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# Mooring Influence on the Productivity of a Pitching Wave Energy Converter

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**Abstract**—The paper aims at investigate the effect of the mooring system on Wave Energy Converter productivity. In this case a pitch resonant device has been considered for the analysis.

The non-linearities of the mooring system require generally a computational effort which cannot be considered in the early design stages of a WEC, and seldom the mooring systems are totally included in WEC models.

Driven by those considerations, a nonlinear mooring solvers, MoorDyn, has been used to carry out the effect of the mooring system on energy production.

As first step a mooring model has been built to take familiarity with the solver and it has been validated against experimental data, through a static pull-out test and with irregular wave. Then, a semi-taut mooring model has been included in the hydrodynamic model.

## I. INTRODUCTION

Nowadays the clean energy production issue is one of the most relevant and challenging engineering field to be explored. In solar, wind and hydropower ambit already exist many well-established techniques to extract power efficiently, while in wave energy conversion still exist large improvement edges. Wave energy sources, as [1], [2] suggests, are widely spread in the world, and their presence may compensate the lack of previous cited renewable energy elements (i.e. in northern areas, for a significant part of the year, solar power is almost completely absent).

To extract power from waves, Wave Energy Converters (WECs) are the state-of-art technology. A WEC is composed by a floating body, which is moved by the waves, a Power Take Off (PTO) system, responsible to extract power from the WEC dynamics, and a mooring system, in charge to keep the WEC in the placing spot and not to allow the sea waves to carry away the WEC itself.

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There exist many types of WECs and so several way to classify them [3]. Considering their distance from shore, WECs could be classified in: On-shore WECs, which are attached to the sea, Near-shore WECs, which operates near by the shore, and Off-shore WECs, which are the most productive ones due to their capability to be placed far away from the coast, where the sea state have a higher energy density.

Recent hybrid applications also exploit WECs as off-shore floating bodies for wind turbine basements, showing the potentiality of hybrid renewable energy converters [4]. On one hand, to evaluate the energy productivity of a WEC an accurate and effective mathematical model is needed indeed [5] but, on the other hand to evaluate the design of the device a simple and fast model must be constructed. This is the main motivation for which high-fidelity and slow models, as Computational Fluid Dynamic (CFD), as stated in [6], [7], are neglected in design stage. In this context, one of the most critical modelling issue regards the mooring WEC system [8].

Moorings in general have a strong influence on the entire system dynamics, and as a consequence on the overall productivity of the device. Moreover, it is complex to model the mooring system with a simple mathematical model without losing some key information about the real layout. The main idea of this work is to build a data-based mooring model, as done in [9], aimed at working well in fast simulations and real-time contexts. The model will also be validated with experimental data. This work has been carried out on the PeWEC device, a pitching resonant floating Wave Energy Converter with an internal pendulum: the wave is intended to move the device on its pitch rolling direction, and the inertial pendulum will extract power oscillating around a parallel-motion axis. The following paper structure is organized as follows: in II the PeWEC model [10]–[12] is presented. In II-B the mooring model is set out. In III the validation results are first shown and then analyzed. IV regards the productivity results analysis obtained from the quasi-static modelling. In

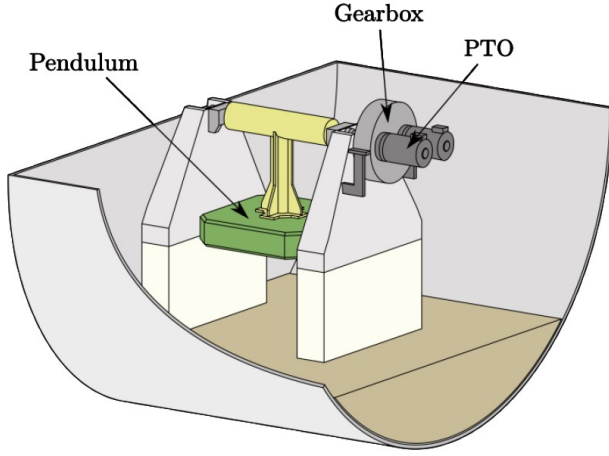


Fig. 1. PeWEC configuration

the last section V, conclusions are presented.

