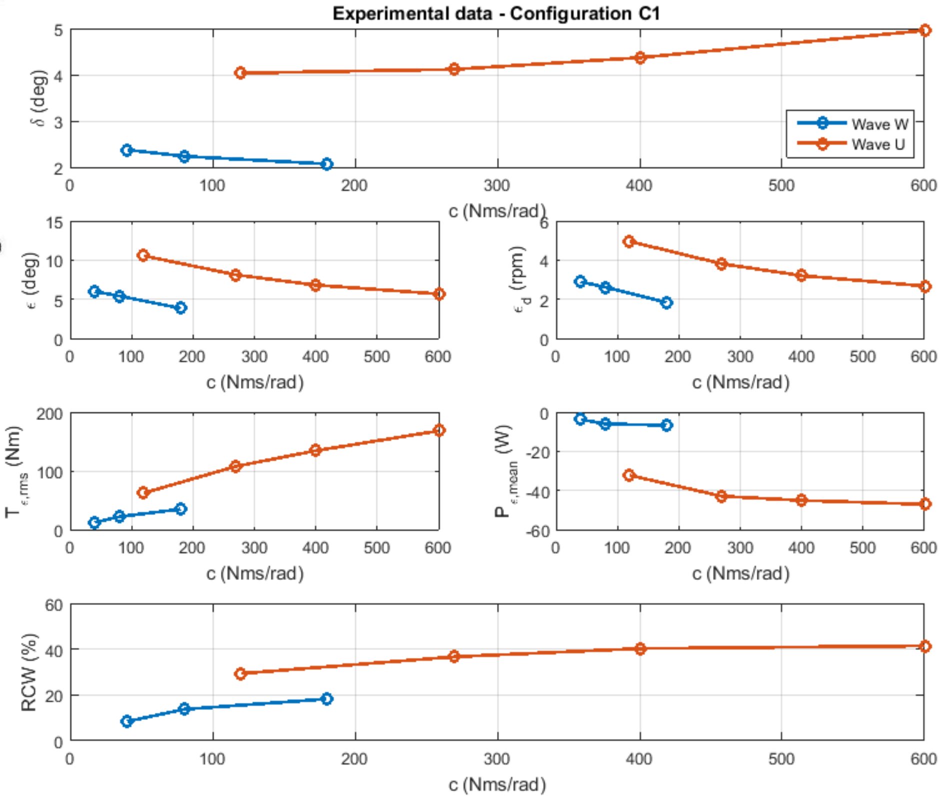


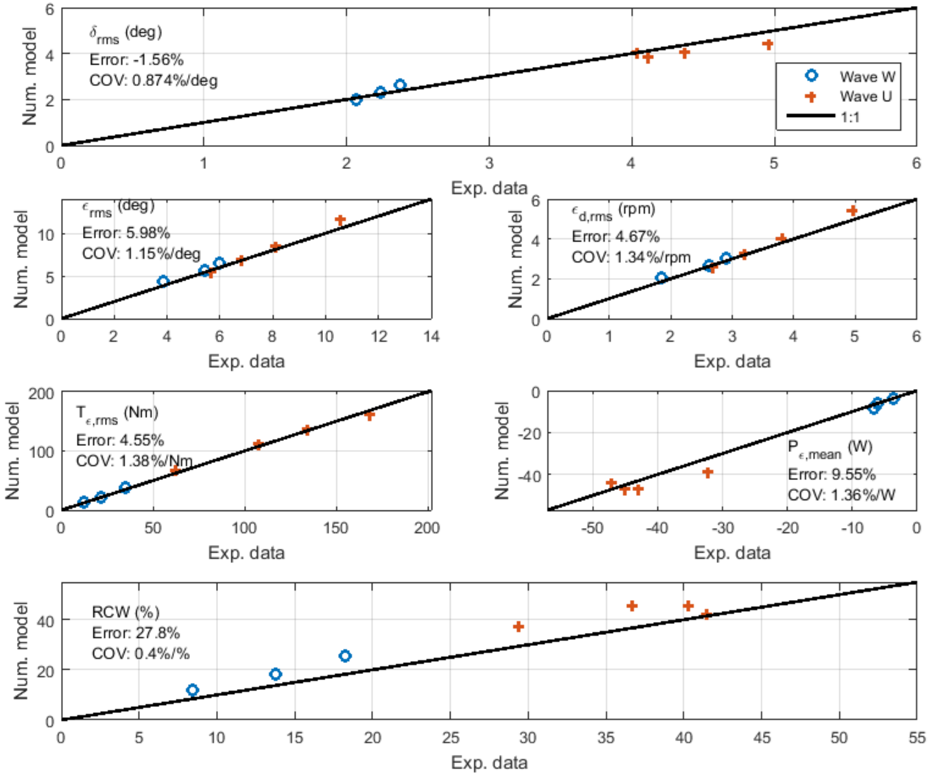


Model validation (3)

