A comparative study of different methods for predicting the long-term extreme structural responses of the combined wind and wave energy concept SFC

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Abstract

The combined wind and wave concept Semisubmersible wind energy and Flap-type wave energy Converter (SFC) was developed in the EU FP7 project MARINA Platform. It consists of a four-column semi-submersible with a 5MW wind turbine placed on top of the central column and three flap-type wave energy converters (WECs) on top of three pontoons that connect the four columns. Numerical and experimental studies have been performed to demonstrate the functionality and the survivability of the combined concept. In extreme conditions, both wind turbine and wave energy converters are set in a protection mode which reduces the dynamic loads and responses. In this paper, different methods for predicting long-term (50-year) extreme responses considering the wind and wave conditions at two given European offshore sites are carried out and structural response quantities are calculated, compared and presented. The full long-term analysis (FLTA) was performed and regarded as the reference method, and the corresponding results are compared with the modified environmental contour method (MECM) and the environmental contour method (ECM). The response quantities studied here are the axial forces and bending moments of the SFC, including those of the wind turbine (blade, shaft, and tower), arms of the flap-type WECs, and mooring lines, as well as the platform motion in six-degrees of freedom. The extreme responses that are dominated by the aerodynamic loadings are effectively calculated either by the FLTA or the MECM. Compared to the FLTA, the ECM gives an under-prediction of the long-term extreme responses of quantities related to the wind turbine (e.g. internal loads of blades and tower). For the extreme responses that are dominated by the hydrodynamic loadings all the three methods provide similar results.

Keywords: SFC wind/wave combined concept; Offshore renewable energy; Extreme response prediction; Long-term performance; Environmental contour method.

1. Introduction

Offshore Wind Turbines (OWTs) technology can be considered as the leading technology in offshore renewable energy sector. Up to January 2017, 3,589 offshore wind turbines are fully grid connected in 81 offshore wind farms across 10 countries in the European Union (EU), with an installed capacity of 12.6 GW. The rated power of an average offshore wind turbine has grown 62% over the past decade; the average rated power per turbine installed in 2016 was 4.8 MW (WindEurope 2017[1]). Apart from bottom-fixed OWTs, floating OWTs of different platform types can be used for supporting turbines with high rated power (Thiagarajan and Dagher[2]). Cost is the main handicap for the further development of the OWTs technology. In addition to offshore wind energy, Wave Energy Converters (WECs) can also be used for the harvesting and exploitation of the available enormous wave energy resources. Up to now, the technology of WECs cannot be considered mature enough for large-scale commercial deployment. A quite big number of concepts have been proposed so far (Falnes[3]). WECs can be efficiently deployed in multi-purpose offshore floating platforms (Michailides and Angelides[4]).

For both OWTs and WECs technologies there is a need for reduction of costs and further development. Combining these energy systems of different technologies in a farm configuration or in one single platform it may result in the efficient use of the ocean space. Possible advantages as a result of the use of combined wind and wave systems are: (a) increase of the energy production per unit area of ocean space, (b) efficient use of the ocean space, (c) decrease of the system balancing cost since the wave resources are more predictable than wind resources, (d) decrease of the cost related with the required electric grid infrastructure since the different technology energy systems will share the electric grid especially with regard to the transportation of the produced power to onshore stations, (e) decrease of the cost related to the sharing of the foundation substructure (e.g. common semisubmersible or spar platform) and (f) decrease of the costs related to operation (e.g. installation) and maintenance (e.g. inspection) compared to the costs that similar pure offshore energy systems have. In the EU project MARINA Platform[5], 110 concepts were initially considered and reduced to ten and finally to three based on an increasingly refined assessment of all the features of the concepts. The three combined concepts have been developed and studied both numerically and experimentally under operational and survival conditions. These combined concepts are the Semisubmersible wind energy and Flap-type wave energy

Converter (SFC) (Michailides et al.[6]), the Spar Torus Combination (STC) (Muliawan et al.[7]) and an array of Oscillating Water Columns (OWCs) in a large V-shaped concrete floating platform and one wind turbine combination (O'Sullivan et al.[8]).

The combined concept SFC consists of a braceless semisubmersible floating platform supporting a 5 MW wind turbine, three rotating flap-type WECs hinged at the pontoons of the semisubmersible through structural arms and linear Power Take-Off (PTO) mechanisms, and a catenary mooring system (Fig. 1). Two different experimental campaigns of the SFC have been conducted at ECN, Nantes, France (Michailides et al.[9]), validating the accuracy of the developed numerical models and tools that was used. The first corresponds to the survivability physical model of the SFC in which the wind turbine is parked and the WECs are rotating with a minimum level of damping (Michailides et al.[10]); the SFC is not producing power. The second corresponds to the functionality physical model of the SFC in which the blades of the wind turbine rotate and the PTOs of WECs are in operation behaving as linear dampers (Michailides et al.[11]); the SFC is in operation and produces power from both wind and waves. Details about the methods that are used for the development of the numerical models of the SFC are presented in Gao et al.[12]. In all the published research for SFC so far, the environmental conditions considered are selected for representative wind speeds and corresponding wave conditions with expected values of Hs and Tp conditional on the mean wind speed at different European offshore sites. However, only using several representative environmental conditions may not be sufficient. Combined concepts like common offshore structures should be designed for specific Ultimate Limit State (ULS) design criteria for all possible sea states available in the operational site. As a result the long-term extreme responses of different components (e.g. wind turbine, tower, WECs, mooring lines) should be calculated appropriately. Different methods have been developed and proposed so far for the long-term extreme response prediction of offshore structures. The most accurate method is the full long-term analysis (FLTA) which integrates the product of the probability of the environmental conditions and the corresponding short-term response probability distribution for a very big number of possible environmental conditions. FLTA is both time and computationally consuming. In order to reduce the required computational time many simplification methods have been proposed for the extreme response prediction using the extremes under each single extreme environmental condition or by reducing the examined environmental cases since the long-term extreme is normally governed by the responses in a small number of environmental conditions. Haver and Winterstein[13] first proposed the environmental contour method (ECM), which finds the long-term extreme response based on the short-term extreme response distribution of a single environmental condition. Such environmental condition is found on a contour line/surface corresponding to a given return period for long-term extreme response prediction and it gives the largest extreme response compared to other environmental conditions on the contour. FLTA and ECM have been applied for the estimation of extreme responses of the combined concept STC dominated by wave loads by Ren et al.[14] and Muliawan et al.[15] respectively. Li et al.[16] proposed the modified environmental contour method (MECM) by including additional environmental contours inside of the one used in the ECM, and extrapolate the appropriate short-term extreme distribution to find the long-term extreme responses prediction of a bottom-fixed OWT.