## II. PEWEC DEVICE

PeWEC is a pitching-resonant floating device composed by an external hull, an internal pendulum subsystem, a PTO system attached to the pivot axis of the pendulum (directly fixed along the pitching axis rotation of the hull), and a mooring system. The pendulum and the PTO are in charge of extracting power from the hull motion, and they are directly enclosed in it to prevent them from early break up. In this configuration (1), the floater pitching motion is directly transformed in electrical power through a generator.

### A. Hull Mathematical Model

If the mooring system is properly designed, the device is able to self-align with the main wave direction. So that, the only considerable motions in PeWEC analysis are surge, heave and pitch, in the following order:

$$X(t) = [x(t), z(t), \delta(t)] \quad (1)$$

Setting our problem in linear wave theory context, and in small floater oscillations scenario, the floater dynamic is described by the Cummins' equation [13]:

$$(M + A_\infty)\ddot{X}(t) + \int_0^t K_r(t-\tau)\dot{X}(t)d\tau + B_v|\dot{X}(t)|\dot{X}(t) + K_hX(t) = F_{ext}(t) \quad (2)$$

The convolution integral part and the added mass term constitute the mathematical representation of the radiation forces. Moreover, the convolution integral term can be approximated with an LTI system, which state space representation is:

$$\begin{cases} \dot{\zeta}_r(t) = A_r\zeta_r(t) + B_r\dot{X}(t) \\ F_r(t) = C_r\zeta_r(t) + D_r\dot{X}(t) \end{cases} \quad (3)$$

This subsystem state space matrices have been computed with tailored system identification software [14]. On the other

TABLE I  
WEC MODELLING VARIABLES

Notation	Description
$M$	Inertia Matrix
$A_\infty$	Added Mass
$K_r$	Radiation Impulse response
$K_h$	Hydrostatic Stiffness
$F_{ext}(t)$	External Forces
$B_v$	Nonlinear viscous Forces Coefficient (computed with CFD tools)

hand, external forces  $F_{ext}$  collect the force exerted by the wave, the mooring force and the forces generated by the PTO and the pendulum. Every one of these contributions are discharged on the hull:

$$F_{ext} = F_{wave} + F_{mooring} + F_{PTO} \quad (4)$$

At the end, it is important to notice that the produced power is given by the direct multiplication between the pendulum oscillation velocity and the produced control torque (the negative sign indicates that the power is absorbed by the system, and not produced).

$$Power = -\dot{\epsilon}T_{control} \quad (5)$$

Nevertheless, containing the PTO an internal gearbox, the PTO torque and the control torque are linked by the reduction ratio:

$$T_{PTO} = \frac{T_{control}}{\tau_{gearbox}} \quad (6)$$

It is also of paramount importance to notice that there is no direct linear link between  $\epsilon$  and  $\delta$ , as equation 7 suggest. Refer to figure 2 for equation 7 notation.

$$\begin{aligned} (I_y + ml^2)\ddot{\epsilon} - ml\cos(\delta + \epsilon)\ddot{x} + ml\sin(\delta + \epsilon)\ddot{z} \\ (I_y + ml^2 - mdl\cos(\epsilon))\ddot{\delta} - mdl\sin(\epsilon)\dot{\delta}^2 \\ + mgl\sin(\delta + \epsilon) + T_{ctrl} = 0 \end{aligned} \quad (7)$$

More information about the device modelling and wave generation, which are out of scope of this work, can be found in [12], [15], [16].

### B. Mooring mathematical Model

The analysis of the mooring system influence on WEC productivity should be carried out by coupling the hydrodynamic model (analysed in the previous section) with the mooring model. There are several ways to describe the mooring system behaviour [17] and the choice of solver depends mainly on the non-linearities of the problem [18], and on the balance between the accuracy and the computational time.

To carry out the analysis, MoorDyn [19] has been chosen as mooring solver. MoorDyn is a dynamic mooring solver that uses a Lumped-Mass method for line defining. As dynamic solver, it takes into account inertia influence and line drag effects hence, the accuracy expected is high.



