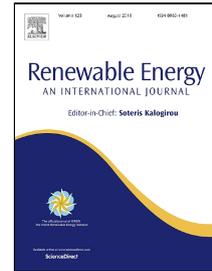


# Accepted Manuscript

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PII: S0960-1481(18)30404-X  
DOI: 10.1016/j.renene.2018.03.087  
Reference: RENE 9956  
To appear in: *Renewable Energy*  
Received Date: 13 October 2017  
Revised Date: 26 March 2018  
Accepted Date: 29 March 2018

Please cite this article as: Liang Li, Zhengshun Cheng, Zhiming Yuan, Yan Gao, Short-term extreme response and fatigue damage of an integrated offshore renewable energy system, *Renewable Energy* (2018), doi: 10.1016/j.renene.2018.03.087

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# Short-term extreme response and fatigue damage of an integrated offshore renewable energy system

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## Abstract

This study addresses short-term extreme response and fatigue damage of an integrated wind, wave and tidal energy system. The integrated concept is based on the combination of a spar type floating wind turbine, a wave energy converter and two tidal turbines. Aero-hydro-mooring coupled analysis is performed in time-domain to capture the dynamic response of the combined concept in a set of environmental conditions. The mean up-crossing rate method is used to evaluate the extreme response, which takes advantage of an extrapolation method to reduce the simulation sample size. The cumulative fatigue damage is computed based on the S-N method. Simulation results show that the tower base fore-aft bending moment is improved, in terms of extreme value and fatigue damage. Nevertheless, the tension force of a mooring line is worsened. The mooring line bears increased maximum tension due to the tidal turbine thrust force and it is subjected to higher fatigue damage load as well.

*Keyword:* extreme response, fatigue damage, renewable energy, floating wind turbine, wave energy converter, tidal turbine

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## 1. Introduction

With expanding global demand for power and increasing public awareness to sustainable development, great efforts are taken to exploit the offshore renewable energy resources and a set of offshore renewable energy devices are developed. Statoil launched a demo project of a spar type offshore floating wind turbine, namely the Hywind concept, which is the first full scale floating wind turbine that has ever been built [1]. Principle Power installed a full scale 2MW WindFloat prototype near the coast of Portugal [2]. At the same time, researchers across the world are working on the numerical and experimental studies of floating wind turbine [3-8]. Apart from floating wind turbine, wave energy converter (WEC) and tidal turbine are also widely used to harvest energy from the ocean. Zhang and Yang [9] captured the power output of an oscillating-body WEC. Two symmetrically oblique springs and a linear damper were applied to model the nonlinear behaviour of the power take off (PTO)

34 system. Elhanafi et al. [10] tested the hydrodynamic performance of a floating-moored WEC in regular  
35 and irregular waves with both experimental and numerical methods. Ning et al. [11] . investigated the  
36 dynamics of a fixed oscillating-water-column WEC in a set of environmental conditions. A critical  
37 wave slope was identified in which the efficiency reaches the maximum. The full wake structure of a  
38 horizontal tidal turbine was experimentally studied by Chen et al. [12] . Lo Brutto et al. [13] developed  
39 a semi-analytic method to optimize the layout of tidal farms, which aimed to maximum the total power  
40 production.

41 Currently, producing power from a single type of ocean energy resource is facing the challenges of  
42 high cost and low harvesting efficiency. Therefore, the concept of offshore integrated renewable energy  
43 system is developed to address these issues. Aubault et al. [14] incorporated an oscillating-water-  
44 column WEC into a semi-submersible floating wind turbine. They showed that the overall cost could  
45 be reduced by sharing the mooring system and the power infrastructure. Muliawan et al. [15] studied  
46 the dynamic response and the power performance of the so-called STC (Spar-Torus Combination)  
47 concept in various operational conditions. Their simulation results revealed a synergy between wind  
48 and wave energy generation. Experimental and numerical studies of the STC in survival mode were  
49 conducted by Wang et al. [16]. Michailides et al. [17] incorporated a flap-type WEC to a semi-  
50 submersible floating wind turbine and investigated the effect of WECs on the response of the integrated  
51 system. Their study showed that the combined operation of the rotating flaps resulted in an increase of  
52 the produced power without affecting the critical response quantities of the semi-submersible platform  
53 significantly. Li et al. [18] proposed a hybrid offshore renewable energy device by combine a floating  
54 wind turbine, a WEC and two tidal turbines. It was shown that the overall power production was  
55 increased while the platform motions were reduced. Bachynski and Moan [19] studied the effects of  
56 three point-absorber WECs on a TLP (tension leg platform) floating wind turbine in operational and  
57 50-year extreme environmental conditions, in terms of power production, structural loads and platform  
58 motions.

59 In practice, the ultimate limit state and fatigue limit state are essential items in the design of an  
60 offshore renewable energy device. Cheng et al. [20] compared the extreme structural response and  
61 fatigue damage of a horizontal axis floating wind turbine and a vertical axis floating wind turbine. Hu  
62 et al. [21] developed an integrated structural strength analysis method for a spar type floating wind  
63 turbine. Inertia and wave-induced loads were addressed with a quasi-static method and the wind force  
64 was dealt with a static approach. Li et al. [22] discussed the limitation of original environmental contour  
65 method in the application to offshore wind turbines. A modified approach was proposed and they  
66 showed that the predicted results were close to full long-term analysis. Michailides et al. [23] examined  
67 the response of a combined wind/wave energy concept in extreme environmental conditions with both  
68 experimental and numerical methods. Liu et al. [24] studied the aerodynamic damping effect on  
69 offshore wind turbine tower fatigue loads and different aerodynamic damping models were used.  
70 Aggarwal et al. [25] studied the nonlinear short-term extreme responses of a spar type floating wind

71 turbine. Li et al. [26] investigated the fatigue analysis for tower base of a spar-type wind turbine. The  
72 effects of simulation length, wind-wave misalignment on the fatigue damage were studied. Marino et  
73 al. [27] investigated the fatigue loads of a floating wind turbine with both linear and nonlinear wave  
74 models. Graf et al. [28] used the Monte Carlo approach to evaluate the long-term fatigue loads of a  
75 floating wind turbine. They found that this approach significantly increased the computational  
76 efficiency but the effectiveness was reduced as nonlinearity effect became important.

77 This work is the second part of the investigation on an integrated wind, wave and tidal energy system.  
78 In previous study [18], platform motions and power production of the hybrid device were simulated and  
79 comparisons were made with a spar type floating wind turbine. It was shown that the overall power  
80 production was enhanced and surge and pitch motions of the platform were reduced at the same time.  
81 Nevertheless, the hybrid system gave a worsened heave motion. This study will examine the short-term  
82 extreme structural response and fatigue damage of the integrated concept in a wide range of  
83 environmental conditions. The mean-up crossing rate method is used to evaluate the extreme response  
84 and the fatigue damage is estimated with the S-N approach. The analysis results will be compared with  
85 those of a spar type floating wind turbine to clarify the effect of the WEC and the tidal turbines.

## 86 2. Model description.

87 The hybrid concept addressed in this study, namely ‘HWNC (Hywind-Wavebob-NACA  
88 Combination)’ [18] (see Fig. 1), is inspired by the spar type floating wind turbine Hywind [29], the two-  
89 body floating WEC ‘Wavebob’ and the tidal turbines with the NACA 638xx aerofoil series. The WEC,  
90 designed to move only in heave mode relative to the platform while no relative surge, sway, roll, pitch  
91 and yaw motions are allowed, is connected to the platform through mechanical facilities. Two tidal  
92 turbines are installed to harvest energy from the sea current. The main dimensions of the HWNC are  
93 presented in Table 1 and the inertial properties of each component are listed in Table 2.

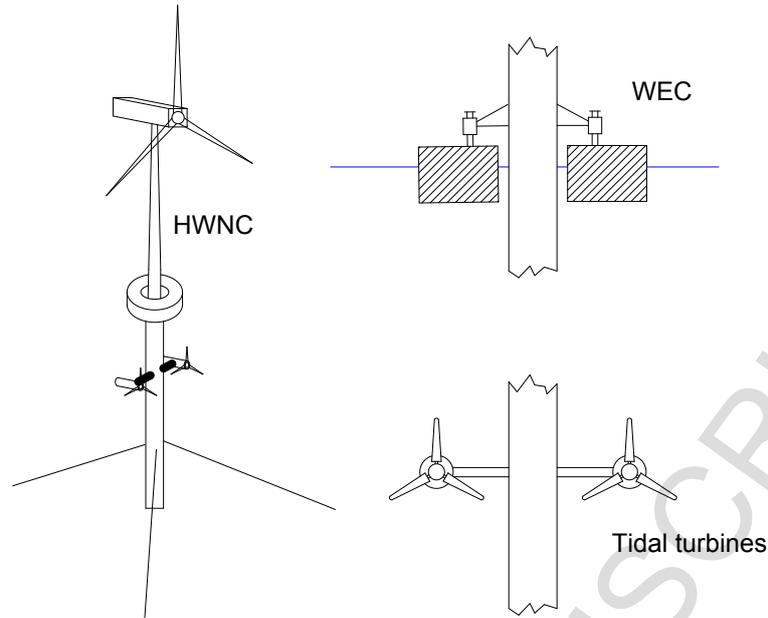


Fig. 1. HWNC concept.