Irregular waves tests – Scale waves from Pantelleria Island site







Full scale device design methodology

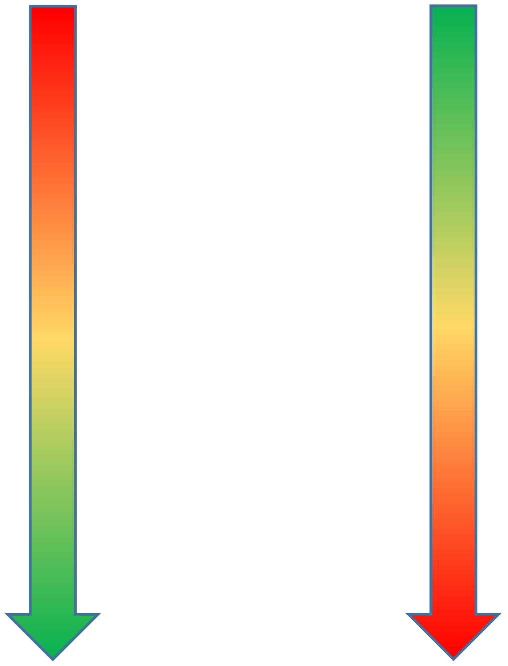
Objectives

- Methodology for the design and optimization of the PeWEC device
- Multiple stage optimization procedure
- Inclusion of the installation site characteristics in the optimization procedure

Methodology layout

- **Linear Optimization Tool:**
  - Preliminary optimization based on the frequency response of the device
  - Combination of the frequency response with the scatter diagram occurrences
- **PeWEC Design Tool:**
  - Linear time-domain model
  - Optimization of the control and performances over the entire site scatter diagram
- **Non-linear PeWEC Parametric Tool:**
  - Nonlinear time-domain model
  - Optimization of the control and performances over the entire site scatter diagram
  - Bearings life and saturations of the PTO are included

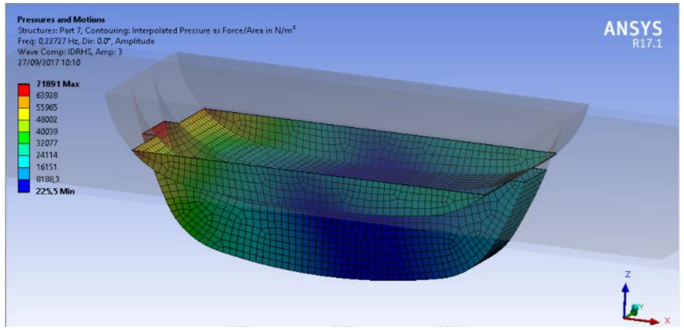
Fidelity **Computational cost**

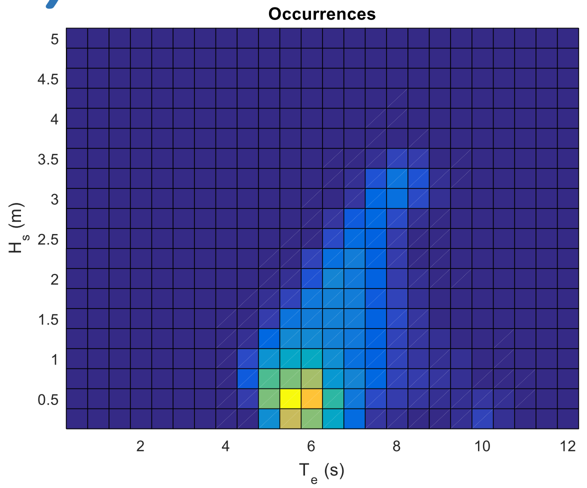


Linear Optimization Tool (LOT)

Input

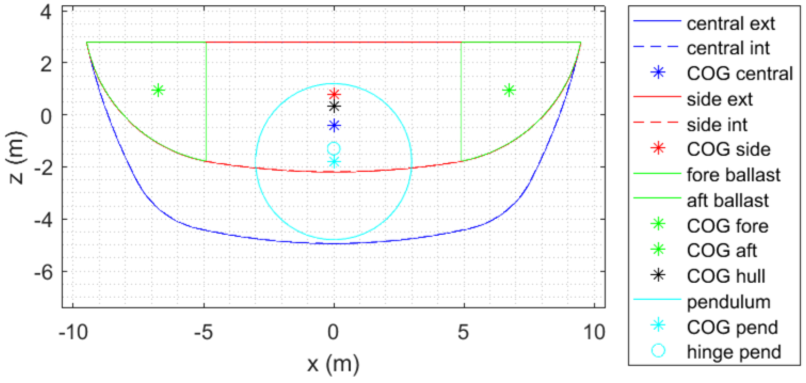
- Floater geometry
- Hydrodynamic database
- Scatter diagram occurrences
- Pendulum geometry

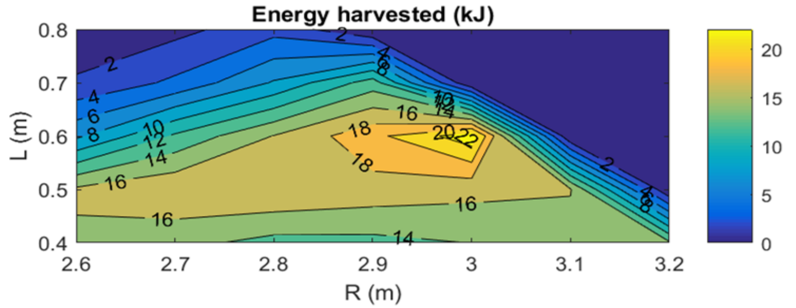


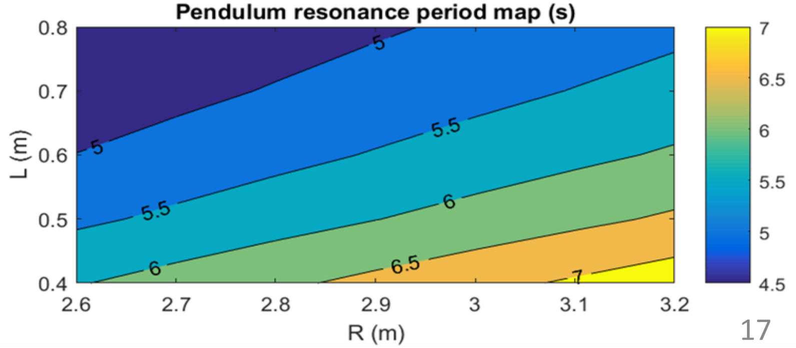


Solver & Optimization (frequency-domain model)