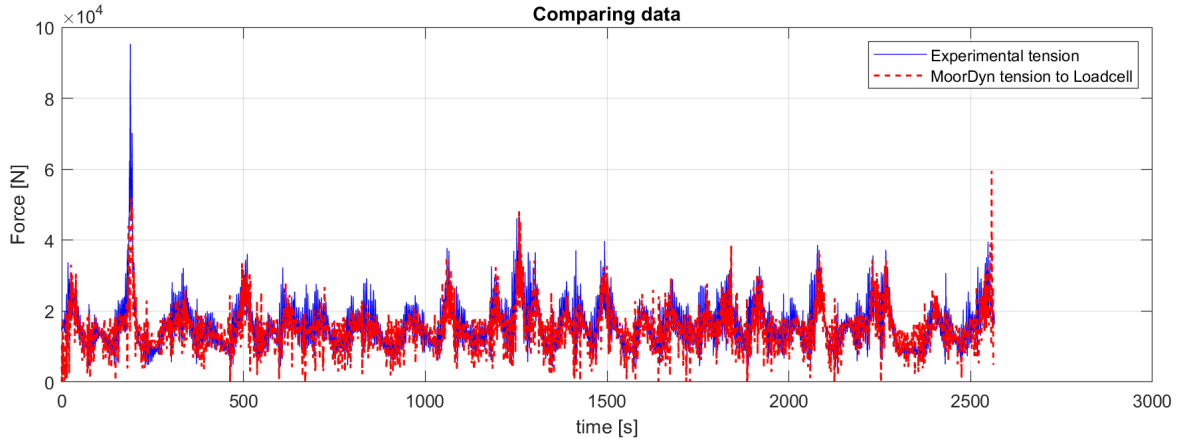


Fig. 5. Dynamic validation of C2a configuration

The model matches the tension function almost perfectly, except for some particular peaks, which represents the snap events. In Table III are presented standard deviation variation and mean value variation between the 2 sets of data, which represent a good index for the model goodness of fit:

$$\Delta_{\mu} = 100 \frac{\mu_{MoorDyn} - \mu_{experimental}}{\mu_{experimental}} \quad (8)$$

$$\Delta_{\sigma} = 100 \frac{\sigma_{MoorDyn} - \sigma_{experimental}}{\sigma_{experimental}} \quad (9)$$

TABLE III  
VALIDATION RESULTS

Configuration	$\Delta_{\mu}$	$\Delta_{\sigma}$
C2a	6.65	10.3

#### IV. PRODUCTIVITY ANALYSIS

##### A. Mooring model and environmental data

The device considered in this analysis has been generated from a genetic algorithm [20] and it is quite different from the pitching device tested during the experimental campaign hence, the same mooring system cannot be used in this analysis.

Among the mooring systems used for WECs [21] [22], a semi-taut mooring has been considered. Clearly the effect on the device motion (and productivity) of a semi-taut mooring system is higher than a catenary mooring [23] but could be interesting to investigate its use considering its cost [24].

The simulated mooring system is formed by 4 lines distributed symmetrically from device edges. Each line forms an angle of 45 degree with the surge prevalent direction hence, it is a mono-directional mooring system that means that the hull is no able to weathervane.

This kind of mooring system could be used for some sites, where there is a prevalent wave direction. The line is composed by 2 polyester parts with a subsurface jumper (a scheme is available in Fig.6).

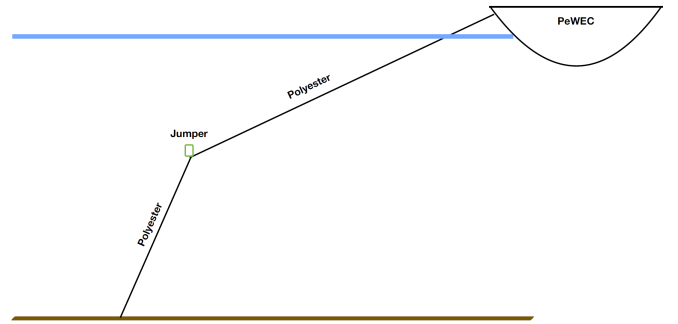


Fig. 6. Diagram of the mooring system considered in the productivity analysis.