Figure 1. An artistic view of the SFC placed in water

In this paper extreme response prediction of different structural components has been performed for the combined concept SFC for two given European offshore sites with the use of the three aforementioned different methods, namely the FLTA, ECM and MECM, which is explained in detail in Section 3.2. A fully coupled numerical model is used for the long-term dynamic response analysis of the SFC. The presented response quantities include internal loads of: (a) blades, (b) shaft, (c) tower, (d) mooring lines and (e) arms of WECs. Moreover, extreme values of motions of the semisubmersible platform and WECs are presented. The long-term (50-year) extreme values are calculated with the use of the three different methods and are compared; the applicability and accuracy of these methods are discussed. Compared to the FLTA, the ECM gives an under-prediction of the long-term extreme values of the responses quantities dominated by aerodynamic loads while the MECM provides reliable results irrespectively of the excitation source.

2. The SFC and long-term response analyses

The combined concept SFC consists of: a) a semi-submersible floating platform with four columns (one central column and three side columns) and three pontoons connecting the side columns to the central column, b) a 5 MW wind turbine placed on the central column of the semi-submersible platform, c) three fully submerged rotating flap-type WECs hinged at the pontoons of the semisubmersible through two structural arms and linear PTO mechanisms and d) three catenary mooring lines positioned at the three side columns of the semisubmersible. The combined concept with two rotating flaps and a semi-submersible platform is shown in Fig. 2.

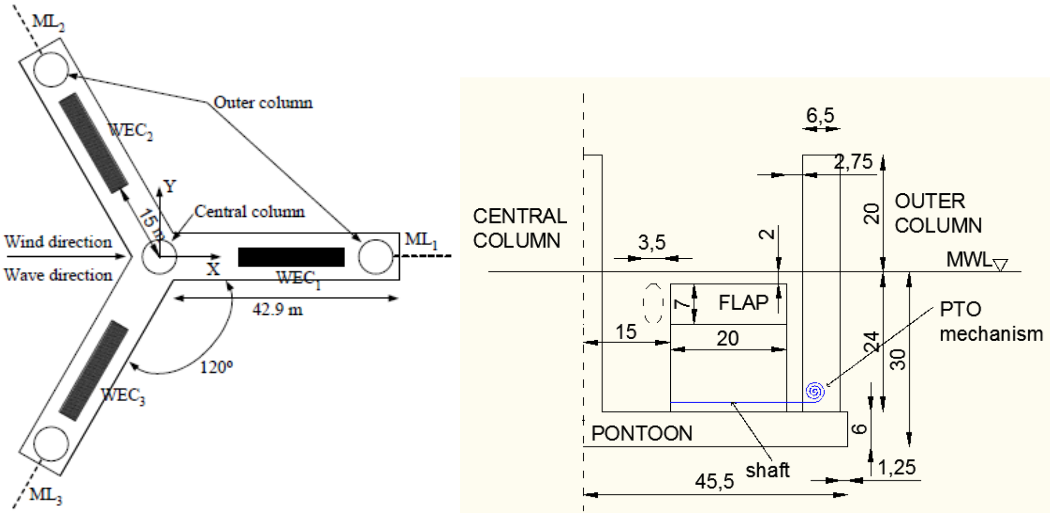

Figure 2. Bird- and side-views of the SFC illustration. The unit of the dimensions of the figure is meter.

The wind turbine of SFC will operate and produce power for environmental conditions with mean wind speed, Uw, in the range 2<Uw<25 m/s. For the rest wind speed cases the wind turbine is parked. With regard to the PTO of WECs, a constant value of PTO damping equal to 650 kN*m*s/deg is applied for all the examined environmental cases. It is noted that the extreme wind and wave environmental conditions may not lead to the long-term extreme responses.

In the present paper an FLTA analysis is performed for the SFC. For performing the FLTA analysis, a big number of different environmental cases are required. FLTA is performed for two different sites, the Site 14 and 15 of the MARINA Platform project (Lin et al. [17]). Site 14 is in the northern North Sea, off the Norwegian coast and has water depth of 200 m while Site 15 is in the North Sea, Denmark and has water depth of 40 m. All the examined environmental conditions represent a range of possible conditions for a given hub-height mean wind speed, Uw, that varies in the range between 2≤Uw≤52 m/sec and 2≤Uw≤42 m/sec for Site 14 and Site 15, respectively. The long-term environmental conditions are defined by the joint distribution of the Uw, Hs and Tp, where Hs is the significant wave height and Tp is the peak period of the JONSWAP spectrum that is used in order to simulate irregular waves. For all the examined wave spectra the peakedness factor is considered equal to 3.3. The turbulence intensity factor is selected based on the IEC 61400-3. Both wind and waves are considered aligned with mean direction that is parallel to the X axis ($\beta=0^o$) (Fig. 2). In total 1,530 and 728 different environmental conditions exist for Site 14 and Site 15, respectively. For every examined environmental condition ten different wind and wave seed numbers have been considered. As a result 15,300 and 7,280 different environmental cases have been analyzed for Site 14 and Site 15, respectively. Hs varies with a step of 1 m in the range $1 \leq Hs \leq 20$ m and $1 \leq Hs \leq 12$ m for Site 14 and Site 15, respectively, while, Tp varies with a step of 2 sec in the range between $2 \leq Tp \leq 24$ sec for both Site 14 and Site 15. For every environmental condition a one-hour (3,600 sec) simulation is performed in the present study. It is noted that the overall simulation time for each environmental condition is 4,100 sec; the first 500 sec involving the start-up analysis have not been considered.

