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Numerical Modelling of a Combined Tension Moored Wind and Wave Energy Convertor System

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Abstract—The offshore wind industry is moving to deeper water sites which generally have more severe environmental conditions. This presents not only a challenge to deploying devices in such conditions but also an opportunity for developing combined hybrid platforms that harvest both wind and wave energy. This paper introduces the novel tension moored combined wind and wave energy converter (WEC) TWindWave. Numerical modelling of the system in power production and novel survival modes is undertaken. Hydrodynamic interaction is analysed and shown to reduce the overall WEC power production. The addition of the WECs onto platform characteristics is described. Novel survival modes which involve ballasting the WEC floats and sinking them along the platform columns, before they rotate around the column and pontoon connecting bends are described and analysed. Future work incorporating these results and more advanced techniques are proposed.

Index Terms—Combined, Hybrid, Wind Turbine, WEC, Point Absorber, Torus, TLP, Survival Mode

I. INTRODUCTION

The offshore wind industry is moving to deeper water sites which generally have more severe environmental conditions. This presents not only a challenge to deploying devices in such conditions but also an opportunity for developing combined hybrid platforms that harvest both wind and wave energy. A number of such platforms have been proposed, for example in the EU fp7 project MARINA where three hybrid concepts were developed to TRL3. A large scale hybrid platform, FPPs POSEIDON [1], has been deployed in sea-trials in Denmark.

This paper presents a novel combined tension moored wind and wave energy convertor (WEC) platform. The wind turbine is NRELs 5 MW reference wind turbine (WT) [2], while the WECs are composed of four torus shaped pitch restrained heaving point absorbers (PA), rated at 250 kW each, resulting in a combined system rated at 6MW. A novel survival mode for the WECs in above rated sea-states is also proposed which helps reduce the overall platform motions and mooring tendon loads. The system is designed for deployment on the west coast of Ireland in water depths of circa 110m.

Wind and wave energy converters may be combined either by co-locating on a single site and sharing grid connection or combined on a single multi-use platform and sharing grid connection, platform and mooring costs.

A. Co-location

Fusco [3] presents a methodology to assess the possible benefits of the combination of wind energy with wave energy for Irish sites. The two resources seem to be significantly uncorrelated and thus the integration of wind and waves in combined farms, at these locations, allows the achievement of a more reliable, less variable and more predictable electrical power production. Cradden [4] assessed the benefits of combining wind and wave energy harvesting for three European marine energy test sites. It was shown that wave and wind power have medium to high correlation at each of the three sites, with evidence that the wave time series lags the wind by between 1 and 5 hours. Chozas [5] analysed the benefits of combining wind and wave power output for day ahead power markets. It has been demonstrated that combined power productions are more predictable than when wind and wave technologies are working individually; and hence, balancing costs reduce. Azzellino [6] used a marine spatial planning approach to investigate the co-location of wind and wave energy farms. Two key benefits were identified as follows, the variability of the produced power can be decreased, and the power availability can be increased. The greater the correlation of the wind and wave resource the less benefit there is. Zanuttigh [7] presents a methodology for multi-criteria design of multi-use offshore platforms for marine renewable energy harvesting. Perez [8] reviewed the methods of combining wind and wave power output for a single farm. The existence of an abundant combined resource together with the strong synergies existing between both technologies makes a compelling argument for combining wave and offshore wind energy to achieve a sustainable and rational exploitation of the offshore energy resources. However, fundamental research is highlighted as crucial to test the validity, sustainability and integration of these combined systems; and to determining to what extent these new or adapted WECs are suitable to be combined with current offshore wind farms.

B. Combined Platform

Combined platforms may share a fixed or floating support structure.
1) Fixed Platform: Baudry [9] assessed the power production of a torus shaped PA WEC reacting against a monopile WT foundation. Latching control was found to significantly increase the power production by an amplification factor of 2.5. Pakrashi [10] studied the structural changes required to add a PA to a monopile WT and found the addition of a PA to a monopile foundation results in a significant increase in structural loading that is dependent on water depth and site conditions.

