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-estabilished techniques to extract power efficiently, while in wave energy conversion still exist large imporovement 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 loosing 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

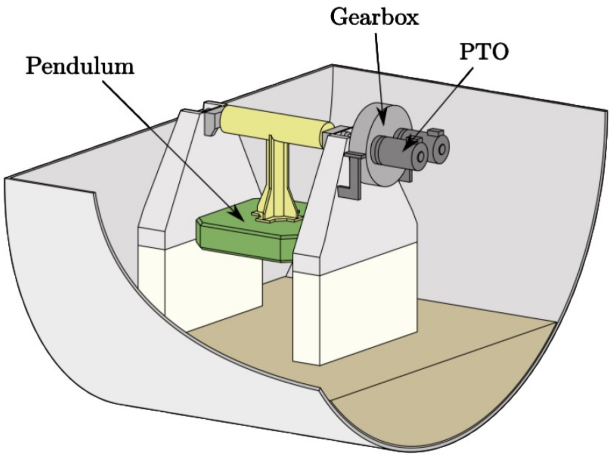

Fig. 1. PeWEC configuration

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 o self-align with the main wave direction. So that, the only considerable motions in PeWEC analisys are surge, heave and pitch, in the following order:

$$X(t) = [x(t), z(t), \delta(t)] \tag{1}$$

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

$$\begin{gathered}(M + A_\infty)\ddot{X}(t) + \int_0^t K_r(t-\tau)\dot{X}(t)d\tau + \\ B_v|\dot{X}(t)|\dot{X}(t) + K_h X(t) = F_{ext}(t)\end{gathered} \tag{2}$$

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:

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

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

TABLE I
WEC Modelling Variables

Notation	Description
M	Inertia Matrix
A_∞	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)

$$F_{ext} = F_{wave} + F_{mooring} + F_{PTO} \tag{4}$$

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) .

$$Power = -\dot{\varepsilon}T_{control} \tag{5}$$

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

$$T_{PTO} = \frac{T_{control}}{\tau_{gearbox}} \tag{6}$$

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

$$\begin{aligned}(I_y + ml^2)\ddot{\varepsilon} - mlcos(\delta+\varepsilon)\ddot{x} + mlsin(\delta+\varepsilon)\ddot{z} \\ (I_y + ml^2 - mdlcos(\varepsilon))\ddot{\delta} - mdlsin(\varepsilon)\dot{\delta}^2 \\ +mglsin(\delta+\varepsilon) + T_{ctrl} = 0\end{aligned} \tag{7}$$

More information about the device modelling and wave generation, which are out of scope of this work, can be fund 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.

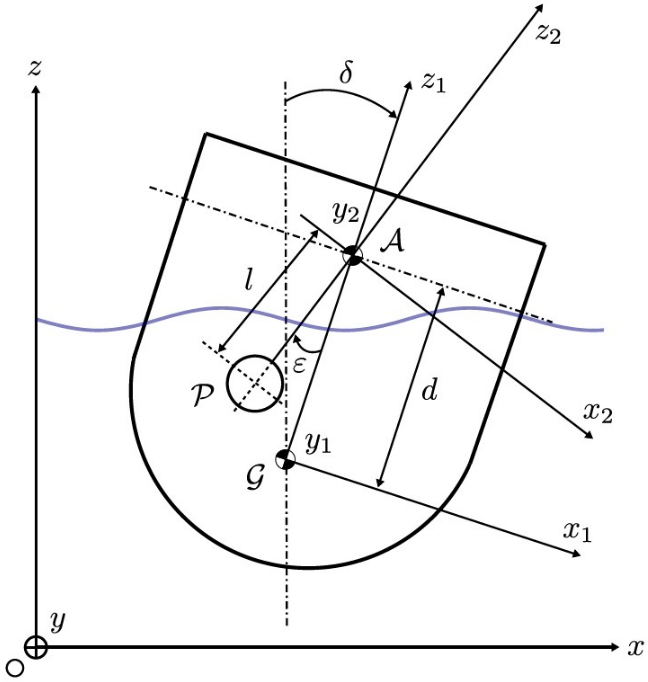

Fig. 2. PeWEC geometric configuration in a general time instant

III. Experimental Validation of the Mooring Model

To gain familiarity with the solver, MoorDyn has been used as validation model against some tests carried out during an experimental campaign that took place in Naples, in 2018. During the experimental campaign the mooring tension has been recorded through a loadcell located just before the bridles (Fig. 3), instead the kinematic data have been recorded through a motion tracking system (camera-based) and an MTi unit.