Long-term (50-year) extreme response quantities of: (a) blades, shaft and tower of wind turbine, (b) mooring lines ML1 and ML2, (c) arm of WEC2 and (d) motions of semisubmersible platform are calculated and presented.

3. Numerical methods for extreme structural response analysis

3.1 Numerical model of SFC

The fully coupled multi body numerical simulations of the combined concept SFC in the time-domain for all the examined environmental conditions, are carried out using the coupled numerical analysis tool Simo[18]/Riflex[19]/AeroDyn (Ormberg and Bachynski[20]). In total four rigid bodies exist, the semisubmersible platform and the three flaps of the WECs, while other parts of the SFC are modeled as flexible beams. The following restrictions have been considered: (a) each WEC can rotate with respect to its rotational axis, (b) the motions and loads on the floating wind turbine and the WECs are fully coupled, (c) the effects of PTO system are included in the numerical model and (d) the environmental loads on the floating wind turbines and the WECs are well represented.

Simo/Riflex/Aerodyn is a state-of-the-art code for time domain numerical simulation of OWTs. The code is generic and a bigger number of rigid floating bodies interconnected can be handled sufficiently. For the case of SFC, slender elements such as blades, shaft of drive train, wind turbine tower, arms of flap-type WECs and catenary mooring lines, are modelled with the use of beam elements in

Riflex. The blades are connected to the tower through the shaft. The hub and nacelle are modeled as rigid bodies attached to the shaft and the top of the tower. Pitch control of the blades and the effect of the generator in the nacelle are added into the numerical model through a dll file. The torque of the generator is calculated by the dll file based on the rotational speed of the shaft. A flex joint is applied to the shaft to make the shaft able to rotate about the longitudinal axis of the shaft, while the loads on the blades, the hub and the shaft and the generator torque, can be transferred through the flex joint to the tower in the numerical model. With the use of flex joints the PTO of the WECs is numerically modeled and the semisubmersible platform is appropriately connected with the WECs. Hydrodynamic loads on semisubmersible platform and flaps of WECs are estimated using potential flow theory and Morison's formula. For the implementation of the coupled analysis in time domain the hydrodynamic interaction between the different rigid bodies, semisubmersible platform and flaps, numerically can be expressed with coefficients of: (a) added mass, (b) radiation damping and (c) excitation loads. The interaction coefficients of added mass and radiation damping between the different bodies (platform and flaps) are not considered in the analysis due to limitations of the tool Riflex.

Numerical analysis is dealt within Riflex and the equation of motion is solved in the time domain based on the following Equation:

$$R^I(\boldsymbol{r},\ddot{\boldsymbol{r}},t) + R^D(\boldsymbol{r},\dot{\boldsymbol{r}},t) + R^s(\boldsymbol{r},t) = R^E(\boldsymbol{r},\dot{\boldsymbol{r}},t) \qquad \text{(Eq.1)}$$

where $\mathbf{R}^{\mathrm{I}}$ is the inertia force vector, $\mathbf{R}^{\mathrm{D}}$ is the damping force vector, $\mathbf{R}^{\mathrm{S}}$ is the internal structural reaction force vector, $\mathbf{R}^{\mathrm{E}}$ is the external force vector and $\boldsymbol{r},\dot{\boldsymbol{r}},\ddot{\boldsymbol{r}}$ are the structural displacement, velocity and accelerations vectors. It is noted that all the force vectors are established by assembly of the element distributions and the specified discrete nodal forces of all different components of SFC. Equation 1 expresses a nonlinear system of differential equations due to displacement dependencies in the inertia and the damping forces between the external load vector and the structural displacement and velocity. In Luan et al.[21] further information and in depth discussion about the development of the numerical model of the SFC with the tool Simo/Riflex/AeroDyn as well as information about limitations of the used tools can be found.

3.2 Methods for long-term extreme prediction

3.2.1 Full long-term analysis (FLTA)

The full long-term analysis is an accurate method to determine the long-term extreme responses. The method integrates the product of the cumulative distribution function (CDF) of the short-term extremes (maximum response of a short-term process) and the probability of occurrence of its environmental condition to find the long-term CDF of the extremes. In this study, the one-hour extreme responses are used so the long-term (N-year) extreme response ξ using FLTA can be obtained as shown in Equation 2. It can also be re-written as Equation 3 if the exceedance probability is used instead of CDF. N is the return period in year. It should be noted that the one-hour short-term extreme is used in this study.

$$F_X^{LT}(\xi) = \iiint F_X^{ST}(\xi) f_{Uw,Hs,Tp}(u,h,t)dudhdt = 1 - 1/(N*365.25*24) \quad \text{(Eq.2)}$$

$$Q_X^{LT}(\xi) = \iiint Q_X^{ST}(\xi) f_{Uw,Hs,Tp}(u,h,t)dudhdt = 1/(N*365.25*24) \quad \text{(Eq.3)}$$

Though accurate, the FLTA is not efficient as it considers all possible environmental conditions among which many conditions contribute very little to the long-term extreme response. Thus, there are other simpler methods such as environmental contour method.

3.2.2 Environmental contour method (ECM)

The ECM is a simplified method for long-term extreme prediction. Its idea is to use a short-term extreme distribution to calculate the long-term result. For example, the ECM uses the short-term extreme response distribution of an environmental condition with 50-year return period to find the 50-year long-term extreme response. Such environmental conditions are called the "design sea state"s. The method in theory is based on the Inverse First-Order Reliability method (IFORM). The method can be described by Equation 4, where p is the empirical fractile level higher than 50% (e.g. 90%).

$$\xi = {F^{LT}}^{-1}\left(1 - \frac{1}{N*365.25*24}\right) \approx {F^{ST}}^{-1}(p|u_{ECM}, h_{ECM}, t_{ECM}) \quad \text{(Eq.4)}$$

To find the design sea state (u_{ECM}, h_{ECM}, t_{ECM}) for ECM, an "environmental contour" has to be created. The points on the contour are the environmental conditions with the same return period. The design sea state is found by checking the environmental conditions on the contour as the one with the largest value of the short-term extreme is considered the design sea states. Usually an empirical higher fractile such as 90% is often used rather than the 50% (median) of the short-term extreme distribution as the long-term prediction. Generally, only part of the contour (such as highest wind speed, highest wave height or important wave period for the response) needs to be checked.