2) Floating Platform: Floating Power Plant [1] is a 37 meter wide off-shore test combined wind and wave energy platform. It has 140 kW of wave energy and three 11 kW WTs. It is the only combined wind and wave energy converter to have sea trials. WindFloat, a semisubmersible floating WT, has been modelled numerically and physically supporting a number of different WEC technology types. These being: A spherical PA installed in the center of the WindFloat platform; two oscillating water columns (OWC) mounted on the platform columns; three pitching flaps mounted on the platform braces [13]. O’Sullivan [14] studied the feasibility of combined wind and wave energy converters, highlighting the difficulties in designing such complex systems. Issues with O&M accessibility to the rotor nacelle assembly were identified due to large numbers of motion induced interruptions. Karimirad [15] studied a combined spar and pitching PA. The Spar was inspired by the HyWind device and was designed to support a 5MW WT. The pitching PA inspired by Wavestar was placed 20m from the spar. Borg [16] proposed the idea of a combined wind and wave energy platform system. The WECs in this system had the shared goal of reducing platform motions and generating power. Michailides [17] and Luan [18] analysed a combined system composed of three flap type WECs on a bracless semi-submersible WT. The Spar Torus Combination (SPC) concept combines a Spar floating wind turbine and a torus-shaped heaving-body WEC [19]. Ren [20] analysed the SPC for long-term fatigue damage prediction of the mooring lines and the annual energy production estimation.

Muliawan [21] numerically analysed the STC in operational and survival mode using the coupled SIMO/THDMILL in the time domain. Wan [22] performed experiments on the STC in survival mode with a scale factor of 1:50 in the towing tank of MARINTEK, Norway. Two survival modes were analysed; locking the WEC to the spar both at the mean surface elevation and in a submerged position. In the submerged position the motion and forces between spar and torus are decreased. Both Mathieu instability and slamming occurred for the mean surface elevation configuration. Bachynski [23] introduced a combined concept consisting of a single column tension leg platform (TLP) which supports a 5MW WT and 3 point absorber WECs, see Figure 1. Two variations of the WECs are considered: one that is constrained to purely heave motion relative to the TLP hull (Type A), and a hinged device which moves in coupled surge and pitch as well as heave (Type B). In operational conditions with aligned wind and waves, the combined concepts showed several benefits compared to the TLPWT: reduced surge and pitch motions, reduced tendon tension and tower base bending moment variation, and slightly reduced WT power variation. The combined concepts introduced increased yaw motion, particularly for WEC type B, and the advantages were generally larger for TLPWT + WEC A. The base bending moment on the WEC guide, however, was significantly larger for TLPWT + WEC A compared to TLPWT + WEC B. In survival conditions, reductions in surge and yaw motions were observed, but significant increases in pitch motions and tendon tension variations were seen (compared to the TLPWT). WEC type A in survival mode 1 caused extreme tendon variations due to impact with the end stops. While the guide bending moment for WEC type A in survival mode 2 was similar to that of survival mode 1, locking the WEC to the lower end stop resulted in better overall combined platform performance. A more complex locking system (survival mode 3) would be best for either type of WEC. Soulard [24] carried out a technical feasibility study for a hybrid ocean energy converter, with balanced wind and wave contributions. A 100m diameter circular barge (CHYP) equipped with floating oscillating wave surge converters (OWSCs) supported a 5MW WT. Soulard [25] proposed a 100m large semi-submersible platform designed with five columns and equipped with floating pitching WECs supporting a 5MW WT. A Wave to Wire model was used to compare the annual average absorbed power figures are compared with published results for existing ocean energy converters. Iturrioz [26] designed a combined wind and wave energy system composed of a semi-submersible concrete structure, supporting a 5MW WT and three 1060 kW OWC WECs. Physical experiments were carried out at 1:35 scale in the Cantabria Coastal and Ocean Basin. Mazarakos [27] designed a combined wind and wave energy system composed of a TLP structure, supporting a 5MW WT and three OWC WECs.