- Pendulum mass and dimensions
- Pendulum position
- Ballast mass
- Extracted power



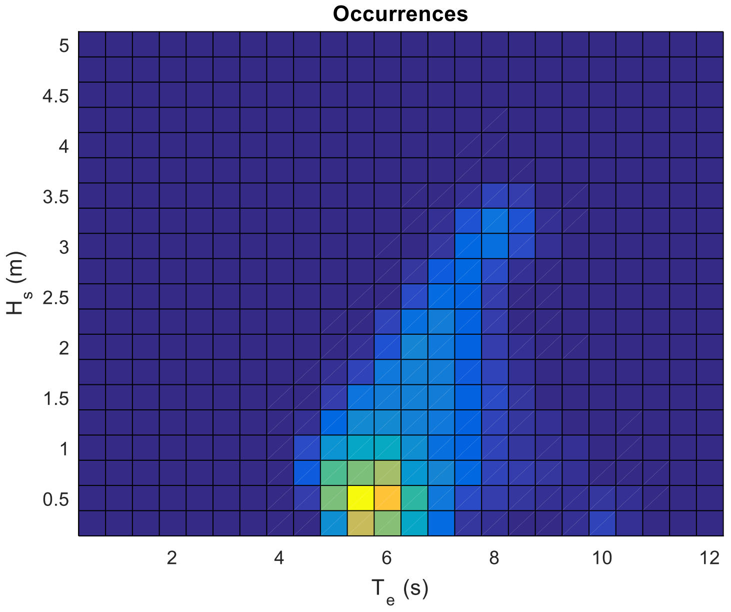


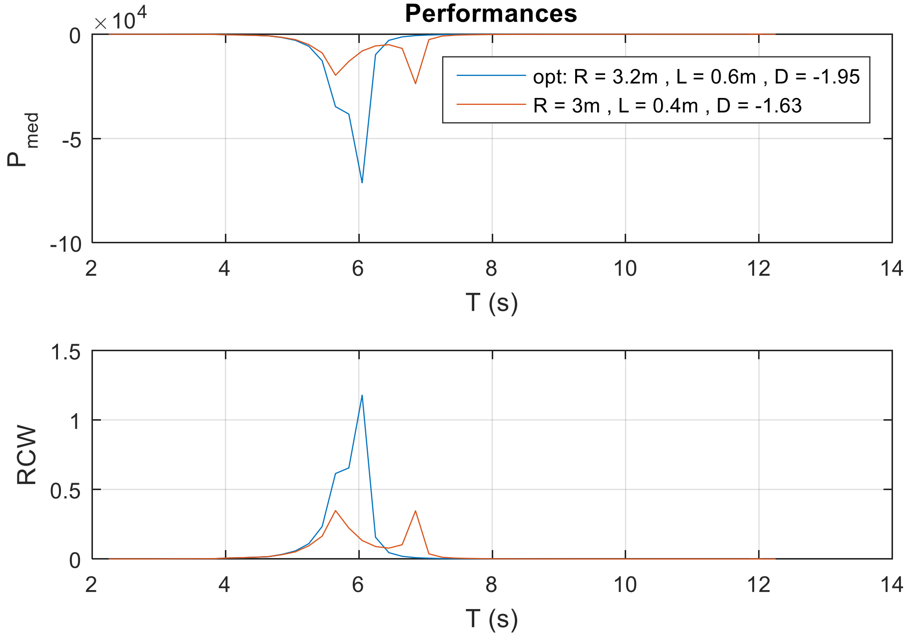


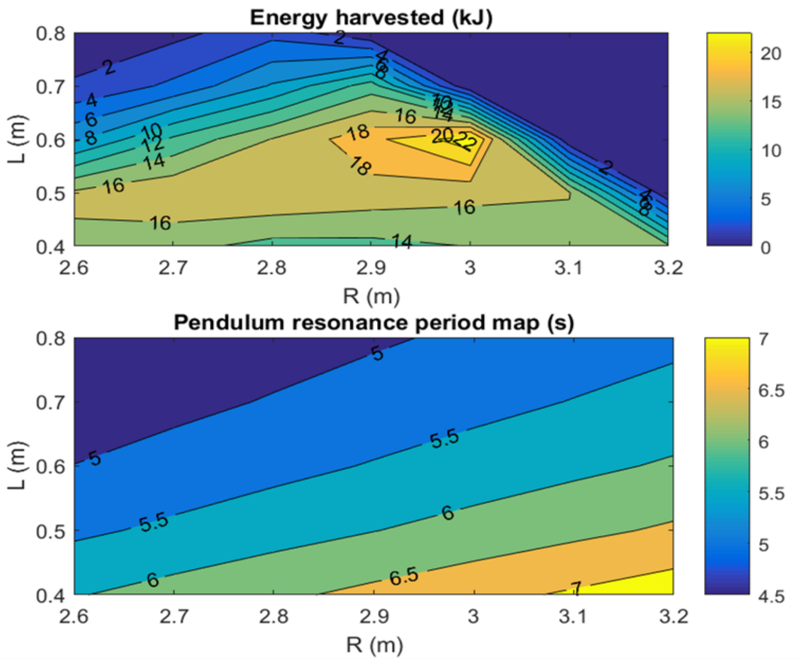
Output

- Optimal configuration is determined:
  - Taking into account the scatter diagram occurrences
  - Geometrical constraints