The ECM requires the responses to be monotonically correlated to the important environmental parameters. For example, the responses should be increasing with the increase of wind speed or wave height, etc. For offshore wind turbines, this requirement may not be satisfied for some wind-dominated responses as they are usually higher within operational range and is lower at extreme wind speed when the turbine is parked. Thus, the ECM is not applicable for these responses. Similarly, if WECs also have operation/park conditions based on environmental parameters, ECM is also not applicable. However, the operation behavior of the WEC in this study is not dependent on environmental parameters.

3.2.3 Modified environmental contour method (MECM)

The MECM is a modification by including additional environmental contours inside of the one of the ECM. By checking these new contours, more environmental conditions that have lower return periods are also examined. Generally, whenever there is a change of the operational mode of the system at a certain environmental parameter (e.g. wind speed or wave height), an additional contour should be included. For wind turbines, an environmental contour with maximum mean wind speed of cut-out or rated wind speed can be added to account for extreme responses that occur during operation. The prediction of the MECM is to find and compare the design sea state for each contour. The one with the largest short-term extreme of all the environmental conditions on the contours is then used for the prediction. The SFC system should be treated similar to a wind turbine as it only changes the operational mode at cut-out wind speed (i.e. wind turbine operates/parks). Therefore, the environmental contour corresponds to the cut-out wind speed is added in addition to the original one of ECM with return period of N-year. The principle of MECM can be summarized by Equation 5. It should be noted that the short-term extreme CDF of the inner contours in Equation 5 are extrapolated to the N_o-year level from the original short-term CDF as shown by Equation 6, in which N is the required return period of the long-term extreme and N_o is the return period for the inner environmental contours. It is required because the inner contour has a lower return period and requires a much higher fractile level of the short-term extreme responses so that the total occurrence rate of the combination of the extreme response and environmental condition is the same (i.e. N-year). The largest value of the extreme responses from all the environmental contours is the result of MECM. Thus, MECM also includes the results of original ECM. Overall, MECM require more environmental conditions to be checked, but it is more reliable and conservative.

$$\xi_1 = {F_{N-yr}^{ST}}^{-1}(p1|u_{contour1}, u_{contour1}, u_{contour1})$$

$$\xi_2 = {F_{N-yr}^{ST}}^{-1}(p1|u_{contour2}, u_{contour2}, u_{contour3})$$

...

$$\xi_{ECM} = {F_{N-yr}^{ST}}^{-1}(p1|u_{ECM}, u_{ECM}, u_{ECM})$$

$$\xi \approx \max(\xi_1, \xi_2, \dots, \xi_{ECM}) \qquad \text{(Eq.5)}$$

$$F_{N-yr}^{ST}(\xi) = F^{ST}(\xi)^{N/N_o} \quad \text{(Eq.6)}$$

4. Results and discussion

The long-term extreme results using the three methods are presented and compared in this section. Since FLTA is considered as the most robust method, the FLTA is used as a reference to determine the performance of ECM and MECM. The responses considered are the axial forces and bending moments of the blades, shaft, tower, mooring lines and arms of the WEC. As explained in Section 3, the applicability of ECM depends on whether the extreme responses are monotonically correlated with the environmental parameters such as mean wind speed or significant wave height. For this study, the ECM should be applicable to the wave-governed responses of mooring line and WEC as they are monotonically correlated with mean wind speed and significant wave height as shown in Figure 3 and 4. The reason that wave-governed responses also increase with wind speed is the natural correlation between mean wind speed and significant wave height based on the long-term environmental statistical data.

On the other hand, the wind-governed responses of blade, shaft and tower generally have a "peak" in the operational wind speed range as shown in Figure 5, due to the higher wind load when wind turbine is in operation. As explained in Section 3.2.2, the ECM does not perform well for these responses shown and requires modification.

It should be noted that the responses of Figures 3 to 5 are all corresponds to the environmental parameters and their most probable (highest probability) conditions. For example, mean wind speed of 20 m/s in Figure 3 represents the environmental condition (Uw=20m/s, Hs=4m, Tp=10s). The environmental conditions for Figures 3 to 5 are shown in Table 1.

Table 1. Environmental conditions used for Figure 3 – 5. The value of Hs and Tp used are rounded to the nearest integer and even number respectively.

Uw [m/s]	Hs [m]	Tp [s]
2	1.6	12.1
4	1.7	11.6
6	1.9	11.3
8	2.1	11.0
10	2.4	10.8
12	2.8	10.7
14	3.2	10.7
16	3.7	10.8

18	4.2	10.8
20	4.7	11.0
22	5.4	11.1
24	6.0	11.3
26	6.7	11.5
28	7.5	11.7
30	8.3	11.9
32	9.1	12.2
34	10.0	12.4
36	11.0	12.7
38	11.9	12.9
40	13.0	13.2
42	14.0	13.4
44	15.1	13.7
46	16.3	14.0
48	17.5	14.2
50	18.7	14.5