II. TWindWAVE

This paper introduces the novel tension moored wind and wave energy converter, TWindWave. It is composed of a 5 MW WT, supported by a four legged tension moored platform, which is used as the reactance device for four pitch restrained heaving point-absorbers, each rated as 250 kW. A preliminary analysis of float shape resulted in a decision to use a wall sided cylindrical geometry. Power production could be increased with inverted cone or hemisphere geometry’s, although these significantly increase the hydrodynamic pitch force which the platform columns must restrain in this device. This paper describes the first iteration of this concepts design, where the buoyancy and mass and thus pretension of the FWT is unchanged due to the addition of the WEC components. It should be noted that this is a significant simplification of the problem, and the mass of the FWT would most likely significantly increase due to the addition of the WECs due to an increase in both fatigue and ultimate loading and the required WEC Power Take-Off (PTO) system. The WT platform, WEC and mooring system details can be seen in Tables I to III.
A. Survival Mode

In contrast to a WT's reliable survival mode for high wind speeds where the blades are pitched out of the wind direction, resulting in a decrease in loading, the survival modes for WECs in above rated power production sea-states offer severe challenges. Unlike wind loading which is generally significantly uni-directional, the wave load vector rotates through full 360 degrees over every wave period, meaning a pitching technique similar to a WT's blades is impossible. The fact that the wave load decreases exponentially in depth, is used for the benefit of the submerging survival mode outlined as follows here. In sea-states above operational conditions, the PTOs are disconnected from each float, the floats are then sea-water ballasted and submerged along the platform column, after which they are locked in position, similar to Wan [22]. The floats are ballasted such that the mass to buoyancy ratio of the system is unchanged. If the floats are submerged below 25m they begin to rotate along the connecting bend between the platform column and pontoon. It is envisaged that this rotation will provide significant benefit to the performance of the platform in extreme waves. In a rotated position the floats have a large surface area perpendicular to the platforms main motion degrees of freedom (DOF): surge and sway, in this way they act as surge plates reducing the motions of these DOF. These surge plates are similar to the traditional heave plates which reduce a floating platforms heave and pitch motion.
by acting as water entrapment plates, greatly increasing the radiation terms of the platform. The increased added mass in the surge direction will beneficially decrease the platform surge natural frequency, increasing the distance between such and the wave frequency range, and thus reducing platform surge motions and tendon loads. This rotational movement requires greater complexity in the float rollers and an increased internal diameter, as they are required to deal with a varying diameter along the bend. To transfer back to an operational condition, compressed air is used to expel the water from the ballast chambers and excess buoyancy returns the floats to the surface. This paper analyses various submergence depths and float angles, which can be seen in Figure 3.

III. NUMERICAL MODELLING

Hydrodynamic parameters are calculated using ANSYS AQWA for 50 wave frequencies from 0.008Hz - 0.4Hz and 12 equally spaced wave directions. Orcaflex is used for time domain simulations. Additional quadratic viscous damping of the platform and WEC floats is added to the model using modified Morrisons equation drag only elements. Drag coefficients are determined using the DNV standards. The tower is modelled as a flexible body of varying stiffness along its length. No wind load is applied. The frequency dependant added mass and damping is converted to the time domain using the Cummins equation [28], implemented by the method proposed by Wichcr [29]. This method involves calculating the Impulse Response Function (IRF), using equation 1, for the vessel and then applying that IRF at each time step using a convolution integral to account for the past motion of the vessel, using equation 2. To save computational expense, rather than integrating the convolution integral equation all the way to the beginning of the simulation, a cut-off time of 150 s is used. To avoid a sharp cut-off of the integral and the possibility of negative damping being applied, the IRF function is smoothly scaled down to zero at the cut-off time using equation 3.

$$IRF(\tau) = c(\tau) \int_{\omega=0}^{\infty} 4B(\omega)\cos(\omega \tau) d\omega$$ (1)

$$F(t) = -A(\infty)x'' - \int_{\tau=0}^{\infty} IRF(\tau)x'(t-\tau) d\tau$$ (2)

$$c(\tau) = e^{\tau} - (-3\tau/T_c)$$ (3)

Where IRF(\tau) is the IRF, c(\tau) is the cut off scaling function, \omega is the wave frequency, B(\omega) is the frequency dependent damping matrix, \tau is a time lag integration variable and T_c is the cut-off time, A(\infty) is the infinite-frequency added mass matrix, x'' and x' are the vessel acceleration and velocity, respectively. The optimum PTO damping is set using equation 4.

$$B_{PTO}(\omega) = \sqrt{B_{33}(\omega) + 1/\omega^2(-(m + A_{33})\omega^2 + K_{H33})^2}$$ (4)

Where B_{PTO}(\omega) is the frequency dependant damping, B_{33}(\omega) is the frequency-dependent heave damping, m is the platform mass, A_{33} is the platform added mass in heave and K_{H33} is the platform heave hydrostatic stiffness. Simulations of a duration of 3600s are run. For operational conditions the sea-states in table I are used, for survival states, white noise waves which span a frequency interval of 0.01 Hz to 0.3 Hz are used. WEC numbers are shown in figure 4.