The environmental data has been taken from 'Rete Ondametrica Nazionale' (RON) [25]. Environmental data has been computed for the site 'Mazara del Vallo' in the south-west part of Sicily, and the waves for the analysis have been chosen as follow:

- The occurrences has been evaluated and a scatter diagram defined.
- The wave power has been established for waves defined in the scatter diagram [26]

$$J = 0.49T_e H_s^2 \quad (10)$$

- Multiplying the wave power for the wave occurrences the site energy grid has been defined.
- 20 Waves have been chosen as the most energetic waves of the site.

##### B. Results

The PeWEC model is totally developed in Simulink/Matlab environment hence, the integration of the MoorDyn mooring model has been facilitated.

To take into account the influence of the mooring on the productivity two models will be considered:

In the first model the device is free to swing around its pitch axis instead, in the second model, the mooring will hinder its pitch motion.

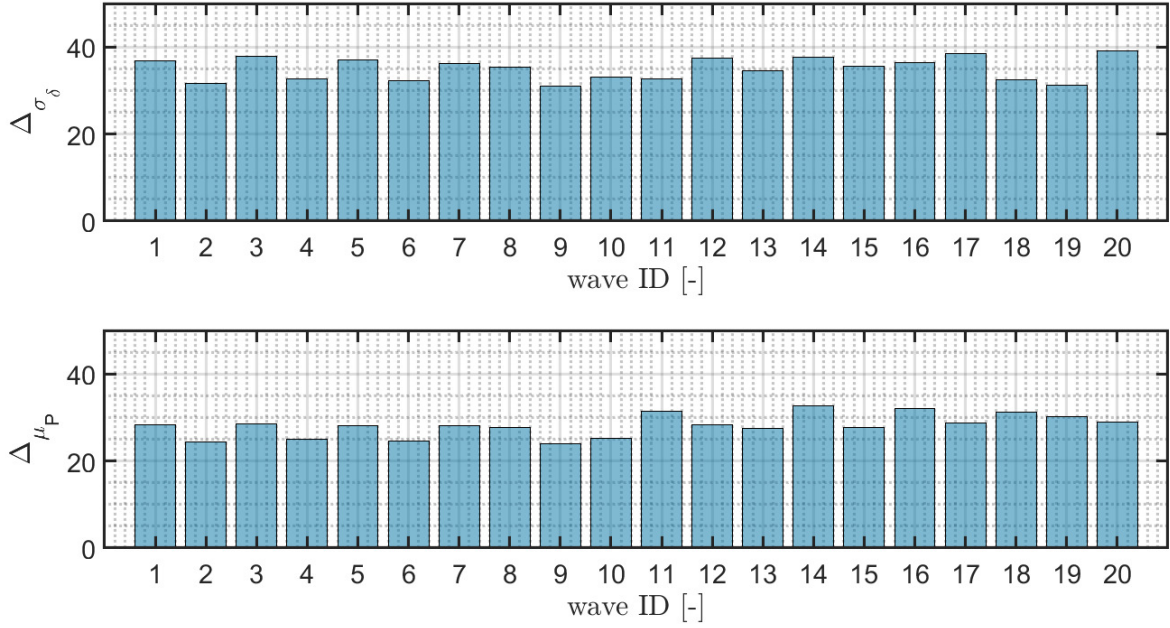


Fig. 7. Mooring influence on device pitch motion and productivity. Comparison between MoorDyn model and no moored model.

TABLE IV  
WAVES

Wave ID	$T_e$ [s]	$H_s$ [m]
1	6	1.25
2	7.5	1.75
3	6	1.5
4	7.5	2.25
5	6.5	2
6	7.5	2
7	6.5	1.75
8	6.5	1.55
9	7.5	1.5
10	7.5	2.5
11	8	2.75
12	6.5	2.25
13	6.5	1.25
14	5.5	1
15	6	1
16	5.5	0.75
17	6	1.75
18	8	2.5
19	8	1.75
20	6	2

TABLE V  
RESULTS

Model	$\bar{\Delta}_{\mu_P}$	$\bar{\Delta}_{\sigma_\delta}$
MoorDyn	28.1	34.9

of the device as percentage.

$$\Delta_{\mu_P} = 100 \frac{\mu_{P,moored} - \mu_{P,no-moored}}{\mu_{P,no-moored}} \quad (12)$$

$\Delta_{\mu_P}$  represents the influence of the mooring system on device productivity. Both values have been reported in Fig. 7, as absolute values.