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96 Table 1

97 Main dimensions of the HWNC.

	Item	Value
Platform	Draft	120 m
	Tower base above still water level (SWL)	10 m
	Depth to top of taper below SWL	4 m
	Depth to bottom of taper below SWL	12 m
	Platform diameter above taper	6.5 m
	Platform diameter below taper	9.4 m
WEC	Draft	4 m
	Outer diameter	20 m
	Inner diameter	10 m
Tidal turbine	Depth below SWL	46.5 m
	Rotor diameter	10 m

98

99 Table 2

100 Inertial properties of subsystem.

	Item	Value
Platform (with tidal turbines)	Total mass	6,995,130 kg
	Centre of mass (CM) below SWL	89.9 m
	Roll inertia about CM	4,229,230,000 kg·m <sup>2</sup>
	Pitch inertia about CM	4,229,230,000 kg·m <sup>2</sup>
	Yaw inertia about CM	164,230,000 kg·m <sup>2</sup>
WEC	Total mass	1,442,000 kg
	CM below SWL	0 m
	Roll inertia about CM	3,139,900 kg·m <sup>2</sup>
	Pitch inertia about CM	3,139,900 kg·m <sup>2</sup>
	Yaw inertia about CM	6,022,200 kg·m <sup>2</sup>

101

102 The HWNC is operated at sea site with a water depth of 320 m and moored by three slack catenary

103 lines. The fairleads are connected to the platform at 70 m below the still water level. Fig. 2 displays the

104 configuration of the mooring system. Three lines are oriented at  $60^\circ$ ,  $180^\circ$ , and  $300^\circ$  about the vertical  
 105 axis. The relevant properties of the mooring lines are listed in Table 3.

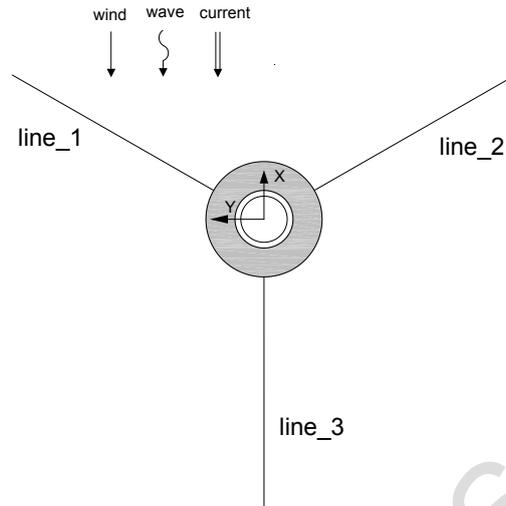


Fig. 2. Configuration of mooring lines.

106  
 107

108 Table 3  
 109 Mooring line properties.

Item	Value
Depth to anchors	320 m
Depth of fairleads	70 m
Radius to anchors	853.87 m
Radius to fairleads	5.2 m
Unstretched mooring line length	902.2 m
Mooring line diameter	0.09 m
Equivalent mooring line mass density	77.7066 kg/m
Equivalent mooring line extensional stiffness	384,243,000 N
Additional yaw stiffness	98,340,000 Nm/rad

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### 111 3. Analysis methodology

#### 112 3.1. Aero-hydro coupled analysis

113 The numerical code used to perform the coupled simulation in this work is based on the combination  
 114 of WindSloke developed by Li et al. [4] and WEC-Sim [30] developed under the collaboration between  
 115 the National Renewable Energy Laboratory (NREL) and the Sandia National Laboratories. The  
 116 aerodynamic module of WindSloke is used in this work to calculate the unsteady wind turbine thrust  
 117 force by a modified blade element momentum (BEM) method. The tidal turbine thrust force is computed  
 118 with the same approach. The unsteadies of the inflow caused by platform motions is considered with a  
 119 dynamic wake model [31]. WEC-Sim is a wave energy converter simulation tool with the ability to  
 120 model offshore systems that are comprised of rigid bodies, PTO systems and mooring systems. WEC-  
 121 Sim computes the hydrodynamic forces acting on the floating bodies based on the combination of  
 122 potential flow theory and Morison equation.

123 Three rigid bodies are established in the numerical model of the HWNC. The spar platform (with  
 124 tidal turbines) and the WEC are treated as two independent floating bodies and their hydrodynamic  
 125 interactions are considered. The two components are connected by the PTO facility, which is  
 126 numerically treated as a spring & damper system. The stiffness coefficient  $K$  is set to 5 kN and the  
 127 damping coefficient  $B$  is set to 80 kN·s/m. The wind turbine is regarded as a non-hydro body, which is  
 128 rigidly mounted on the platform. Please note that deflection of the tower is not considered in this study.  
 129 The mooring line is modelled with the lumped-mass approach, which divides the mooring line into a  
 130 series of evenly-sized segment represented by connected nodes and spring & damper systems. The  
 131 lumped-mass approach merely models the axial properties of the mooring lines while the torsional and  
 132 bending properties are neglected. The effects of wave kinematics and any other external loads on the  
 133 lines are also ignored in the lumped-mas model.

### 134 3.2. Extreme load estimation

135 The extreme values of stochastic responses are estimated based on the mean up-crossing rate method  
 136 [32]. In an arbitrary time interval  $T$ , it can be assumed that the random number of up-crossing is  
 137 approximated by Poisson distribution on condition that the up-crossing is statistically independent. This  
 138 assumption is valid if the response process is not narrow banded. Once a level  $y_0$  is selected, the  
 139 distribution of extreme value  $y_{max}$  for a random signal  $y(t)$  is described as

$$140 \quad P(y_{max} \leq y_0) = \exp\left(-\int_0^T v^+(y_0, t) dt\right) \quad (1)$$

141 where  $v^+(y_0, t)$  is the up-crossing rate corresponding to level  $y_0$ , which denotes the instantaneous  
 142 frequency of the positive slop crossings of the defined level. In this circumstance, the probability of  
 143  $y_{max}$  exceeding a defined level  $y_0$  is given by

$$144 \quad \begin{aligned} P(y_{max} > y_0) &= 1 - \exp(-\hat{v}^+(y_0)T) \\ \hat{v}^+(y_0) &= \frac{1}{T} \int_0^T v^+(y_0, t) dt \end{aligned} \quad (2)$$

145 The mean up-crossing rate  $\hat{v}^+(y_0)$  can be easily obtained from the time series of the signal that is  
 146 going to be analysed. For example, if we have  $k$  independent realizations of the random process and let  
 147  $n_j^+(y_0, T)$  denote the number of up-crossings in realization  $j$ , then the sample-based mean up-crossing  
 148 rate is given by

$$149 \quad \begin{aligned} \hat{v}^+(y_0) &\approx \bar{v}^+(y_0) \\ \bar{v}^+(y_0) &= \frac{1}{kT} \sum_{j=1}^k n_j^+(y_0, T) \end{aligned} \quad (3)$$

150 Eq. (3) is the basic formula to approximate the mean up-crossing rate  $\hat{v}^+(y_0)$  through numerical  
 151 simulations. If the defined level  $y_0$  is not very high, then just a few simulation realizations of the random  
 152 process will produce satisfactory approximation. Nevertheless, extensive simulations are required to  
 153 evaluate the extreme values in the tail region. To save computation resources, the extrapolation method  
 154 proposed by Naess and Gaidai [33] is used in this study to predict the mean up-crossing rate  
 155 corresponding to high level  $y_0$ .

156 The extrapolation method is based on the observation of marine structures so that it is applicable in  
 157 this study. The mean up-crossing rate is approximated by

$$158 \quad \begin{aligned} \bar{v}^+(y) &\approx v_{fit}^+(y) \\ v_{fit}^+(y) &= q \cdot \exp\{-a(y-b)^c\}, y \geq y_0 \end{aligned} \quad (4)$$

159 where  $q$ ,  $a$ ,  $b$  and  $c$  are all constant values. In the work of Naess and Gaidai [33], the first procedure is  
 160 to determine the value of  $q$ . Afterwards, it is easy to find that plotting  $\log|\log(v_{fit}^+/q)|$  versus  $\log(y-b)$   
 161 exhibits a linear tail behaviour. Fig. 3 shows the extrapolation of mean up-crossing rate, which can  
 162 approximate the mean up-crossing fairly well at low defined level  $y_0$ . Nevertheless,  $\bar{v}^+$  becomes  
 163 unstable in the tail region as the sample size (10 independent simulation realizations in this study) is  
 164 sufficient to produce reliable results. Therefore, the fitted up-crossing rate  $v_{fit}^+$  is used in the following  
 165 part of this paper to represent the extreme responses in the tail region.

166 A method to examine whether the sample size is sufficient to extrapolate the up-crossing rate is to  
 167 check the 95% confidence interval  $CI$

$$168 \quad \begin{aligned} CI_{\pm}(y_0) &= \bar{v}^+(y_0) \pm 1.96 \cdot \frac{\sigma(y_0)}{\sqrt{k}} \\ \sigma(y_0)^2 &= \frac{1}{k-1} \sum_{j=1}^k \left( \frac{n_j^+(y_0, T)}{T} - \bar{v}^+(y_0) \right)^2 \end{aligned} \quad (5)$$

169 The confidence interval obtained with 10 simulation realizations is displayed in Fig. 3. As shown, the  
 170 accuracy is acceptable. 10 simulation realizations are collected to extrapolate the up-crossing rate in the  
 171 following part of this paper.