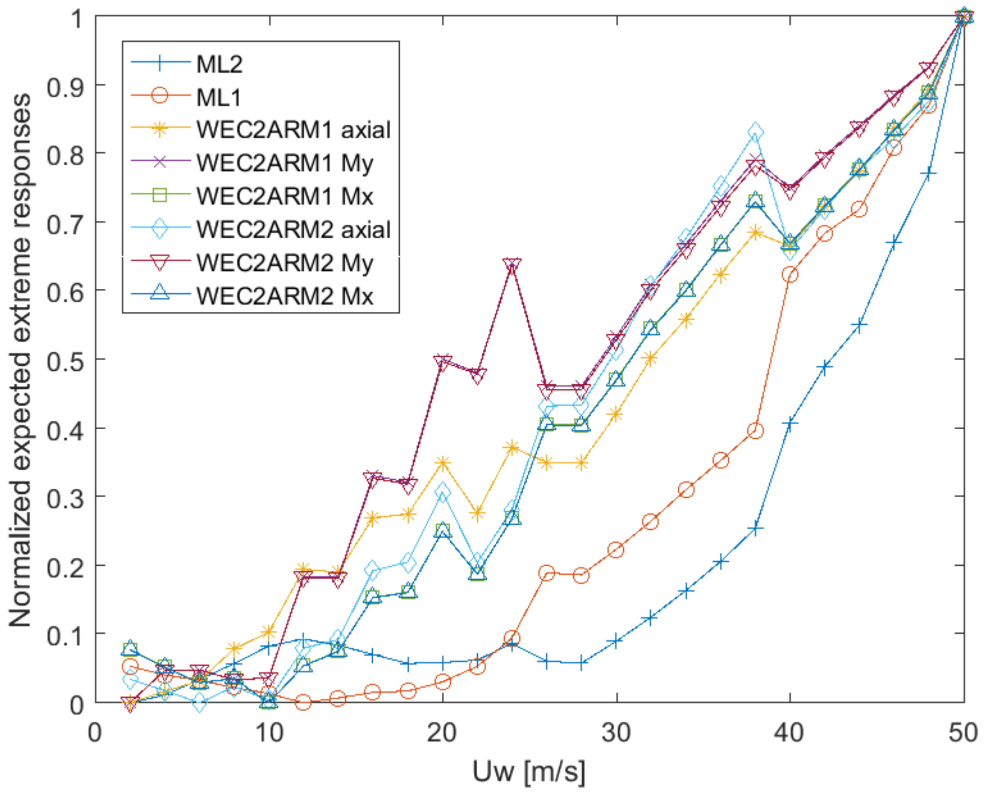

Figure 3. Wave-dominated (mooring lines and WEC) extreme responses vs. mean wind speed. The y-axis is the normalized value of the expected extreme responses for the corresponding mean wind speed (Uw) and its most probable sea state (Hs and Tp) for site 14. The relation will also be similar with Hs as Uw and Hs are positively correlated as shown in Figure 4.

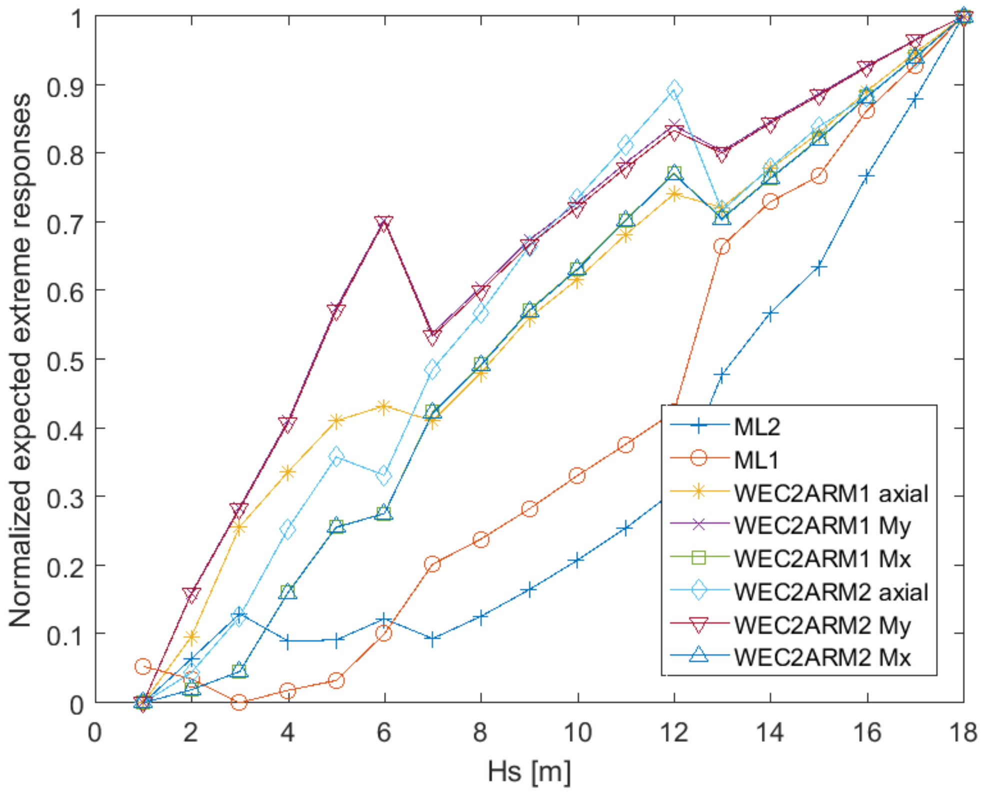

Figure 4. Wave-dominated (mooring lines and WEC) extreme responses vs. significant wave height. The y-axis is the normalized value of the expected extreme responses for the corresponding significant wave height (Hs) and its most probable wind speed (Uw) and peak spectral period (Tp) for site 14.