## V. CONCLUSIONS

The results show a significant influence of the mooring system on device productivity. This is mainly due by the semi-taut nature of the mooring system that effects enormously the device pitch motion. Of course, this kind one of the worst cases has been taken as test case, but the main goal has been achieved, and the importance of considering a proper mooring model in the productivity analysis is clear.

As said, the paper purpose is to show the effect of a mooring model on WEC productivity, and a cost and LCOE analysis is outside this work.

For the sake of clarity, both models have been built with MoorDyn to take into account the correlation between surge and pitch motions, but in the no-mooring model the pitch moment due to the mooring system has been set to zero.

The Fig. 7 exposes the results of the simulations, where:

$$\Delta_{\sigma_\delta} = 100 \frac{\sigma_{\delta,moored} - \sigma_{\delta,no-moored}}{\sigma_{\delta,no-moored}} \quad (11)$$

$\Delta_{\sigma_\delta}$  represents the in influence of the mooring on pitch motion

## REFERENCES

- [1] G. Mattiazzo, "State of the Art and Perspectives of Wave Energy in the Mediterranean Sea: Backstage of ISWEC," *Frontiers in Energy Research*, vol. 7, 2019.
- [2] S. Astariz and G. Iglesias, "The economics of wave energy: A review," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 397–408, 2015.
- [3] B. Guo and J. V. Ringwood, "Geometric optimisation of wave energy conversion devices: A survey," *Applied Energy*, vol. 297, p. 117100, 2021.
- [4] B. Fenu, V. Attanasio, P. Casalone, R. Novo, G. Cervelli, M. Bonfanti, S. A. Sirigu, G. Bracco, and G. Mattiazzo, "Analysis of a Gyroscopic-Stabilized Floating Offshore Hybrid Wind-Wave Platform," *Journal of Marine Science and Engineering*, vol. 8, no. 6, p. 439, 2020.
- [5] A. Trueworthy and B. DuPont, "The Wave Energy Converter Design Process: Methods Applied in Industry and Shortcomings of Current Practices," *Journal of Marine Science and Engineering*, vol. 8, no. 11, p. 932, 2020.
- [6] J. V. Ringwood, "Wave energy control: status and perspectives 2020," *IFAC-PapersOnLine*, vol. 53, no. 2, pp. 12 271–12 282, 2020.
- [7] G. Giorgi and J. V. Ringwood, "Implementation of latching control in a numerical wave tank with regular waves," *Journal of Ocean Engineering and Marine Energy*, vol. 2, no. 2, pp. 211–226, 2016.
- [8] S. A. Sirigu, M. Bonfanti, E. Begovic, C. Bertorello, P. Dafnakis, G. Giorgi, G. Bracco, and G. Mattiazzo, "Experimental Investigation of the Mooring System of a Wave Energy Converter in Operating and Extreme Wave Conditions," *Journal of Marine Science and Engineering*, vol. 8, no. 3, p. 180, 2020.
- [9] B. Paduano, G. Giorgi, R. P. Gomes, E. Pasta, J. C. Henriques, L. M. Gato, and G. Mattiazzo, "Experimental validation and comparison of numerical models for the mooring system of a floating wave energy converter," *Journal of Marine Science and Engineering*, vol. 8, no. 8, 2020.
- [10] E. Pasta, F. Carapellese, and G. Mattiazzo, "Deep Neural Network Trained to Mimic Nonlinear Economic Model Predictive Control: An Application to a Pendulum Wave Energy Converter," in *2021 IEEE Conference on Control Technology and Applications (CCTA)*. San Diego, US: IEEE, 2021.