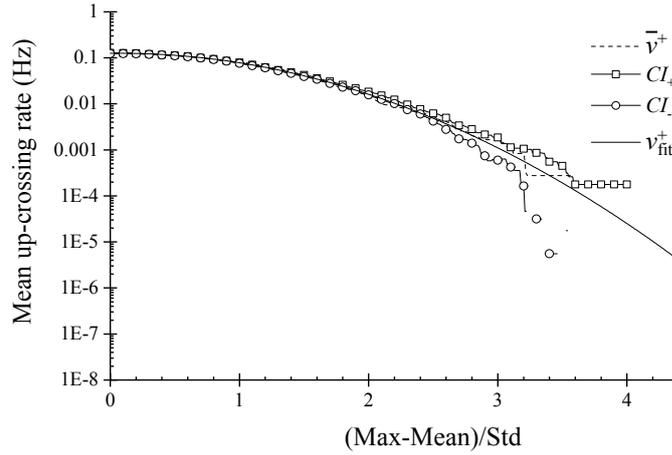


Fig. 3. Extrapolation of mean up-crossing rate of the tower base fore-aft bending moment in LC2.

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### 174 3.3. Fatigue damage estimation

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The short-term fatigue analysis is performed with MLife [34]. Wind, wave and inertial loads applied at certain structural components will cause fluctuation which will lead to fatigue damages. S-N method is used to evaluate the fatigue damages caused by these fluctuating loads. The fluctuating loads are broken down into individual hysteresis cycles by matching local minima with local maxima in the time series, which are characterized by a load-mean and range. It is assumed that the damage accumulates linearly with each of these cycles according to Miner's Rule. In this case, the overall damage rate produced by all the cycles is given by

182

$$DR = \sum_i \frac{n_i}{N_i(L_i^{RF})} / T \quad (6)$$

$$N_i(L_i^{RF}) = \left( 2 \cdot \frac{L^{ult} - |L^{MF}|}{(L_i^{RF})} \right)^m$$

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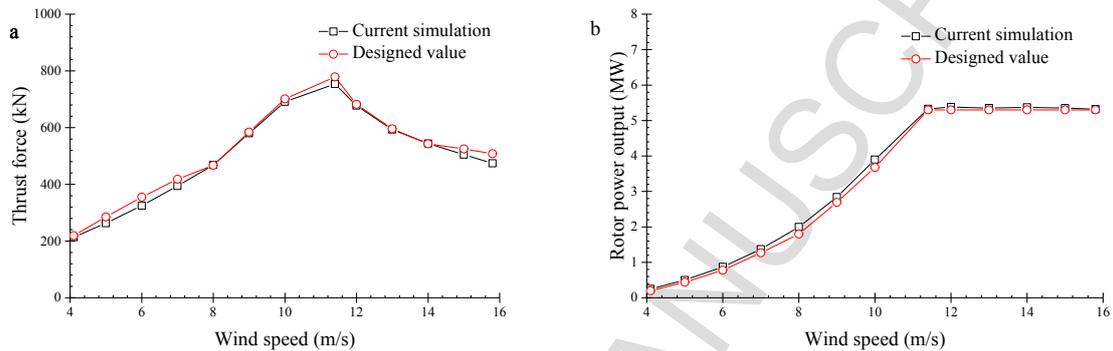
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$n_i$  is the damage count,  $N_i$  is the number of cycles to failure,  $L_i^{RF}$  is the cycle's load range corresponding to the fixed load-mean  $L^{MF}$ ,  $L^{ult}$  is the design ultimate load and  $m$  is the Wholer exponent. In this study, the design ultimate load for tower base fore-aft bending moment and mooring line tension is 680,000 kN·m and 2550 kN, respectively. The value of  $m$  is based on DNV design standard [35]. Considering the shape of the tower base and mooring line, the B1 S-N curve is selected. Afterwards, the 'air' category and 'sea water' category is selected for the tower base fore-aft bending moment and the mooring line tension, respectively. Consequently,  $m = 4$  selected for both fore-aft bending moment and tension force.  $T$  is the simulation time length.

## 191 4. Validation

## 192 4.1. Aerodynamics validation

193 Since the thrust forces acting on the wind turbine and the tidal turbines are simulated with the same  
 194 approach, only aerodynamic force is validated here. Firstly, the steady aerodynamic performance of the  
 195 wind turbine is simulated. Fig. 4 displays the steady aerodynamic performance of the wind turbine, in  
 196 terms of thrust force and rotor power output. As shown, a good agreement with the designed value [36]  
 197 is reached. It should be noted that the rated rotor power output of the NREL 5WM baseline wind turbine  
 198 is 5.3 WM (The rated generator power output is 5MW).



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Fig. 4. Aerodynamic performance of the wind turbine. (a) thrust force; (b) rotor power output.

201 For a floating wind turbine, the wind force acting on the rotor is unsteady due to platform motions.  
 202 To validate the unsteady aerodynamic performance, the wind turbine thrust force is simulated under a  
 203 set of sinusoidal winds and the simulation results are compared with those obtained by FAST [37]. The  
 204 speed of sinusoidal wind is defined as

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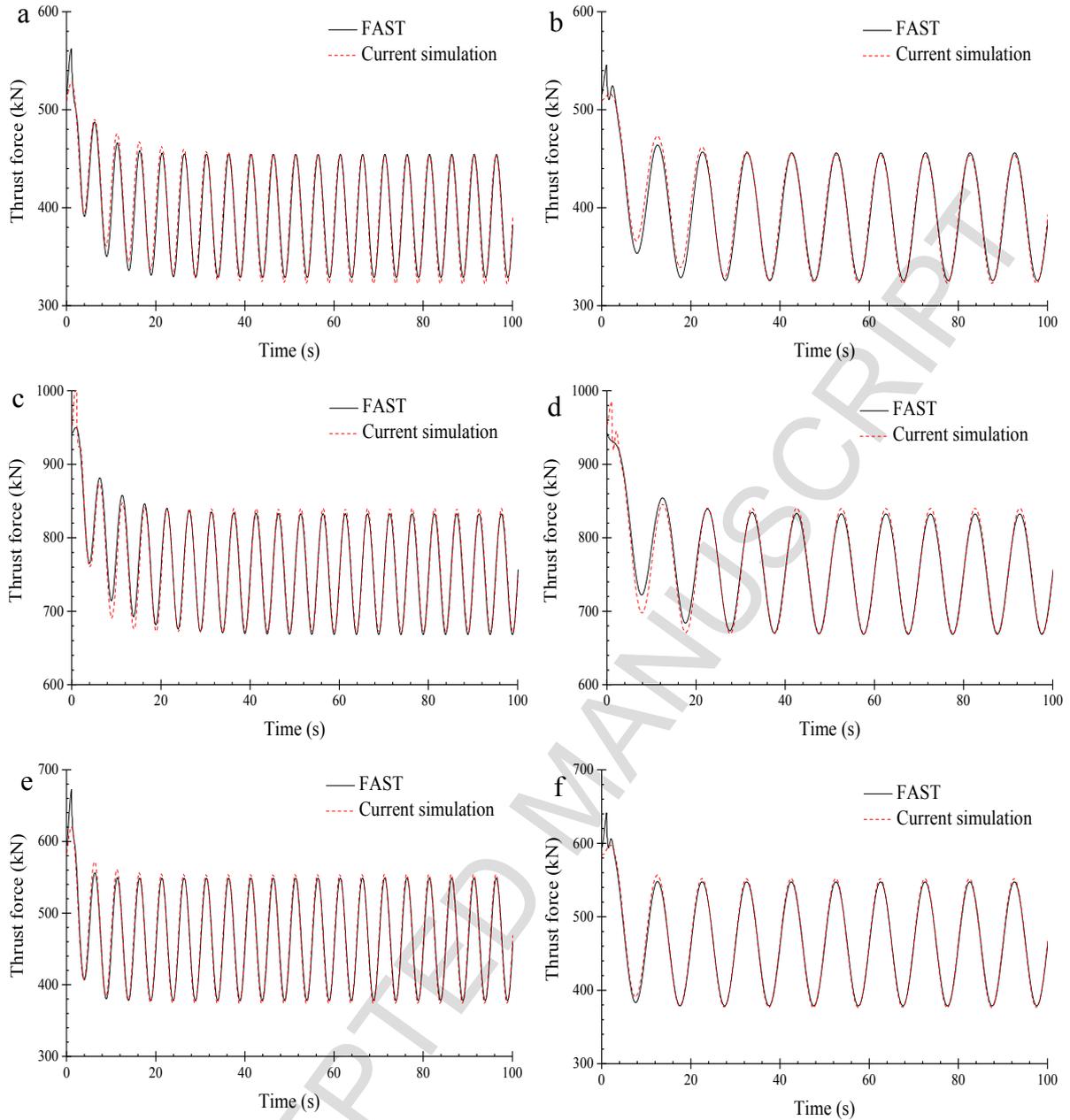
$$V(t) = V_0 + \sin(\omega t) \quad (7)$$

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where  $V_0$  is the mean wind speed and  $\omega$  is the varying frequency. Fig. 7 displays time series of the  
 unsteady wind turbine thrust forces predicted by the simulation tool and FAST. The agreement with  
 FAST is satisfactory.