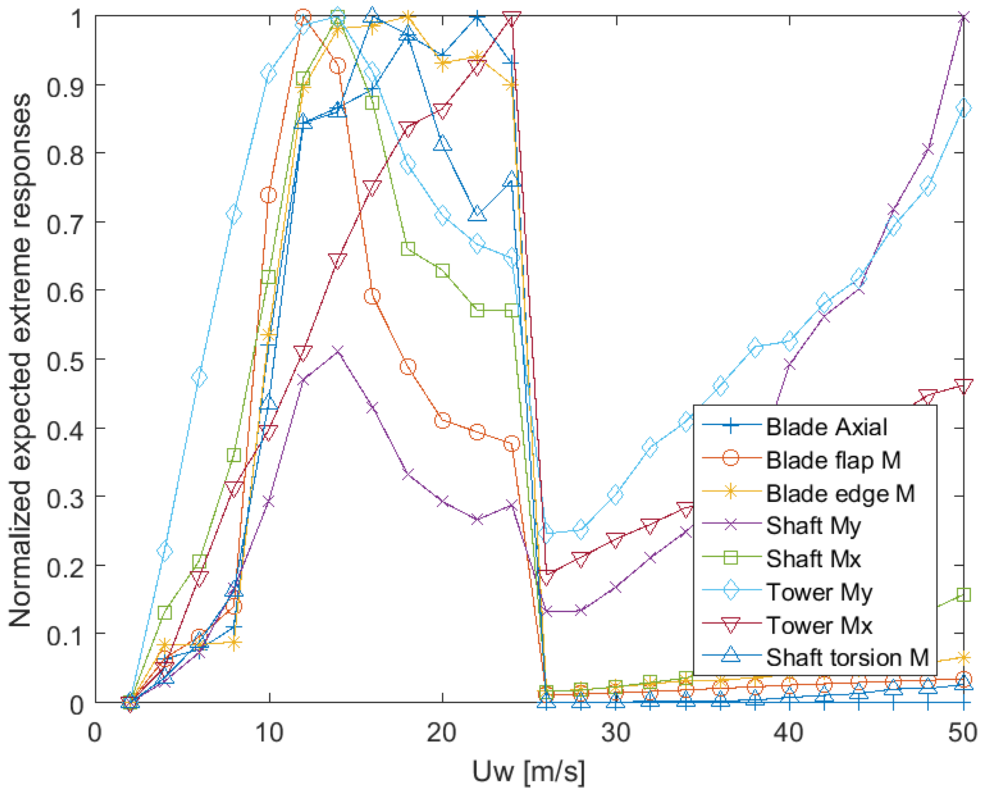

Figure 5. Wind-dominated (blade, shaft, and tower) extreme responses vs mean wind speed. The y-axis is the normalized value of the expected extreme responses for the corresponding mean wind speed (Uw) and its most probable sea state (Hs and Tp) for site 14. Peaks can be observed below cut-out wind speed (25 m/s).

4.1 Long-term extreme results of FLTA

The full long-term analysis provides the most accurate results compared to other simplified methods as it includes all the environmental conditions. The extreme structural response quantities of different parts of the SFC with the use of the FLTA method are shown in Table 2 and 3. In addition, Table 4 and 5 show the extreme motion responses predicted by FLTA method. These results are used as reference for comparison purposes in the Sections 4.2 and 4.3.

Table 2. Extreme response quantities in Site 14 with the use of the FLTA method. “Positive” and “Negative” indicates the direction of the extreme responses. For axial forces, “Positive” represents tension and “Negative” represents compression.

Response parameters (unit)	Positive	Negative
Blade axial force (kN)	3.82E+04	2.40E+04

Blade flapwise bending moment (kNm)	2.38E+05	2.38E+05
Blade edgewise bending moment (kNm)	1.68E+05	1.81E+05
Shaft torsional moment (kNm)	1.33E+05	1.49E+05
Shaft moment in y (kNm)	1.05E+08	1.10E+08
Shaft moment in x (kNm)	1.18E+08	9.96E+07
Tower axial force (kN)	-	8.15E+03
Tower moment in y (kNm)	2.20E+05	1.00E+05
Tower moment in x (kNm)	6.30E+04	4.29E+04
ML2 axial force (kN)	4.35E+03	-
ML1 axial force(kN)	4.92E+03	-
WEC2 arm1 axial force (kN)	3.10E+03	-
WEC2 arm1 bending moment in y (kNm)	1.81E+04	1.74E+04
WEC2 arm1 bending moment in x (kNm)	6.58E+03	6.17E+03
WEC2 arm2 axial force (kN)	2.84E+03	-
WEC2 arm2 bending moment in y (kNm)	1.83E+04	1.73E+04
WEC2 arm2 bending moment in x (kNm)	6.63E+03	6.20E+03

Table 3. Extreme response quantities in Site 15 with the use of the FLTA method. “Positive” and “Negative” indicates the direction of the extreme responses. For axial forces, “Positive” represents tension and “Negative” represents compression.

Response parameters (unit)	Positive	Negative
Blade axial Force(kN)	4.33E+04	2.88E+04
Blade flapwise bending moment (kNm)	2.10E+05	1.95E+05
Blade edgewise bending moment (kNm)	1.87E+05	2.01E+05
Shaft torsional moment (kNm)	1.58E+05	1.67E+05
Shaft moment in y (kNm)	1.07E+08	1.03E+08
Shaft moment in x (kNm)	1.10E+08	9.73E+07
Tower axial force (kN)	-	8.35E+03
Tower moment in y (kNm)	2.14E+05	8.79E+04
Tower moment in x (kNm)	6.74E+04	4.53E+04
ML2 axial force (kN)	3.35E+03	-
ML1 axial force(kN)	3.57E+03	-
WEC2 arm1 axial force (kN)	2.87E+03	-
WEC2 arm1 bending moment in y (kNm)	1.43E+04	1.45E+04
WEC2 arm1 bending moment in x (kNm)	5.38E+03	5.25E+03
WEC2 arm2 axial force (kN)	2.71E+03	-
WEC2 arm2 bending moment in y (kNm)	1.44E+04	1.43E+04
WEC2 arm2 bending moment in x (kNm)	5.39E+03	5.27E+03

Table 4. Extreme motion response quantities in site 14 with the use of FLTA method. “x”, “y”, and “z” are the translational motion in x, y, and z direction. “rx”, “ry”, and “rz” are the rotational motion. “Positive” and “Negative” indicates the direction of the extreme responses.

Response parameters (unit)	Positive	Negative

x (m)	1.57E+01	5.49E+00
y (m)	1.44E+00	2.00E+00
z (m)	6.04E+00	7.01E+00
rx (deg)	4.15E+00	2.21E+00
ry (deg)	1.60E+01	4.10E+00
rz (deg)	4.42E+00	5.68E+00

Table 5. Extreme motion response quantities in site 15 with the use of FLTA method. “x”, “y”, and “z” are the translational motion in x, y, and z direction. “rx”, “ry”, and “rz” are the rotational motion. “Positive” and “Negative” indicates the direction of the extreme responses.

Response parameters (unit)	Positive	Negative
x (m)	1.50E+01	3.50E+00
y (m)	1.17E+00	1.95E+00
z (m)	4.20E+00	4.59E+00
rx (deg)	4.11E+00	2.18E+00
ry (deg)	1.57E+01	3.10E+00
rz (deg)	4.46E+00	5.49E+00

4.2 Long-term extreme results of ECM

The prediction of ECM in this study is the commonly used 90% fractile level of the short-term extreme responses on the 50-year environmental contour. The results of ECM are presented in Figure 3 and 4, which show the percentage difference with the FLTA results, so the values that are closer to the FLTA results (i.e. 0%) suggest a better performance. Positive values also indicate that the ECM predictions are more conservative. It is assumed here that predictions within 10% difference are considered to be acceptable.