LOT optimization algorithm detail







$$Hp: T_e \sim T \ \rightarrow f_{Occ}(T) = \sum_{i=H_{s,min}}^{H_{s,max}} Occ(T, H_{s,i})$$

$$E = \int_{T_{min}}^{T_{max}} P_{med}(T) f_{occ}(T) dT$$

PeWEC Design Tool (PDT)

Input

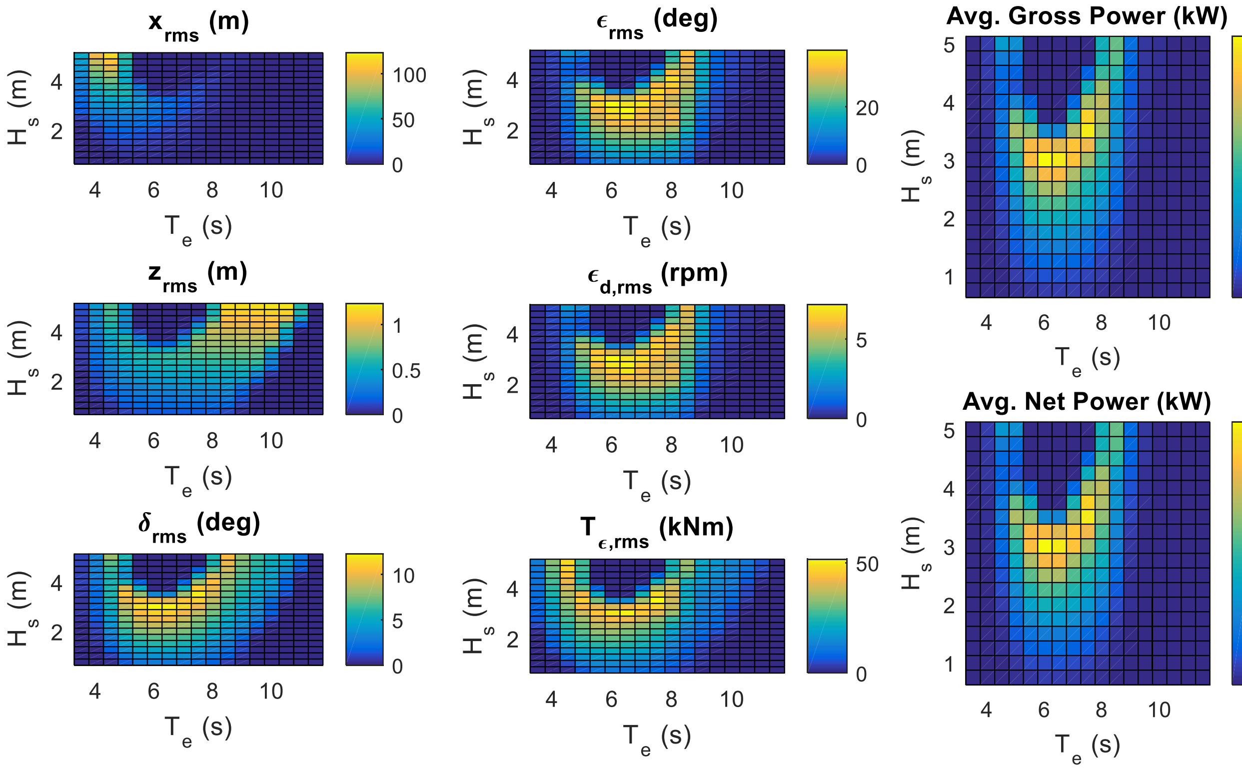
- Optimal parameters from LOT
- Irregular waves
- Scatter diagram occurrences
- PTO power and torque constraints

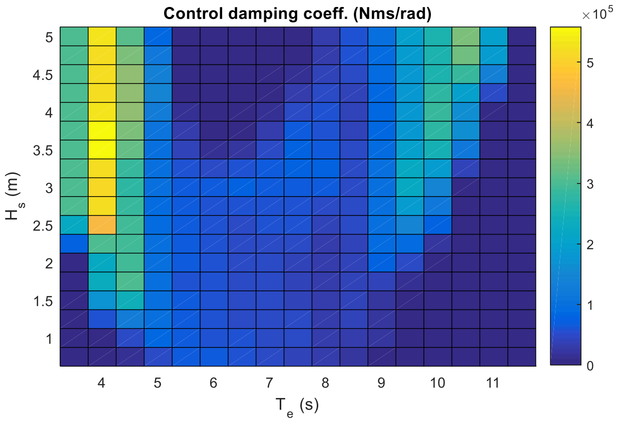
Solver & Optimization

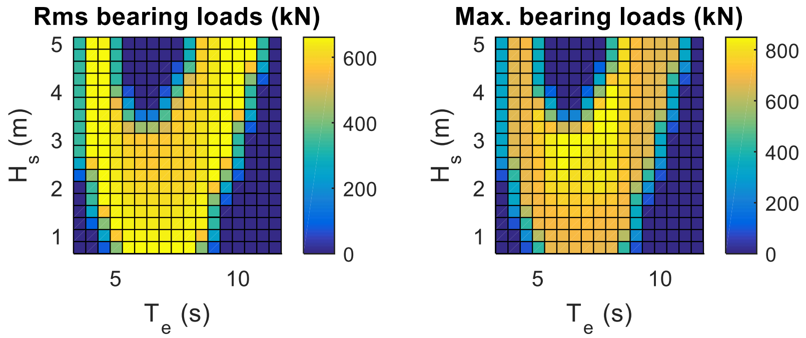
- Linear time domain model
- System performances optimization over the scatter diagram