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Fig. 5. Times series of unsteady wind turbine thrust forces. (a)  $V_0 = 8 \text{ m/s}$ ,  $\omega = 1.26 \text{ rad/s}$ ; (b)  $V_0 = 8 \text{ m/s}$ ,  $\omega = 0.63 \text{ rad/s}$ ; (c)  $V_0 = 11.4 \text{ m/s}$ ,  $\omega = 1.26 \text{ rad/s}$ ; (d)  $V_0 = 11.4 \text{ m/s}$ ,  $\omega = 0.63 \text{ rad/s}$ ; (e)  $V_0 = 14 \text{ m/s}$ ,  $\omega = 1.26 \text{ rad/s}$ ; (f)  $V_0 = 14 \text{ m/s}$ ,  $\omega = 0.63 \text{ rad/s}$ .

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#### 4.2. Aero-hydro-mooring validation

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The model test of a spar type floating wind turbine conducted by Koo et al. [38] is used to validate the numerical modelling of platform-wind turbine couplings. The spar type floating wind has an identical platform geometry with the Hywind, despite that the mass and inertia of the platform were changed. Please refer to [38] for more details of the model test set-up. White noise waves were generated in the model test to get the response amplitude operator (RAO) of platform motions in the presence of rated wind turbine thrust force. The same procedure is employed in the numerical simulation. Fig. 6 compares the RAOs acquired by the simulation tool and the experiment.

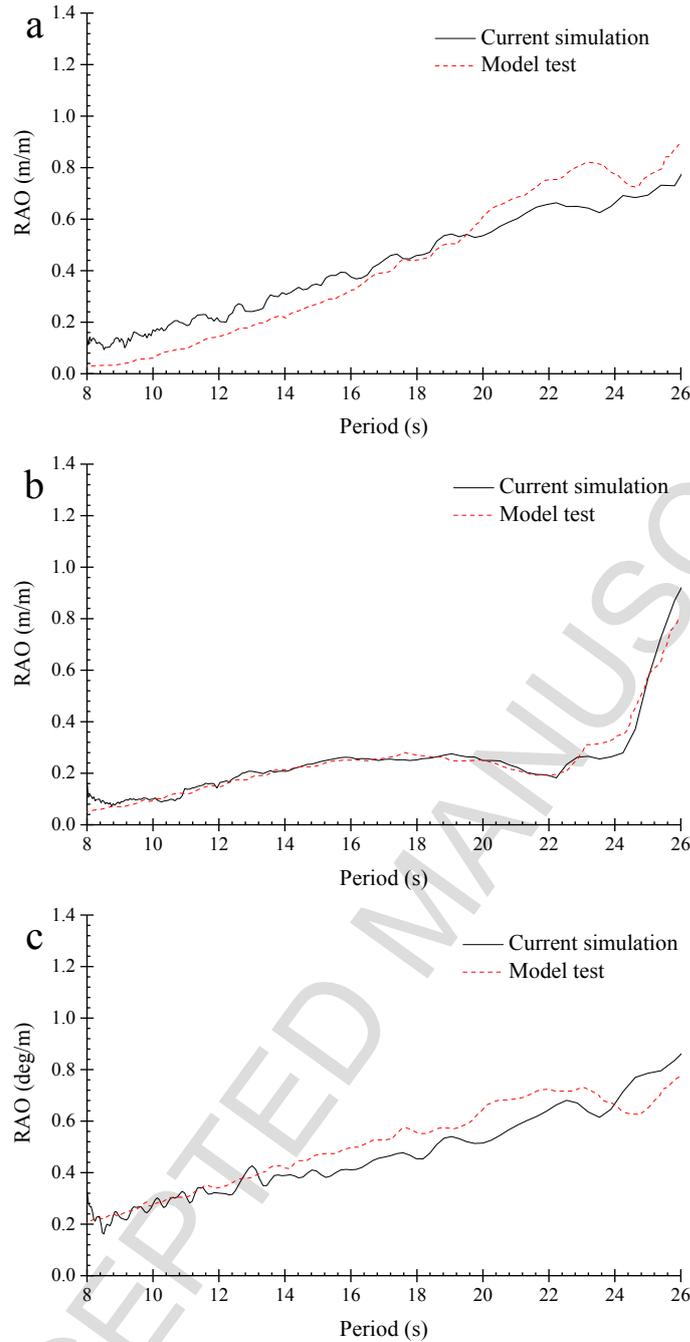


Fig. 6. RAOs of platform motions. (a) surge motion; (b) heave motion; (c) pitch motion.

## 5. Environmental conditions and Load cases

In a realistic sea site, the wind and the wave are correlated. The selection of environmental conditions is based on the joint probabilistic model of mean wind speed  $U_w$  at 10 m above the mean sea level, significant wave height  $H_s$  and peak period  $T_p$  that proposed by Johannessen et al. [39]. It is a pity that the tidal speed is not included in the joint model so that it is set to 1 m/s in all load cases. Firstly, the mean wind speed  $U_w$  is chosen. Subsequently, the fitting curve provided in [39] is used to acquire the mean significant wave height corresponding to a given mean wind speed. Finally, the mean peak period at given  $U_w$  and  $H_s$  is determined according to Eq. (8). The environmental condition considered in this

231 study are listed in Table 4. Steady wind field without consideration of turbulence is adopted in all  
 232 simulation cases.

$$233 \quad T_p = (4.883 + 2.68 \cdot H_s^{0.529}) \cdot \left[ 1 - 0.19 \cdot \left( \frac{U_w - (1.764 + 3.426 \cdot H_s^{0.78})}{1.764 + 3.426 \cdot H_s^{0.78}} \right) \right] \quad (8)$$

234 Table 4  
 235 Environmental conditions.

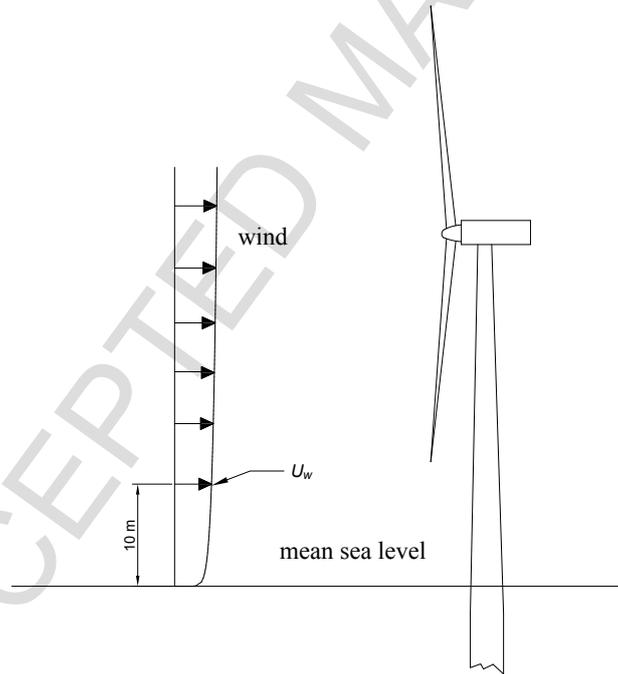
	$U_w$ (m/s)	$U_{\text{hub height}}$ (m/s)	$H_s$ (m)	$T_p$ (s)	Tidal stream speed (m/s)
LC1	5	6.8	2.38	9.84	1
LC2	8	10.8	3.13	10.17	1
LC3	10	13.6	3.55	10.29	1
LC4	12	16.3	4.17	10.62	1
LC5	14	19.0	4.75	10.89	1

236

237 The wind speed varies with height implying that the blades are subjected to time-varying inflow due  
 238 to rotor rotation. A power law is used to estimate the wind profile  $U(z)$  at the height of  $z$  above the mean  
 239 sea level (see Fig. 7)

$$240 \quad U(z) = U_w \left( \frac{z}{10} \right)^\alpha \quad (9)$$

241  $\alpha$  is the power law exponent which is selected to be 0.14 according to IEC 61400-3 [40].



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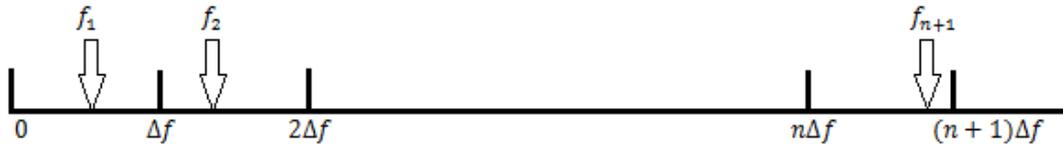
Fig. 7. Wind profile.

244 In each simulation case, the stochastic wave elevations are pre-generated and input to the HWNC  
 245 and the Hywind respectively to ensure a reasonable comparison between the two systems. A linear wave  
 246 model is adopted to generate the stochastic wave elevations, which consists of a set of regular waves  
 247 with different oscillating frequency

$$\eta(t) = \sum_{j=1}^N A_j \cos(2\pi f_j t + \varepsilon_j) \quad (10)$$

$$A_j = \sqrt{2S(f_j)\Delta f}$$

248 where  $A_j$ ,  $f_j$  and  $\varepsilon_j$  are the wave amplitude, frequency and random phase of the regular wave component  
 249  $j$ .  $S(f)$  is the JONSWAP wave spectrum. If  $f_j$  is uniformly distributed over the wave frequency range,  
 250 the stochastic wave elevations will start to repeat after a certain time interval [41]. Apparently, it has a  
 251 substantial influence on the statistics of the stochastic responses, especially the prediction of the extreme  
 252 values. To address this issue, the correct method used in [4] is adopted here. The wave frequency range  
 253 is firstly uniformly divided in to  $N$  segments and  $f_j$  is randomly distributed within segment  $j$  (see Fig.  
 254 8). The stochastic wave elevations corresponding to a specific load case are independently realized ten  
 255 times. Then the ten sets of simulation results are collected to extrapolate the mean up-crossing rate and  
 256 evaluate the extreme responses according to the procedures in Section 3.2.  
 257



258  
 259 Fig. 8. Random distribution of wave frequency.