- [11] G. Pisacane, G. Sannino, A. Carillo, M. V. Struglia, and S. Bastianoni, "Marine Energy Exploitation in the Mediterranean Region: Steps Forward and Challenges," *Frontiers in Energy Research*, vol. 6, 2018.
- [12] N. Pozzi, G. Bracco, B. Passione, S. A. Sirigu, G. Vissio, G. Mattiazzo, and G. Sannino, "Wave Tank Testing of a Pendulum Wave Energy Converter 1:12 Scale Model," *International Journal of Applied Mechanics*, vol. 9, no. 2, 2017.
- [13] W. Cummins, "The impulse response function and ship motions. Technical Report 1661," Department of the Navy, David Taylor model basin, Washington DC, Tech. Rep., 1962.
- [14] N. Faedo, Y. Peña-Sanchez, and J. V. Ringwood, "Finite-order hydrodynamic model determination for wave energy applications using moment-matching," *Ocean Engineering*, vol. 163, pp. 251–263, 2018.
- [15] N. Pozzi, G. Bracco, B. Passione, S. A. Sirigu, and G. Mattiazzo, "PeWEC: Experimental validation of wave to PTO numerical model," *Ocean Engineering*, vol. 167, pp. 114–129, 2018.
- [16] N. Pozzi, A. Bonetto, M. Bonfanti, G. Bracco, P. Dafnakis, E. Giorcelli, B. Passione, S. A. Sirigu, and G. Mattiazzo, "PEWEC: Preliminary design of a full-scale plant for the Mediterranean Sea," in *Technology and Science for the Ships of the Future - Proceedings of NAV 2018: 19th International Conference on Ship and Maritime Research*, 2018, pp. 504–514.
- [17] J. Davidson and J. V. Ringwood, "Mathematical modelling of mooring systems for wave energy converters—a review," vol. 10, no. 5, p. 666, number: 5 Publisher: Multidisciplinary Digital Publishing Institute. [Online]. Available: <https://www.mdpi.com/1996-1073/10/5/666>
- [18] M. Bhinder, M. Karimirad, S. Weller, Y. Debruyne, M. Guerinel, and W. Sheng, "Modelling mooring line non-linearities (material and geometric effects) for a wave energy converter using AQWA, SIMA and orcaflex."
- [19] M. Hall and A. Goupee, "Validation of a lumped-mass mooring line model with DeepCwind semisubmersible model test data," vol. 104, pp. 590–603.
- [20] S. A. Sirigu, L. Foglietta, G. Giorgi, M. Bonfanti, G. Cervelli, G. Bracco, and G. Mattiazzo, "Techno-Economic optimisation for a wave energy converter via genetic algorithm," *Journal of Marine Science and Engineering*, vol. 8, no. 8, 2020.
- [21] A. Pecher, A. Foglia, and J. P. Kofoed, "Comparison and sensitivity investigations of a calm and salm type mooring system for wave energy converters," *Journal of Marine Science and Engineering*, vol. 2, no. 1, pp. 93–122, 2014. [Online]. Available: <https://www.mdpi.com/2077-1312/2/1/93>
- [22] B. Zanuttigh, L. Martinelli, and M. Castagnetti, "Screening of suitable mooring systems," 01 2011.
- [23] R. Harris, L. Johanning, and J. Wolfram, "Mooring systems for wave energy converters: A review of design issues and choices," 2004, pp. 180–189, the Institute of Marine Engineering, Science and Technology, IMarEST ; Conference date: 01-01-2004.
- [24] L. Castro-Santos, S. Ferreno, and V. Diaz Casas, "Methodology to calculate mooring and anchoring costs of floating offshore wind devices," *Renewable Energy and Power Quality Journal*, pp. 268–272, 03 2013.
- [25] R. Piscopia, R. Inghilesi, and L. Franco, "MISURE STRUMENTALI DI MOTO ONDOSO DELLA RETE ONDAMETRICA NAZIONALE: ANALISI STATISTICA AGGIORNATA DEGLI EVENTI ESTREMI."
- [26] W. M. Organization (WMO) and W. M. O. (WMO), *Guide to Wave Analysis and Forecasting*, 2018th ed., ser. WMO. WMO.