Output

- Optimal PTO control damping map
- Productivity
- Floater dynamics map
- Pendulum dynamics map
- Bearings loads
- PTO loads map

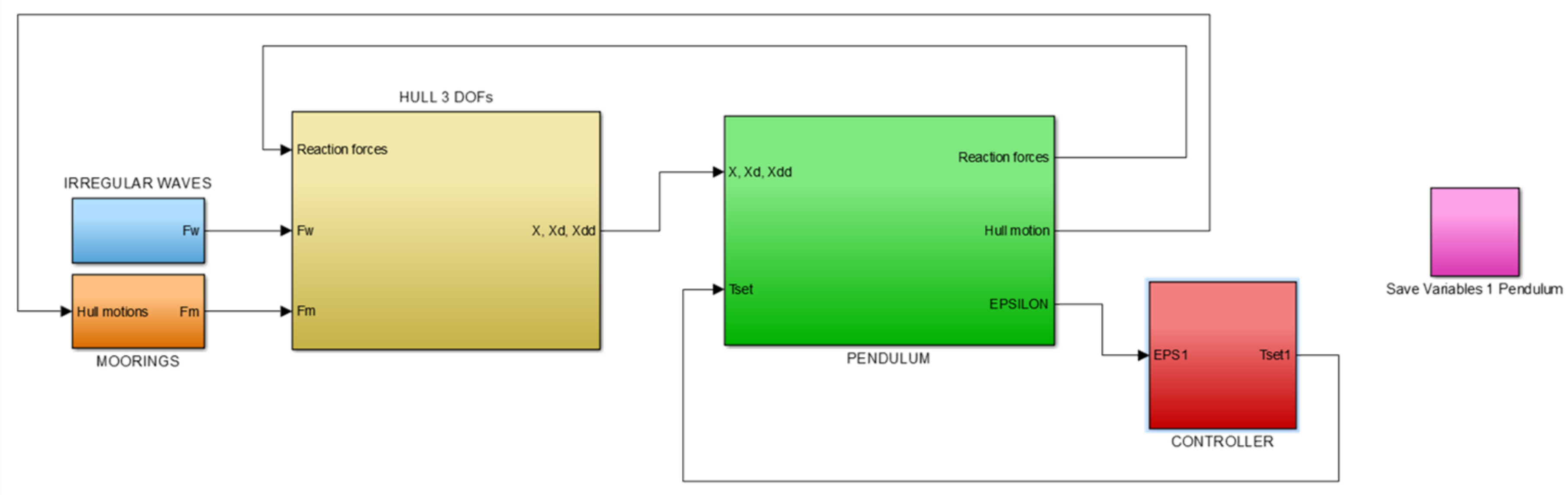






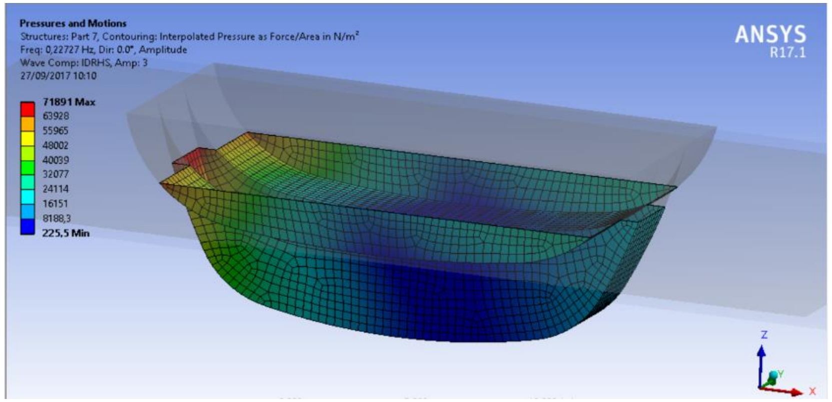
Nonlinear Parametric Tool

- Similar to the PDT tool but a fully nonlinear model is considered
  - Hydrodynamic nonlinearities
  - Nonlinear mooring force-displacement characteristic
  - Nonlinear pendulum dynamic equations
  - PTO velocity and torque saturations
- Used for
  - A final verification of the LOT and PDT results
  - Productivity assessment and optimization
  - Bearings life calculation