## 260 6. Simulation results

261 The responses of the HWNC subjected to various environmental excitations are simulated.  
 262 Comparisons will be made against the Hywind to demonstrate whether the installation of the WEC and  
 263 the tidal turbines can improve the performance of the HWNC. 1-hr extreme response and fatigue  
 264 damage are investigated. The total simulation length is set to 4000 s and only data of the last 3600 s  
 265 will be collected to get rid of the transient effects arising in the initial simulation stage. A ramp function  
 266  $R_f$  is also added to eliminate the transient effects

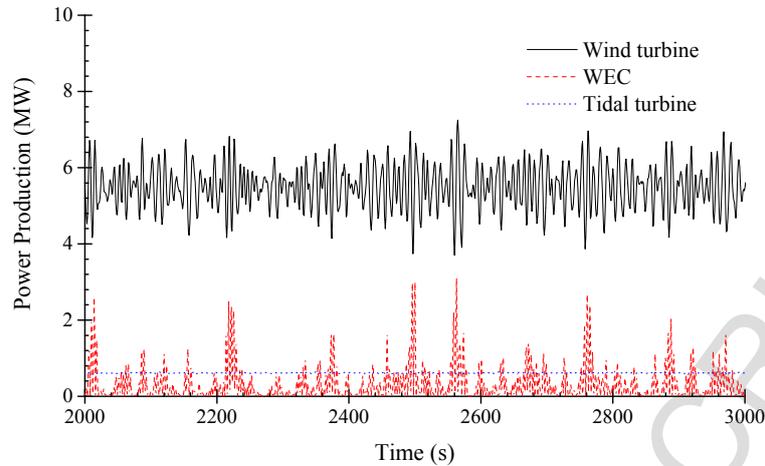
$$R_f = \begin{cases} (1 + \cos(\pi + \pi t / t_r)) / 2 & t < t_r \\ 1 & t \geq t_r \end{cases} \quad (11)$$

268 where  $t_r$  is the ramp time.

### 269 6.1. Power production and platform motions

270 The power production is firstly investigated. Fig. 3 displays the time series of power production of  
 271 the HWNC. As shown, the contribution from the WEC and the tidal turbines are remarkable. Since the

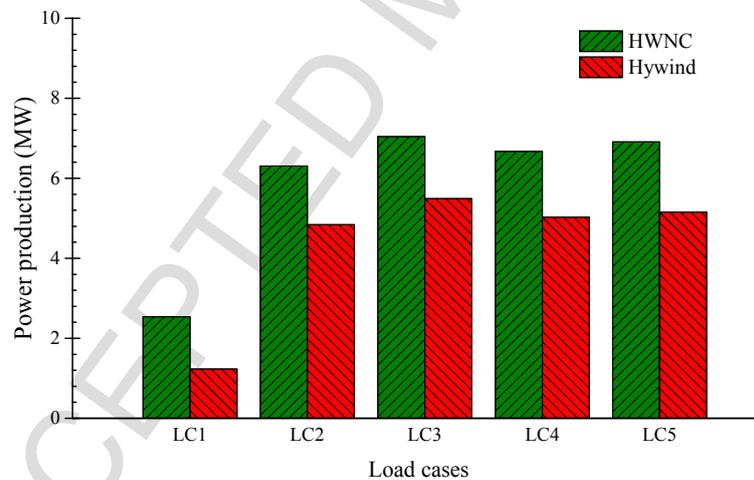
272 tidal turbines are installed close to the CoG of the platform, surge-pitch coupling is not significant and  
 273 therefore the power output of the tidal turbines are very stable.



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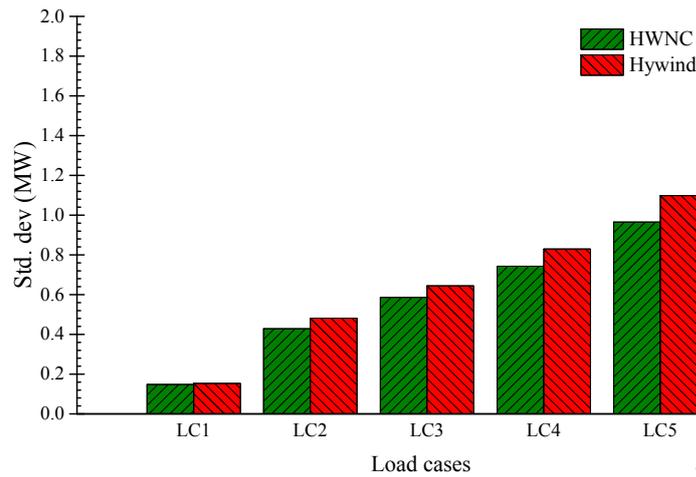
Fig. 9. Time series of power production, LC3.

276 The mean power production of the HWNC and the Hywind in various load cases are shown in Fig.  
 277 10. Generally, the HWNC produces approximately 25% more power than the Hywind and this  
 278 percentage is even higher in below-rated operational condition. Fig. 11 compares the standard deviation  
 279 of wind turbine power production. The standard deviation of the HWNC is lower than that of the  
 280 Hywind, regardless of environmental conditions. It implies that the wind turbine power output is more  
 281 stable with the WEC and the tidal turbines, which is obviously beneficial to the net grid.



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Fig. 10. Mean value of overall power production.



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Fig. 11. Standard deviation of wind turbine power production.

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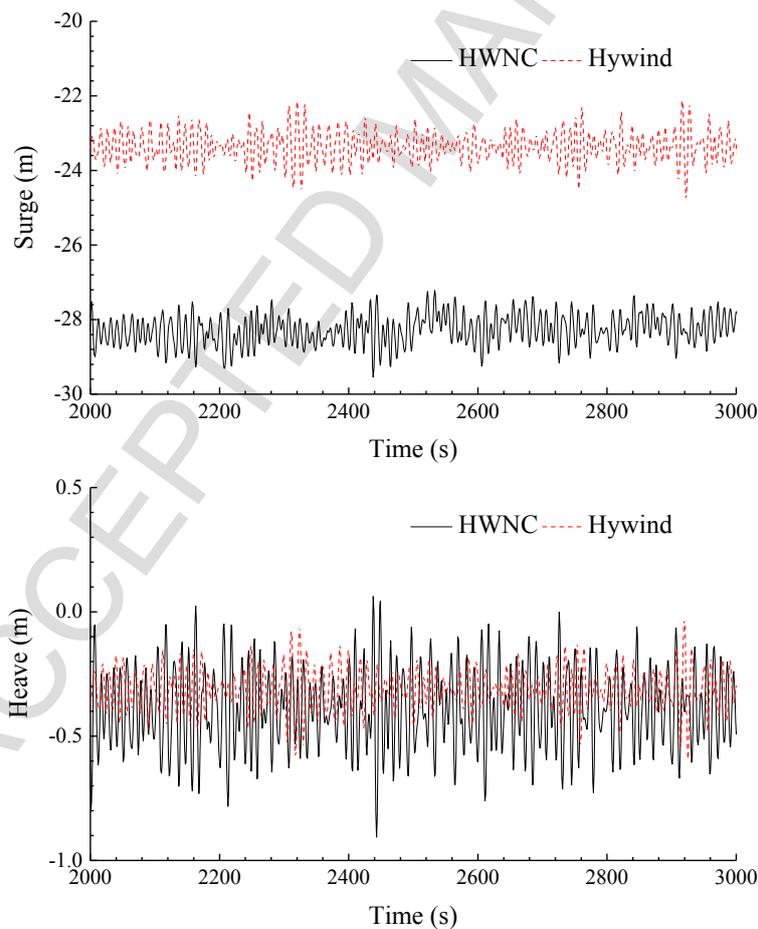
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Fig. 12 plots the time series of platform motions and Table 5 summarises the statistics. It is desirable to see that the surge and pitch motions are reduced. Nevertheless, the mean pitch and surge position is pushed further away from the initial equilibrium position due to the extra thrust force on the tidal turbines. It inherently implies that the mooring lines will bear more loads. Also, the heave response of the HWNC is excited considerably, much stronger than that of the Hywind.



291

292

Fig. 12. Time series of platform motions, LC2.