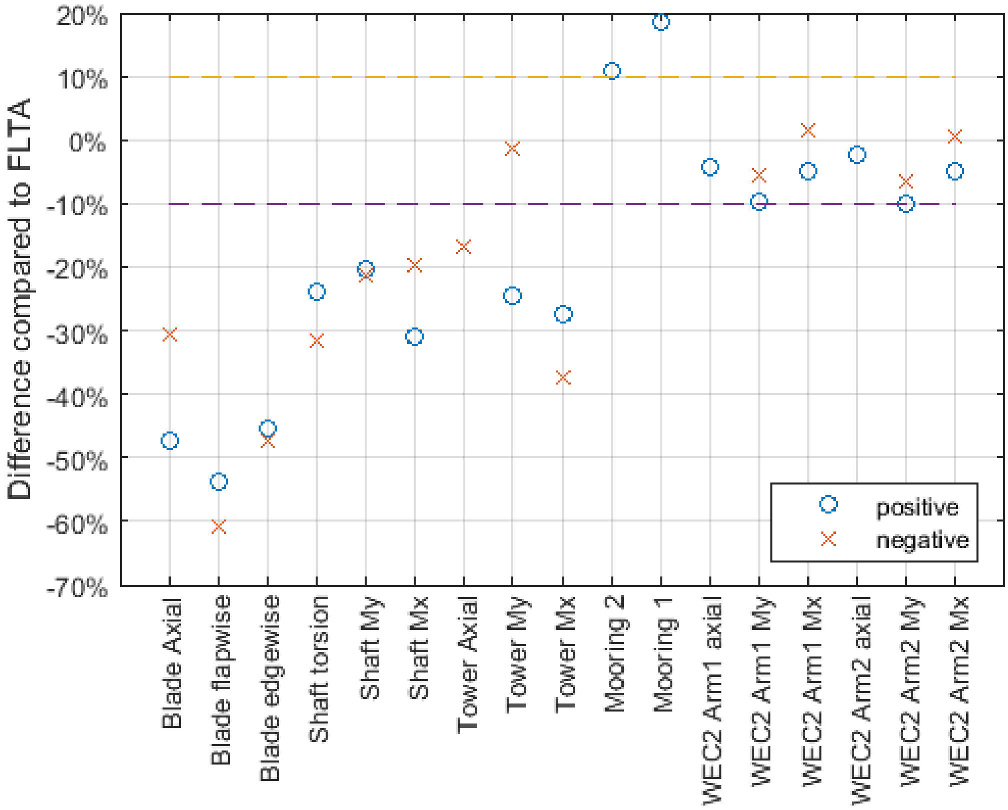

Figure 6. ECM percentage differences for structural responses compared to FLTA for Site 14. For axial forces, “Positive” represents tension and “Negative” represents compression.

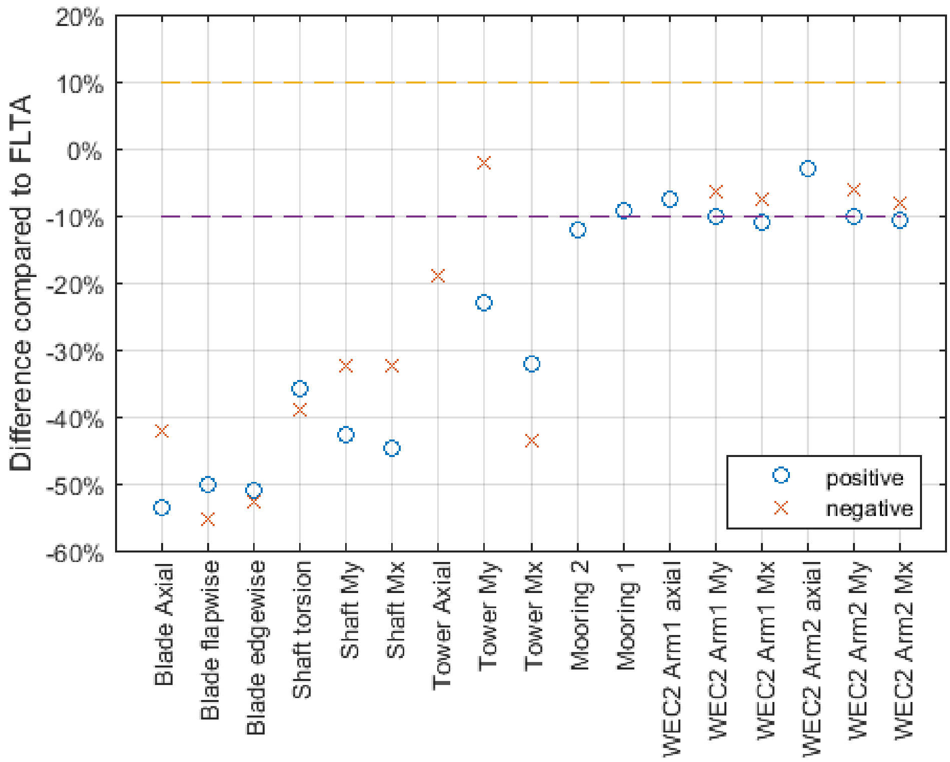

Figure 7. ECM percentage differences for structural responses compared to FLTA for Site 15. For axial forces, “Positive” represents tension and “Negative” represents compression.

Figure 6 and 7 show that the ECM performance for structural responses is very similar for both sites. It can be seen that ECM performs well for responses of mooring lines and internal loads of arm of WEC2, with all of them very close or above the -10% threshold value as these responses are mainly governed by wave load effects. As expected, the ECM is not suitable for responses that are wind-dominated, including blades, shaft and tower responses, which is also included in Figure 5. The ECM generally under-predicts these responses, especially for blade responses with under-prediction of around 50%.