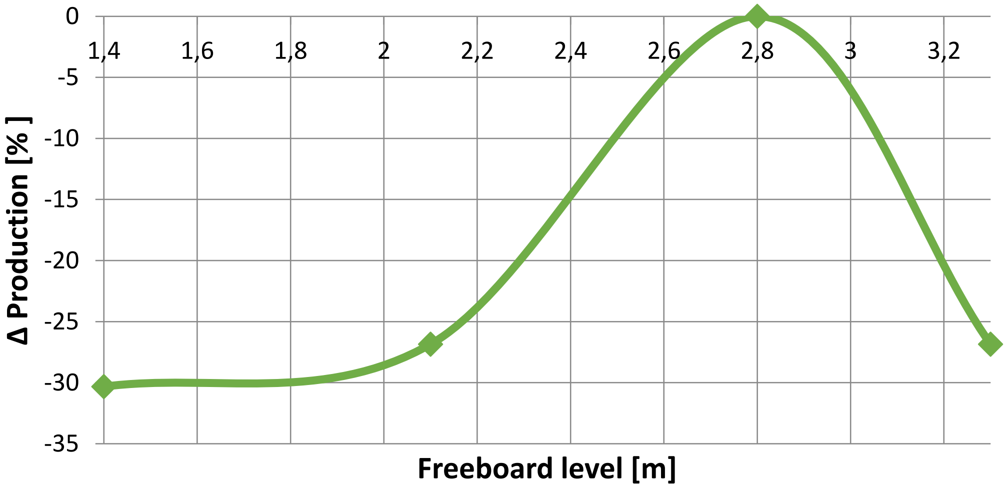


PeWEC full scale design results

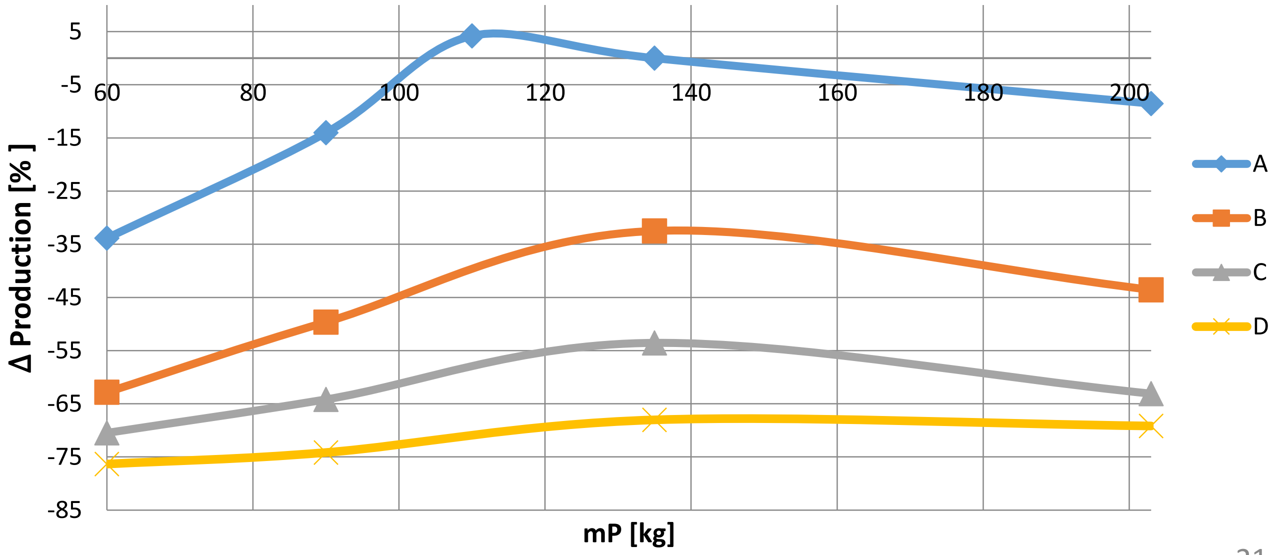
Name	L [m]	Width [m]	W central [m]	Height [m]	Mass system [ton]
C19A	21.4	10	3	9	501
C19B	19	10	3	8	393
C19C	16	10	3	8	335
C19D	16	8	2.5	8	268



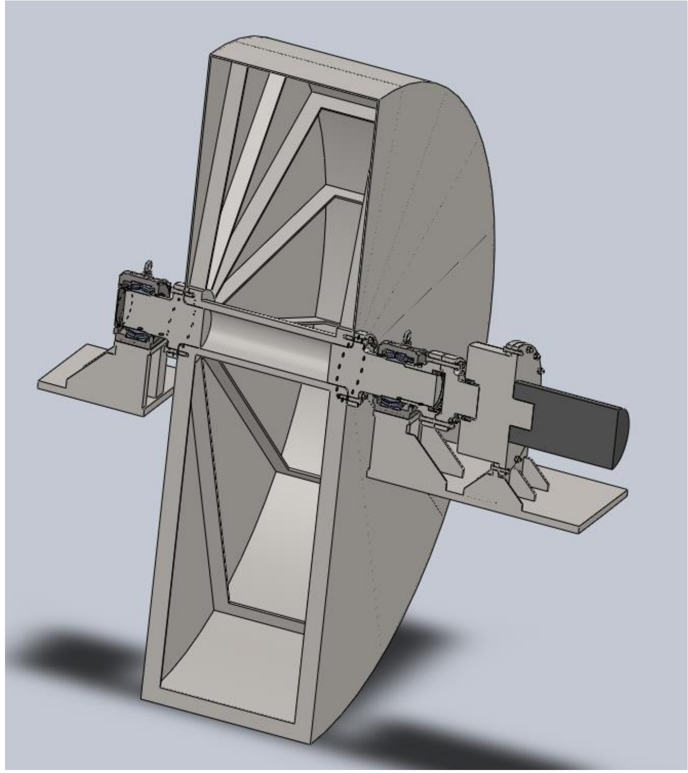
Δ Production Of C19A, 135ton vs. freeboard