293 Table 5  
 294 Statistical results of platform motions, LC2.

		Max	Min	Mean	Std. dev
HWNC	Surge (m)	-26.96	-30.85	-28.31	0.44
	Heave (m)	0.11	-0.91	-0.39	0.15
	Ptich (deg)	-3.20	-4.23	-3.91	0.15
Hywind	Surge (m)	-21.01	-26.15	-23.37	0.51
	Heave (m)	-0.03	-0.59	-0.31	0.08
	Pitch (deg)	-3.18	-4.45	-3.79	0.18

295

296 The reduction of surge and pitch motions can be attributed to the tidal turbines, which produce  
 297 damping force. Considering that the sea current propagates along negative  $X$  direction, the thrust force  
 298 acting on the tidal turbine can be approximated by

$$299 \quad T(\dot{x}) = -C_T \cdot \frac{1}{2} \rho \pi R^2 (u + \dot{x})^2 \quad (12)$$

300 where  $C_T$  is the steady thrust force coefficient,  $u$  is the sea current speed,  $\dot{x}$  is velocity of the tidal turbine  
 301 along  $X$  direction. Applying Taylor expansion at  $\dot{x} = 0$ , the following series is derived

$$302 \quad T(\Delta\dot{x} + 0) = T(0) - C_T \rho \pi R^2 u \Delta\dot{x} - C_T \rho \pi R^2 u \Delta\dot{x}^2 + O(\Delta\dot{x}^2) \quad (13)$$

303 The first term on the right side is a constant component, which only influences the mean position of  
 304 the platform. The constant component also has an influence on the extreme response, which will be  
 305 discussed in the following part of this paper. The third term is of second-order and can be regarded as  
 306 a small component compared to the first-order term. The second term is a damping component which  
 307 helps to reduce the platform motions.

308 The amplified heave motion is caused by the WEC. As shown in Fig. 13, the vertical wave excitation  
 309 force acting on the spar platform is very limited considering the geometry of the spar buoy.  
 310 Comparatively, the WEC is subjected to much larger vertical excitations since the water plane area of  
 311 the WEC is 3.4 times that of the spar buoy. The vertical excitations will transfer to the spar buoy through  
 312 the PTO facility and therefore the mooring lines will be excited significantly. The increased vertical  
 313 excitation force is a negative effect produced by the WEC, which leads to worse dynamic response of  
 314 the mooring lines.

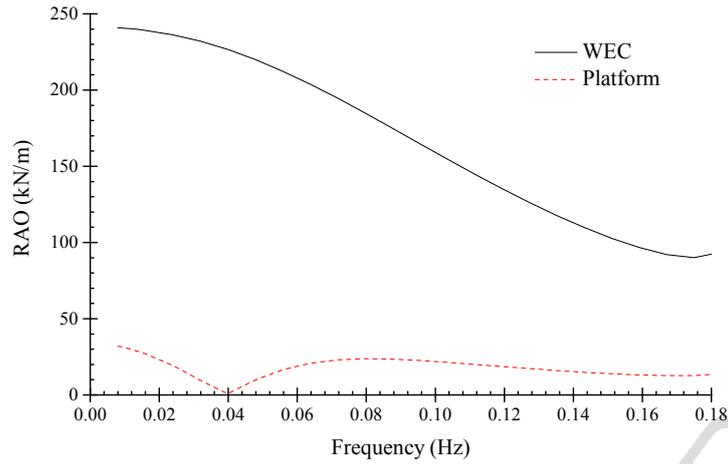
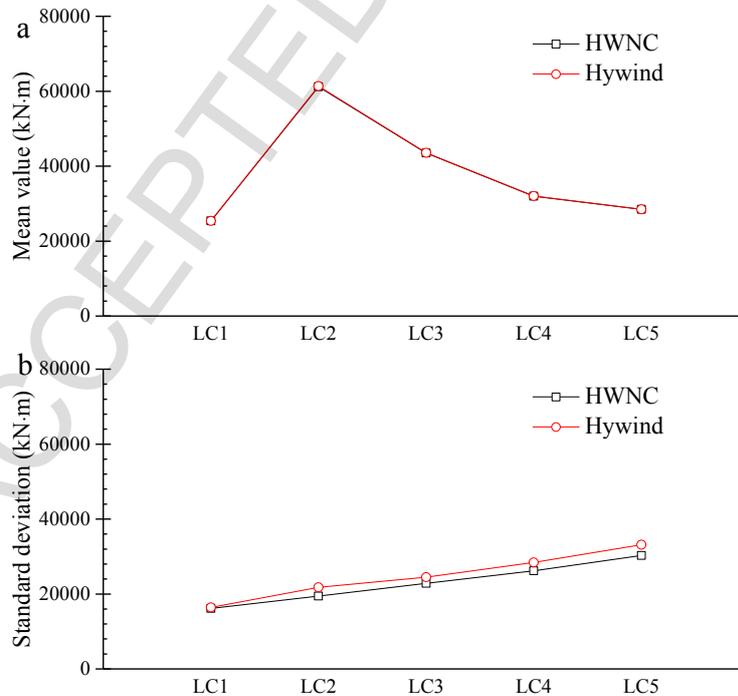


Fig. 13. RAO of vertical wave excitation force.

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## 317 6.2. Structural responses

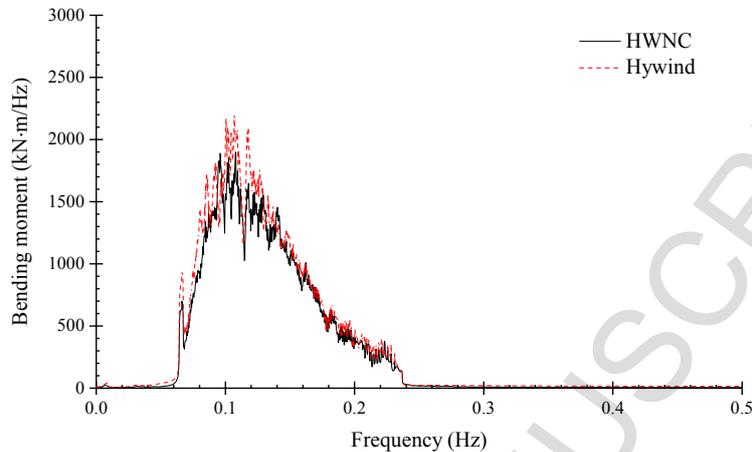
318 Fig. 14 shows the mean value and standard deviation of tower base fore-aft bending moment of the  
 319 HWNC and the Hywind. It is found that the mean fore-aft bending moments of the two systems are  
 320 nearly identical regardless of the environmental conditions. The good agreement between the two  
 321 curves are not unexpected as the mean fore-aft bending moment at tower base is mainly produced by  
 322 the thrust force acting on the wind turbine. It explains why the mean fore-aft bending moment does not  
 323 increase from LC1 to LC6 although the wave condition becomes increasingly severe. Although the  
 324 HWNC is subjected to an additional pitch moment produced by the tidal turbines, this extra component  
 325 is undertaken by the mooring system and the hydrostatic restoring force. Moreover, the HWNC gives a  
 326 smaller standard deviation than the Hywind in both below-rated and over-rated operational conditions.



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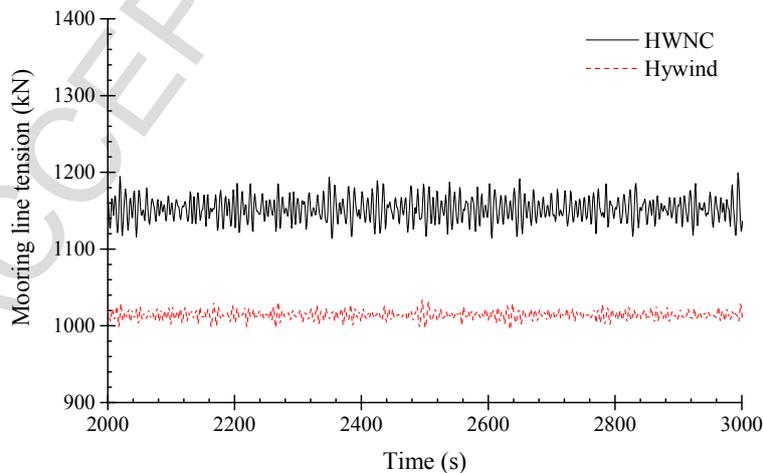
Fig. 14. Statistical results of tower base bending moment. (a) mean value; (b) standard deviation.

329 To further demonstrate the dynamic response of tower base, the time series of fore-aft bending  
 330 moment is analysed with fast Fourier transform (FFT) method to acquire the power spectrum which is  
 331 shown in Fig. 15. The majority of response energy concentrates within the wave frequency range and  
 332 the response peak is observed at 0.09 Hz, which is close to the peak period of the stochastic waves. The  
 333 HWNC generally gives a smaller response than the Hywind across the wave frequency range.



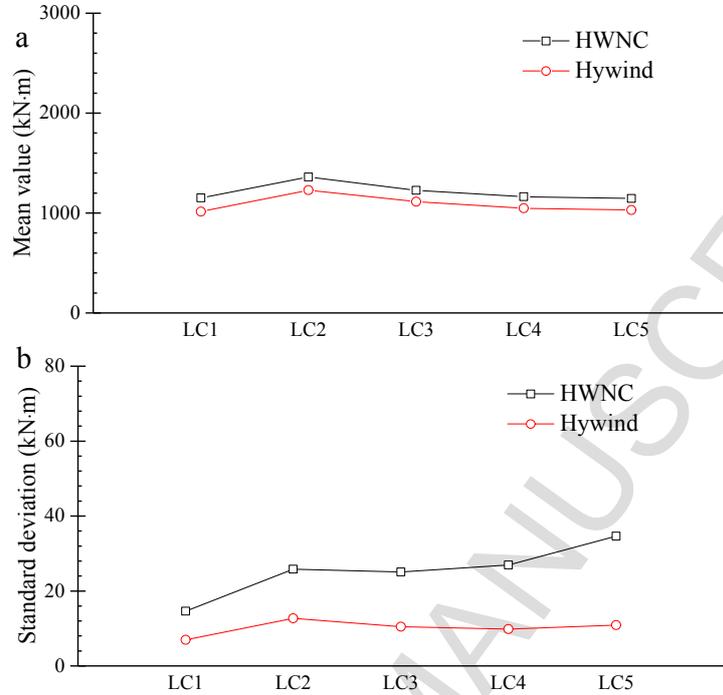
334 Fig. 15. FFT analysis results of tower base fore-aft bending moment, LC2.