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Fig. 3: Meshes for mode cases analysed: (a) Operational, (b)-(j) Survival Submergence: (b) 5 m, (c) 10 m, (d) 15 m, (e) 20 m, (f) 25 m, (g) 22.5°, (h) 45.0°, (i) 67.5°, (j) 90.0°

Fig. 4: WEC and tendon numbering scheme
TABLE IV: Simulated Sea-states

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<th>Hs (m)</th>
<th>Tz (s)</th>
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<td>2</td>
<td>1</td>
<td>6.64</td>
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<td>7.47</td>
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<td>9.13</td>
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<td>2</td>
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IV. Results

A. Hydrodynamic Interaction

Firstly the five body hydrodynamic interaction matrix is analysed in the frequency domain. Strong interaction is noted between the platform surge and float surge motions, the float surge and float heave motions and the float pitch on the other floats pitch motion. This is shown in figures 5 to 10, where the bodies main diagonal radiation terms indicates the scale of the interaction. Figures 5 and 6 shows strong coupling for both radiation terms between the platform surge and float surge for high frequency waves. The terms are opposite in sign and thus the floats damp the platform motion. For coupling between float surge and float heave, figure 7 shows mild coupling for added mass, while figure 8 shows strong coupling for the radiation damping. For coupling between the floats pitch motion the same trend can be seen. A weak interaction for added mass, figure 9, while a strong interaction can see for the radiation damping component, where the interaction effect dominates over the bodies main diagonal term.

B. Power Production

The instantaneous power of each WEC is calculated using equation 5, and converted to an average power for each sea-state by equation 6. This is the mechanical power and no attempt has been made to take into account electrical and/or other losses. Figure 11 shows this averaged power for each sea-state, for both the interacting and non-interacting cases. For the upwave WEC 1, the power is generally slightly underpredicted by the non-interacting case, apart from the short wave period sea-states 1 and 4. For the symmetric WECs 2 and 4, the average power is averaged between the two devices. The non-interacting case significantly over predicts absorbed power, of between 13.3% and 3.7%, the effect seems to be decreasing with increased wave height. For the downwave WEC 3, the non-interacting case vastly over predicts absorbed power, of
C. Platform Performance

The floating wind turbine platform performance is compared next, between the hydrodynamic interaction, non interaction and without the WECs completely. Figure 12 compares the WT towers max and RMS bending moments (BM). For nearly all sea-states the WECs can be seen to increase these BM. Sea-states 2 and 5 are the exception to this, where it is the FWT alone which has the highest BM. Sea-state 4 shows the largest increase in tower BM of 106%. These results show that the ultimate and fatigue strengths of the WT tower would need to be increased to accommodate the WECs. Figure 13 shows the platform surge, heave, pitch and nacelle accelerations. The addition of the WECs significantly increases all of these output parameters, with the hydrodynamic interaction damping these increases somewhat. The percentage increases are also similar across all parameters. Figure 14 shows the change in tendon tension, where the addition of the WECs increases the maximum and decreases the minimum thus, increasing the risk of a snap loading event. Therefore the WECs must enter survival mode when this tension fluctuation becomes too large.