A. Static Validation

To validate the model, as first step the load-excursion curves could be analysed. This process consists in moving the WEC along the x direction (the surge path), and then to sample for each time the tension force and to store it into a vector. This process is presented for C2a configuration 3

It can be seen from figure 4 that the model and experimental collected data almost match: in the vertical asymptotic line direction, which behaviour is mainly due to the mooring length and lines axial stiffness, there is almost a perfect coincidence. Moreover, the horizontal graph lines, whose comportment depends mostly on the static load (restoring force due to line weight), show a good matching rate too. Their little differences may be caused by the friction on the seabed (tank test floor), a phenomenon difficult to evaluate in the experimental tests.

B. Dynamic Validation

Another part of the validation process has been performed with irregular wave. Nevertheless, mooring motions must be imposed because the software cannot solve the system hydrodynamics, and the intent of this validation regards only the mooring model hence, the hydrodynamic part has been excluded. In experimental campaign, many waves have been used as system input. Anyway, because of a technical problem to the load cell, just few data have been registered with plausible and reliable tension time vector. Table II resumes the tested wave features.

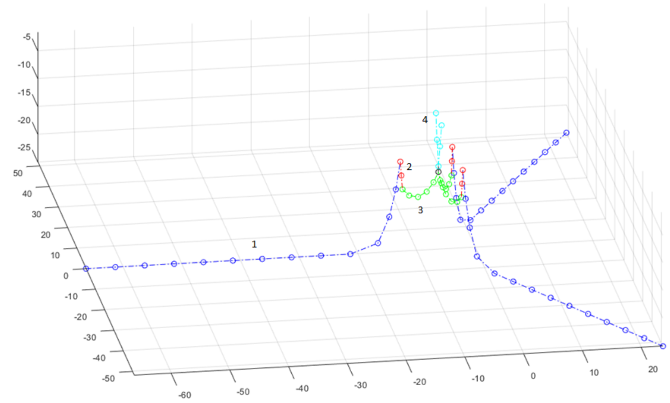

Fig. 3. Mooring system configuration

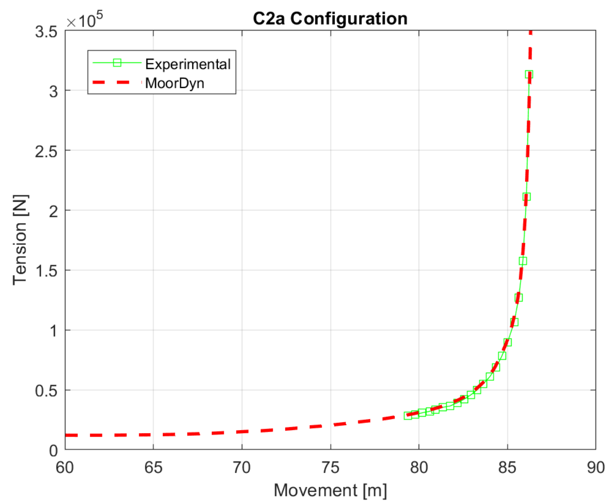

Fig. 4. Static validation of C2a configuration

TABLE II
TESTED WAVE PROPERTIES

Variable	Unit	C2a Configuration
Energetic Period, Te	s	5.05
Peak Period, Tp	s	5.41
Significant Wave Height, Hs	m	2.08

As for static validation, the process involves a time comparison between the registered tension by the load cell, and the tension value obtained with MoorDyn software.

For C2a configuration results are very promising, as it can be seen in figure 5.

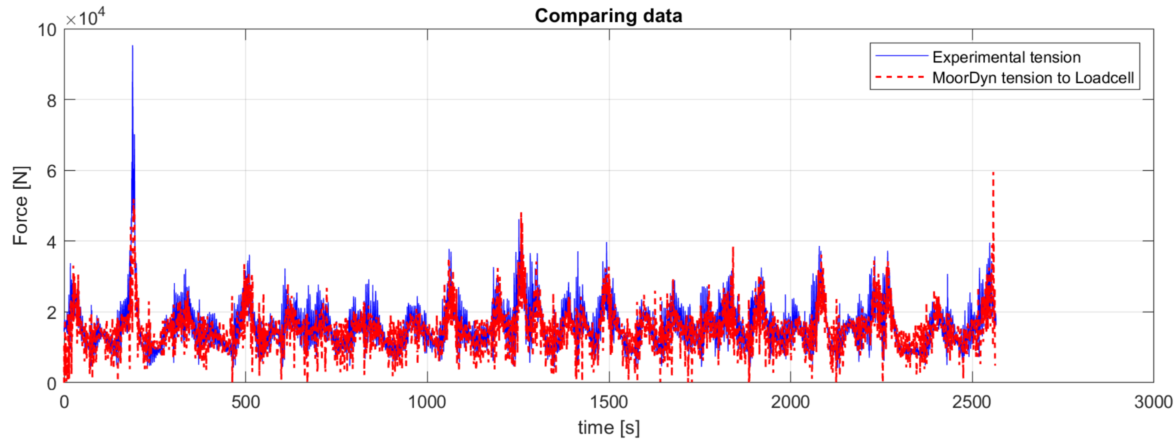

Fig. 5. Dynamic validation of C2a configuration

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:

$$\Delta_\mu = 100\frac{\mu_{MoorDyn} - \mu_{experimental}}{\mu_{experimental}} \tag{8}$$

$$\Delta_\sigma = 100\frac{\sigma_{MoorDyn} - \sigma_{experimental}}{\sigma_{experimental}} \tag{9}$$

TABLE III
VALIDATION RESULTS

Configuration	Δ_μ	Δ_σ
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).

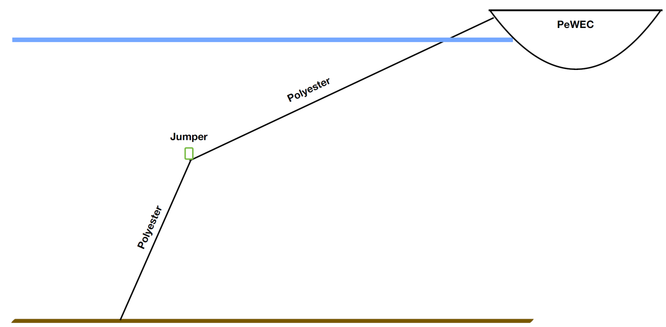

Fig. 6. Diagram of the mooring system considered in the productivity analysis.

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]

$$J = 0.49 T_e H_s^2 \tag{10}$$

- 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.

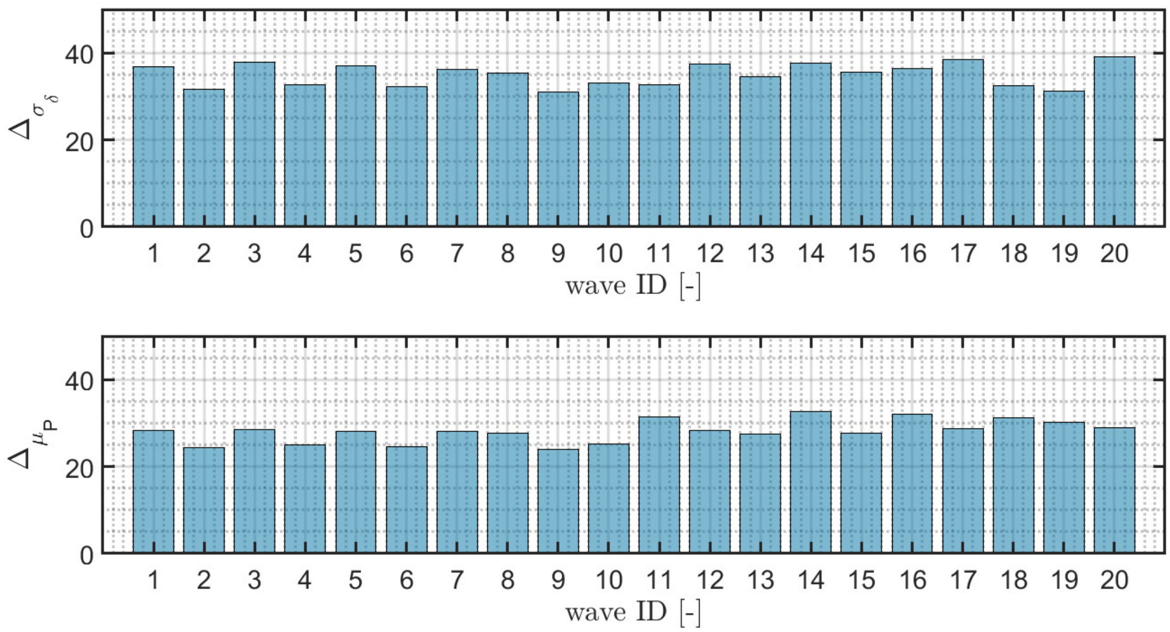

Fig. 7. Mooring influence on device pitch motion and productivity. Comparison between MoorDyn model and no moored model.

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

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:

$$\Delta_{\sigma_\delta} = 100\frac{\sigma_{\delta,moored} - \sigma_{\delta,no-moored}}{\sigma_{\delta,no-moored}} \tag{11}$$

Δ_{σ_δ} represents the in influence of the mooring on pitch motion

TABLE V
RESULTS

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

of the device as percentage.

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

Δ_{μ_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.

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