336 Apart from the tower base fore-aft bending moment, the tension force of mooring line\_1 is selected  
 337 as another representation of the structural responses of the HWNC. Fig. 16 displays the time series of  
 338 mooring line tension force in LC1. As shown, the mean value of the HWNC is larger than that of the  
 339 Hywind. Statistics of the mooring line tension in other load cases are shown in Fig. 17. The mean  
 340 mooring line tension forces of the two systems exhibit identical variation trend, which is very like that  
 341 of the mean fore-aft bending moment. In fact, both the mean mooring tension force and the mean fore-  
 342 aft bending moment is governed by the wind force whereas the wave force merely dominates the  
 343 fluctuation. Nevertheless, a constant gap exists between the HWNC and the Hywind due to the thrust  
 344 force acting on the tidal turbines.



345 Fig. 16. Time series of line\_1 tension force, LC1.

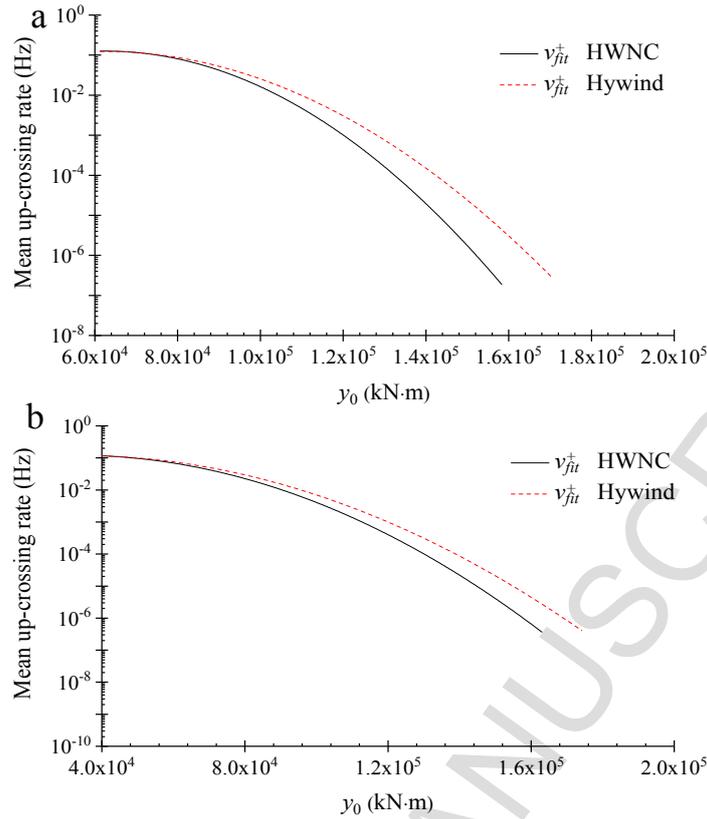
347 In spite of the reduced tower base fore-aft bending moment, the mooring line tension of the HWNC  
 348 is substantially increased. Although the tidal turbine can produce damping forces, the constant  
 349 component also brings more loads to the mooring system. Besides, the HWNC suffers additional  
 350 vertical wave excitation forces.



351 Fig. 17. Statistical results of line\_1 tension force. (a) mean value; (b) standard deviation.  
 352

### 353 6.3. Extreme structural response

354 The 1-hr extreme values of tower base fore-aft bending moment and mooring line tension force are  
 355 predicted based on the extrapolation method presented in Section 3.2. Fig. 18 shows the extrapolated  
 356 up-crossing rate of the tower base fore-aft bending moment. Regardless of the environmental conditions,  
 357 the up-crossing rate of the HWNC is generally lower than that of the Hywind at a given level  $y_0$ .  
 358 According to Eq. (2), it implies that the fore-aft bending moment of the HWNC has a smaller  
 359 probability to exceeds  $y_0$ . The level corresponding to up-crossing rate of  $10^{-5}$  is selected in this study  
 360 to represent the extreme values.



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362

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Fig. 18. Extrapolated up-crossing rate of tower base fore-aft bending moment (a) simulation case LC2; (b) simulation case LC4.

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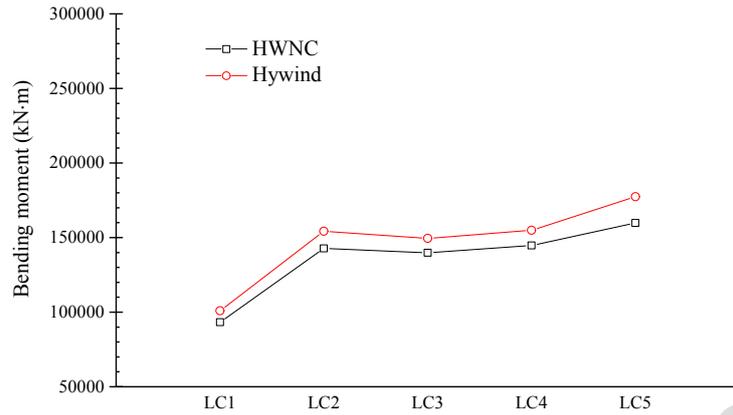
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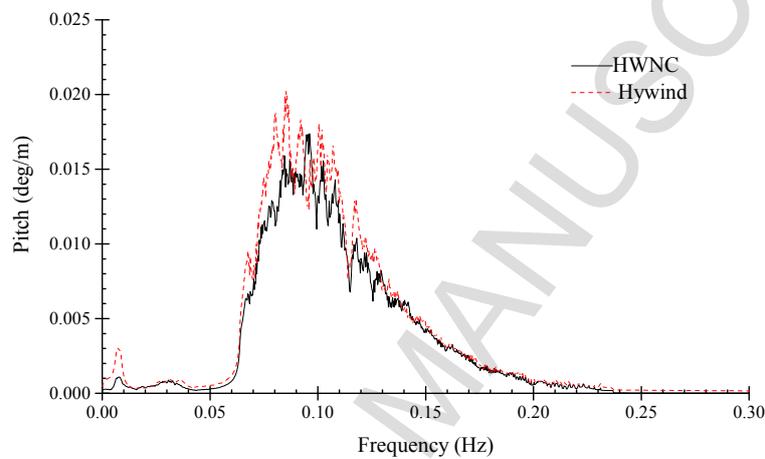
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The extreme tower base fore-aft bending moments of the HWNC and the Hywind are demonstrated in Fig. 19. Generally, the extreme fore-aft bending moment is monotonic and it increases as the sea waves become severe. Nevertheless, the extreme value in simulation case LC2 reaches a relatively high level despite that the sea waves are moderate. According to the environmental conditions in Table 4, the wind thrust force is the largest in LC2 (the wind speed is closed to the rated value 11.4 m/s in LC2), which induces a substantial fore-aft bending moment at the tower base and it is why the mean fore-aft bending moment is the largest in LC2. Therefore, the extreme fore-aft bending moment can still reach a very high level even if the sea waves are moderate. Although the wind turbine is parked and the system is subjected to no wind force in LC6, the extreme fore-aft bending moment is still the largest in all simulation cases due to the rare sea waves. Moreover, the HWNC gives a smaller extreme value than the Hywind. Considering that the fore-aft bending moment produced by the wind force is identical for the two systems, it can be deduced that the smaller extreme response of the HWNC is mainly attributed to the reduced pitch motion (see Fig. 20).



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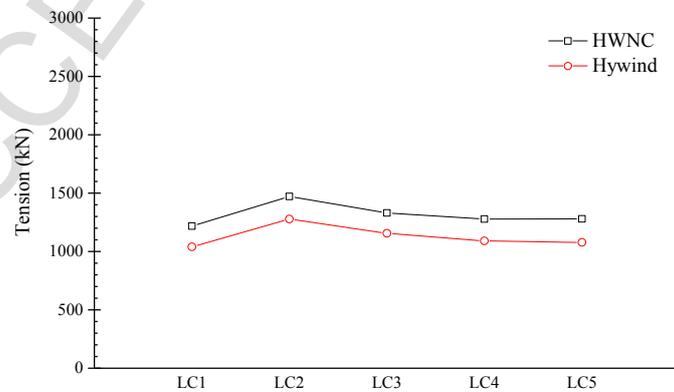
Fig. 19. Extreme tower base fore-aft bending moment.



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Fig. 20. Spectrum density of pitch motion, LC2.