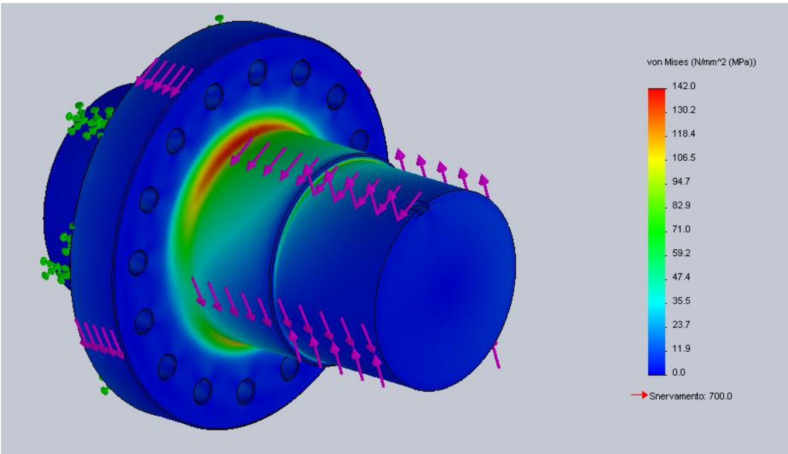


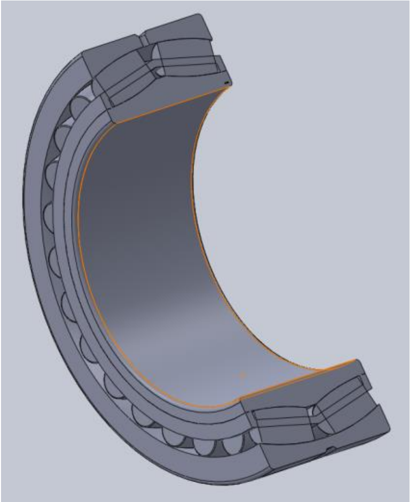
Δ Production w.r.t. C19A,135ton vs. mP

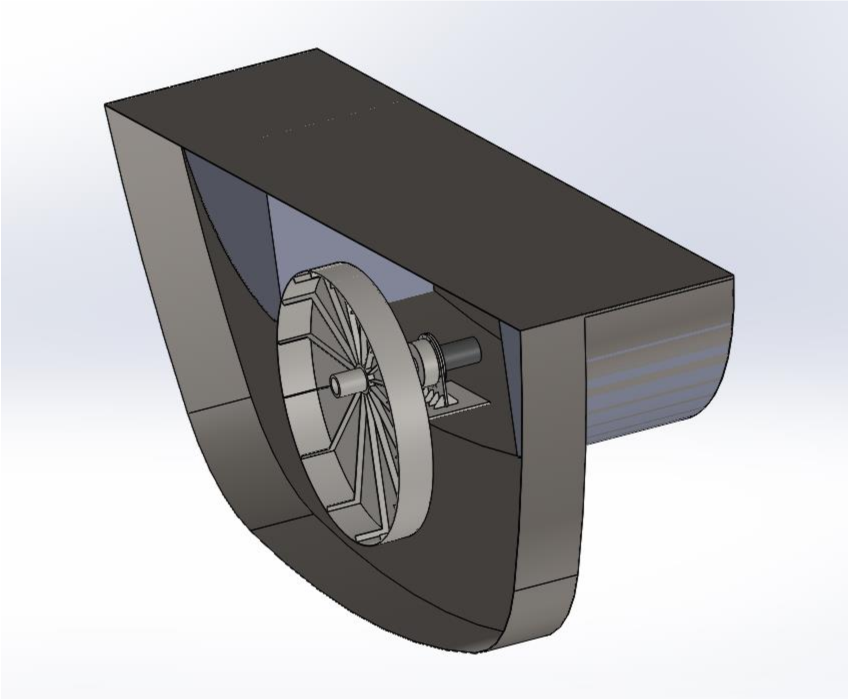


Pendulum technological solution and structural design





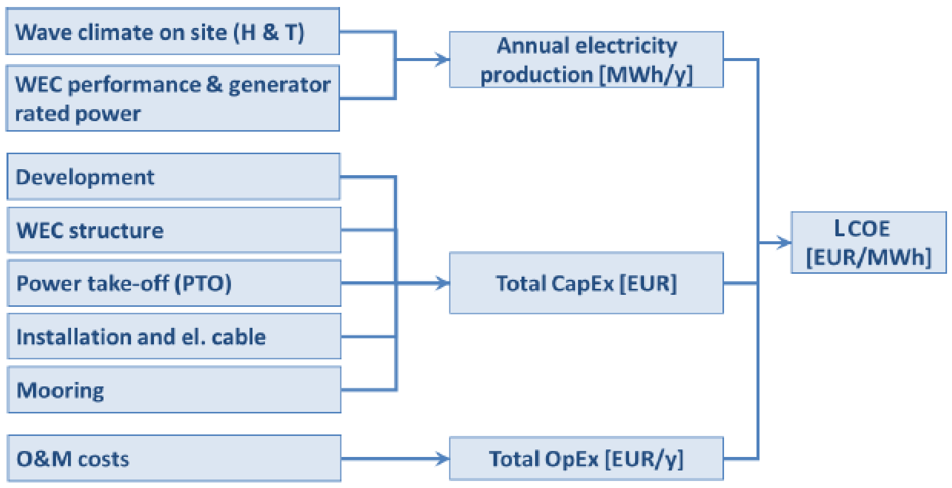




Concrete filled steel pendulum

- m = 115 ton
- R = 3 m
- W = 1,6 m

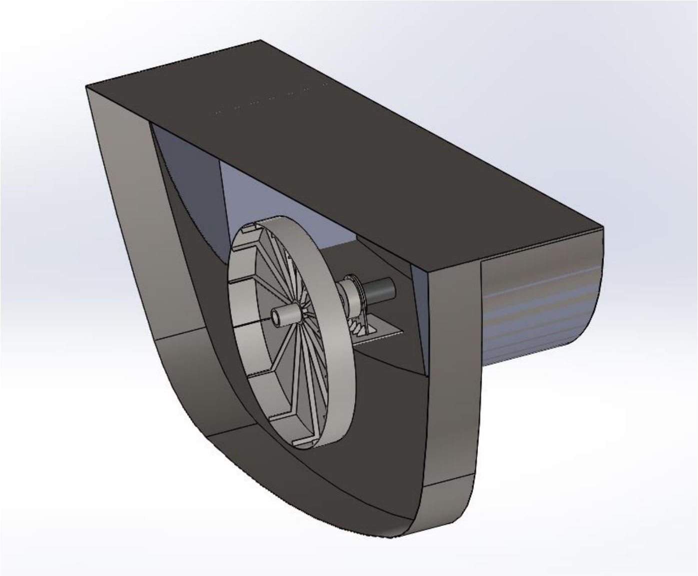
Techno-economic analysis

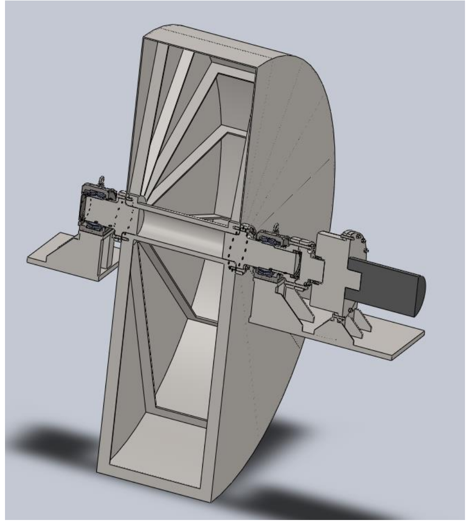


model	CAPEX [€]	OPEX [€]	LCOE [€/MWh]
C19A115ton2800draftPTO4	679222,60	16980,57	+0%
C19A115ton2800draftPTO2	698054,71	17451,37	+3,7%
C19A135ton2800draftPTO4	752519,56	18812,99	+9,75%
C19A135ton2800draftPTO2	771351,66	19283,79	+13%
C19A135ton2800draftPTO1	757894,80	18947,37	+18%
C19B135ton1400draftPTO2	733753,10	18343,83	+54,4%
C19C90ton2800draftPTO1	581239,55	14530,99	+108,3%
C19C90ton2800draftPTO2	594696,41	14867,41	+111,6%
C19D90ton2800draftPTO2	562741,66	14068,54	+263,5%

model	C19A135ton2800draftPTO1	C19A115ton2800draftPTO4
hull mass [kg]	95661	95661
mat cost [€/kg]	3	3
hull cost [€]	286984	286984
ballast mass [kg]	270708	296369
mat cost [€/kg]	0,05	0,05
ballast cost[€]	13535	14818
pend steel mass [kg]	39000	13000
pend concr mass [kg]	91600	100000
pend steel cost [€/kg]	3	3
pend concr cost [€/kg]	0,5	0,5
pendulum cost [€]	162800	89000
shaft mass [kg]	910	871
mat cost [€/kg]	10	10
shaft cost [€]	18200	17420
bearings model	24068 CC/W33	24068 CC/W33