D. Survival Modes

RAOs are generated using the Cross Correlation Auto Correlation (CSAS) method, which involves dividing the cross spectral density of the input and output by the auto spectral density of the input, as shown in equation 7. Figure 15 shows the platform surge, heave, pitch, nacelle acceleration, tendon 1 tension and tower bending moment RAOs. Of most significance is the change in pitch and tendon tension RAO. It can be seen that the survival states had the intended effect of decreasing motions and tendon tensions, but only for waves with period greater than 6s, below this period, the proposed survival modes exhibit a high pitch response at 5.3s - 5.8s, which dominates the tendon tension. Surge and heave RAOs can be seen to slightly decrease as the WECs move to a
Table V: Results of Submergence Method

<table>
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<th>Z</th>
<th>RY</th>
<th>A</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
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Where C is the Case, and the first four numbers in this column refer to vertical submergences and the last four refer to vertical submergences combined with angular rotations in degrees deeper draft. As some results are visually inconclusive from the figure, Table V shows the area under each of these RAO curves. The area is calculated using a trapezoidal integration method. These results are then compared to the case of -5m submergence. Taking a summed equal weighting of each of the outputted results for each case (i.e. the average of each row in the table), submergence strategies with an angle of 45° and 90° give most advantage over the basecase. These results demonstrate the prove of concept of the survival mode, showing decreased tendon loading for long period waves, but also show that a redesign is required to avoid the increase in pitch response for short period waves. Now that the hydrodynamics of the system are well understood, the next step involves numerical modelling of the fully coupled WT and WEC system, using software such as FAST. Tank testing will be carried out to validate the numerical models and analyse nonlinear effects such as WEC green water and slamming which may be of concern to a combined system like this.

V. Conclusions

The novel combined tension moored wind and wave energy converter TWindWave has been introduced in this paper. The effect hydrodynamic interaction of the platform and WECs has been shown and quantified, showing the importance of taking these effects into account. Overall power production is shown to decrease when hydrodynamic interaction is taken into account. The structural and hydrodynamic effect of including the WEC onto the platform is then shown, increasing the platform design requirements. Novel rotated WEC survival modes are also introduced and demonstrated. These results demonstrate the prove of concept of the survival mode, showing decreased tendon loading for long period waves, but also show that a redesign is required to avoid the increase in pitch response for short period waves. Now that the hydrodynamics of the system are well understood, the next step involves numerical modelling of the fully coupled WT and WEC system, using software such as FAST. Tank testing will be carried out to validate the numerical models and analyse nonlinear effects such as WEC green water and slamming which may be of concern to a combined system like this.

Acknowledgment

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Sea-state Number | Max Bending Moment (kNm) | Max Tower bending moment
--- | --- | ---
1 | 4.7 | 20.1
2 | 3.2 | 18.9
3 | 1.3 | 16.2
4 | 0.8 | 15.0
5 | 3.0 | 12.8
6 | 0.9 | 12.2
7 | 2.3 | 11.7
8 | 3.7 | 11.2
9 | 4.2 | 10.5
10 | 2.8 | 10.3

RMS Tower bending moment:

Sea-state Number | RMS Bending Moment (kNm) | RMS Tower bending moment
--- | --- | ---
1 | 21.5 | 18.6
2 | 18.6 | 16.5
3 | 16.2 | 14.4
4 | 14.4 | 12.7
5 | 12.8 | 11.3
6 | 11.7 | 10.6
7 | 12.7 | 12.0
8 | 14.4 | 13.7
9 | 16.5 | 15.1
10 | 18.6 | 17.2

Fig. 12: Tower bending moment, numbers in black indicate percentage change from hydrodynamic interaction to no interaction case, numbers in bold blue indicate percentage change from interaction case to no WEC case.

Platform Surge:

X (m) | Platform Surge
--- | ---
1 | 4.1
2 | 0.7

Platform Heave:

Z (m) | Platform Heave
--- | ---
1 | 4.0
2 | 0.6

Platform Pitch:

RY (°) | Platform Pitch
--- | ---
1 | 1.0
2 | 0.9

Nacelle Acceleration:

Accleration (m/s²) | Nacelle Acceleration
--- | ---
1 | 4.7
2 | 0.7

Fig. 13: Platform Surge, Heave Pitch and Nacelle Acceleration, numbers in black indicate percentage change from hydrodynamic interaction to no interaction case, numbers in bold blue indicate percentage change from interaction case to no WEC case.
Fig. 14: Platform tendon tension, numbers in black indicate percentage change from hydrodynamic interaction to no interaction case, numbers in bold blue indicate percentage change from interaction case to no WEC case.

Fig. 15: RAO’s for platform surge, heave and pitch motions, nacelle acceleration, tendon 1 tension, and tower bending moment for various submergence methods.