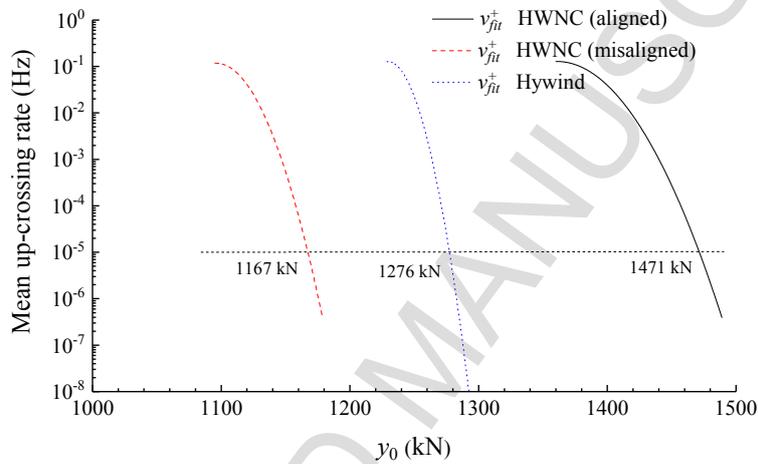
381 Fig. 21 presents the extreme values of the mooring line tension force. The maximum mooring tension  
 382 seems to be dominated by the wind force while the sea wave effect is limited. The maximum value does  
 383 not increase with the significant wave height. Instead, the maximum mooring tension and the wind force  
 384 have a similar variation trend. It implies that the critical condition for the mooring line is the rated  
 385 operational condition rather than the extreme sea condition.



386  
387

Fig. 21. Extreme mooring line tension force.

388 Despite the reduced maximum tower base fore-aft bending moment, the HWNC gives a worse  
 389 extreme mooring tension. It is obviously a negative aspect produced by the installation of the WEC  
 390 and the tidal turbines. The first item expands the fluctuation range of mooring line tension whereas the  
 391 second term increases the average tension. Nevertheless, it should be noted that the wind and the sea  
 392 current are aligned in the above simulation cases, which is the most unfavourable scenario for the  
 393 HWNC. If the wind and the sea current propagate along opposite directions, the thrust forces acting on  
 394 the wind turbine and the tidal turbines will offset each other, leading to a reduced extreme mooring  
 395 tension. Fig. 22 shows the fitted up-crossing rate of the mooring tension when the sea current propagates  
 396 along positive  $X$  axial. Due to the change of sea current propagation direction, the extreme mooring  
 397 tension is significantly reduced. It indicates that the tidal turbine can play either a positive role or a  
 398 negative role depending on the wave-current misalignment.



399 Fig. 22. Extrapolated mean up-crossing rate of mooring line tension force, LC2.  
 400

#### 401 6.4. Fatigue damage calculation

402 The fatigue analysis is represented with the damage rate discussed in Section 3.3. The tower base  
 403 fore-aft bending moment and the tension force of line\_1 are considered here.

404 Fig. 23 displays the short-term fatigue damage rate of the tower base fore-aft bending moment. The  
 405 damage rates of the two systems both increase when the sea wave becomes severe. Generally, the  
 406 HWNC gives a lower damage rate than the Hywind. For example, the damage rate of the HWNC in  
 407 LC2 is  $9.63 \times 10^{-6}$  Hz, approximately 30% lower than that of the Hywind ( $1.36 \times 10^{-5}$  Hz). Nevertheless,  
 408 the discrepancies are less notable in LC1 and LC4. According to the results presented in Fig. 14(b), the  
 409 fluctuation range of tower base fore-aft bending moment is narrowed due to installation of the WEC  
 410 and the tidal turbines, which contributes to the reduced fatigue damage loads suffered by the HWNC.

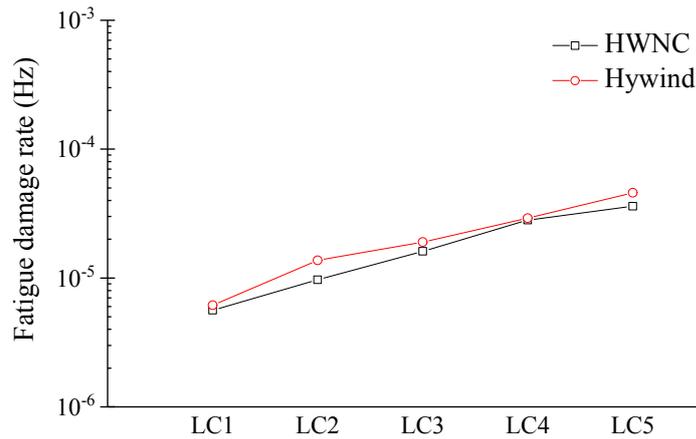


Fig. 23. Short-term damage rate of tower base fore-aft bending moment.

411  
412

413 The fatigue damage rate of mooring tension is presented in Fig. 24. The contribution of WEC and  
414 tidal turbines to the fatigue damage rate is notable. Due to the thrust force acting on the tidal turbines,  
415 the mooring line will bear more loads to sustain the spar buoy. Also, the HWNC is subjected to much  
416 larger vertical wave excitation force and variation range of mooring line tension increase accordingly.  
417 The two factors together enhance the fatigue damage rate of the mooring line tension. The damage rate  
418 reaches a very high level in LC2, which is applicable to both the HWNC and the Hywind. It implies  
419 that the wind force has a dominating influence on the mooring line fatigue load.

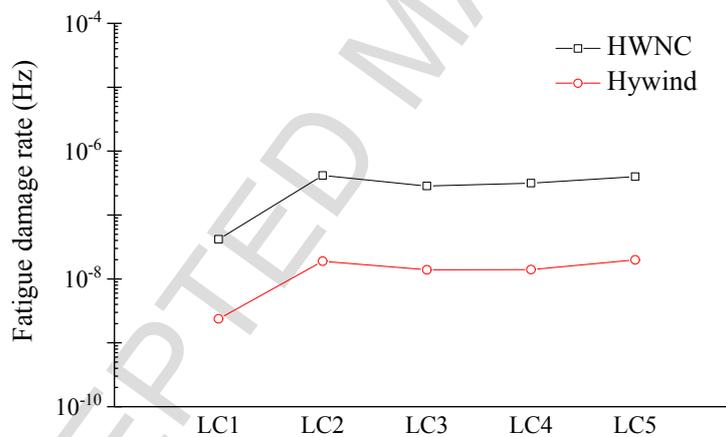


Fig. 24. Short-term damage rate of mooring line tension force.

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421

422 According to Fig. 24, the fatigue damage rate shows observable discrepancies between the HWNC  
423 and the Hywind due to the thrust forces acting on the tidal turbines. To investigate the sensitivity of  
424 fatigue damage rate to the tidal turbine forces, the current speed in LC2 is varied. Table 6 lists the  
425 fatigue damage rate of mooring line tension when the HWNC is subject to various current speeds. As  
426 expected, the current speed (or tidal turbine force) has a negative effect on the mooring line since the  
427 mooring line will bear more loads to sustain the platform in the case of high current speed.

428 Table 6  
429 Sensitivity of mooring tension fatigue damage rate to current speed

	1.0 m/s	1.1 m/s	1.2 m/s
Fatigue damage rate (Hz)	$4.2 \times 10^{-7}$	$4.6 \times 10^{-7}$	$5.9 \times 10^{-7}$

430

## 431 7. Conclusions

432 The structural responses of an integrated wind, wave and tidal energy system are addressed in this  
433 study. The integrated system is based on the combination of a spar type floating wind turbine, a point  
434 oscillating WEC and two tidal turbines. The mean up-crossing method is used to predict the extreme  
435 values of the stochastic responses. The size of simulation realizations is reduced by an extrapolation  
436 method, which approximates the up-crossing rate in tail region. The cumulative fatigue damage rate is  
437 calculated based on the S-N method. A comparative study between the integrated system and a spar  
438 type floating wind turbine is conducted to illustrate how the installation of the WEC and the tidal  
439 turbines influences the dynamic performance.

440 The stochastic responses of tower base fore-aft bending moment and mooring line tension force  
441 under a set of environmental conditions are simulated. It is favourable to see that the fore-aft bending  
442 moment are reduced as a result of the damping force produced by the tidal turbines. Nevertheless, the  
443 extra vertical wave excitation force acting on the WEC increases the response of mooring line  
444 substantially. A possible solution to this problem is adjustment of the PTO parameters, namely the  
445 stiffness coefficient  $K$  and the damping coefficient  $B$ . An appropriate configuration of the two  
446 parameters may help to relieve the problem or even eliminate it.

447 Based on the extrapolated up-crossing rate, the extreme values of the stochastic responses are  
448 estimated. Owing to the damping forces produced by the tidal turbines, the maximum fore-aft bending  
449 moment of the HWNC is smaller than that of the Hywind. It is an advantage of the HWNC. Nevertheless,  
450 the HWNC gives an extraordinary higher maximum mooring tension due to the thrust force acting on  
451 the tidal turbines. It should be noted that the wind and the sea current are set to propagate along the  
452 same direction in this study, which is the most dangerous scenario for the HWNC. An extra simulation  
453 shows that the maximum mooring tension of the HWNC can be reduced and even lower than that of  
454 the Hywind when the direction of sea current changes.

455 The cumulative damage rate is used to indicate the short-term fatigue damage caused to the structural  
456 component. It is shown that the tower base has a smaller probability to fail when the WEC and the tidal  
457 turbines are installed. On the contrary, the mooring line is subjected to higher damage loads.

## 458 8. Future work

459 A limitation of the current study is that wave-current couplings and wind turbulence are not  
460 considered. Future work aims to include the two factors in the numerical modelling to predict the  
461 performance of the HWNC in the natural world more accurately.

## 462 Acknowledgment

463 The authors would like to acknowledge China Scholarship Council for the financial support (No.  
464 201506230127).

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- Short-term extreme response and fatigue damage of an integrated renewable energy device are investigated.
- The hybrid device combines a floating wind turbine, a WEC and two tidal turbines
- Mean up-crossing rate method and S-N method is used.
- Extreme value and fatigue damage of bending moment is reduced.

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