bearings cost [€] (tot)	20000	20000
gearbox cost	37000	37000
PTO model	PTO1	PTO4
PTO motor [€]	28455	35000
PTO drive [€]	10921	17000
PTO tot [€]	39375,248	52832
mooring cost [€]	120000	120000
onboard instruments [€]	60000	60000
TOT [€]	757894	679222

Full-scale device features





C19A115ton2800draftPTO4	
Floater	
Length [m]	21
Width [m]	10
Height [m]	9
Steel mass [kg]	95661
Ballast mass [kg]	296369
Total mass [kg]	392030
Pendulum	
Steel mass [kg]	15000
Concrete mass [kg]	100000
Total mass [kg]	115000
Bearings	
Bearings model	SKF 24068 CC/W33
Inner diameter [mm]	340
Gearbox	
Ratio	10
PTO	
Model	Siemens 1FW3287-2E
Rated torque [Nm]	7000
Rated speed [rpm]	120
Rated power [kW]	110

Conclusions & Further work

Conclusions

- Numerical modeling of a pendulum based WEC
- Implementation of the 3 DOF hydrodynamic model
- Experimental testing of 1:45 and 1:12 scale models
- Numerical model validation
- Development of a design methodology for the full scale device
- Design and techno-economic analysis of the full scale device for the Pantelleria Island site

Further work

- LCOE reduction
  - Test and implementation of more sophisticated control techniques
  - Test of the hydraulic PTO solution
  - More detailed floater structural design
- Improvements of the Linear Optimization Tool
  - Integration of a open source hydrodynamic BEM
  - Optimization via genetic algorithm instead of a parametric run

POLITECNICO DI TORINO

Thank you!