Based on the results, the ECM is not applicable for wind-dominated responses and requires modifications. It can also be seen that the ECM performance is similar for both Sites 14 and 15, which means that the applicability of ECM is considered as site independent. Figure 6 also shows an over-prediction of around 20% for mooring line responses for Site 14. The reason is that the actual fractile level is around 50% for this response and the commonly used empirical fractile level of 90% will thus lead to an over-prediction. However, this over-prediction is acceptable as it is still conservative.

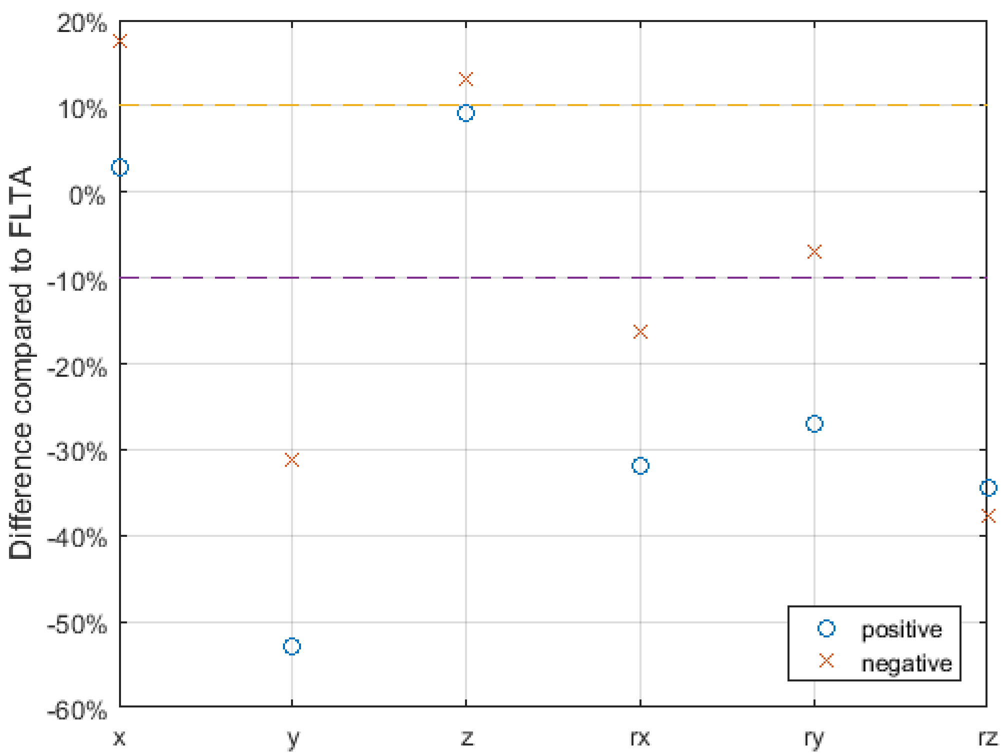

Figure 8. ECM percentage differences for extreme motion responses compared to FLTA for Site 14.

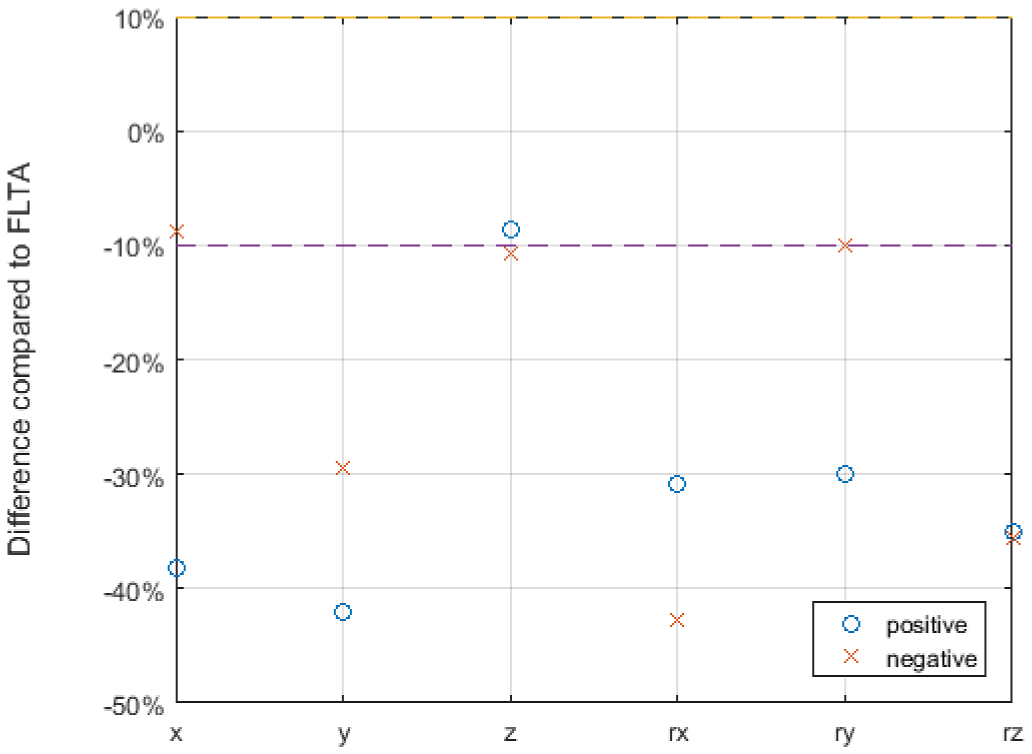

Figure 9. ECM percentage differences for extreme motion responses compared to FLTA for Site 15.

In addition to the structural responses, Figure 8 and 9 display the ECM performance for extreme motion responses for site 14 and 15 respectively. Similarly, it can be seen that ECM can estimate the heave motion (z) for both sites but under-predicts for other motions as they are more affected by wind turbine loads. Thus, the MECM is required to achieve a close prediction to the FLTA results for the wind-dominated extreme structural and motion responses.

4.3 Long-term extreme results of MECM

Compared to ECM, MECM includes another environmental contour corresponding to the cut-out wind speed, which aims to improve the performance of long-term extreme predictions of wind-dominated responses. The results of MECM are the combination of the 90% fractiles of the short-term extreme distribution of the environmental conditions from 50-year contour and the 50% fractiles of the extrapolated short-term extreme distribution of the cut-out wind speed contour.

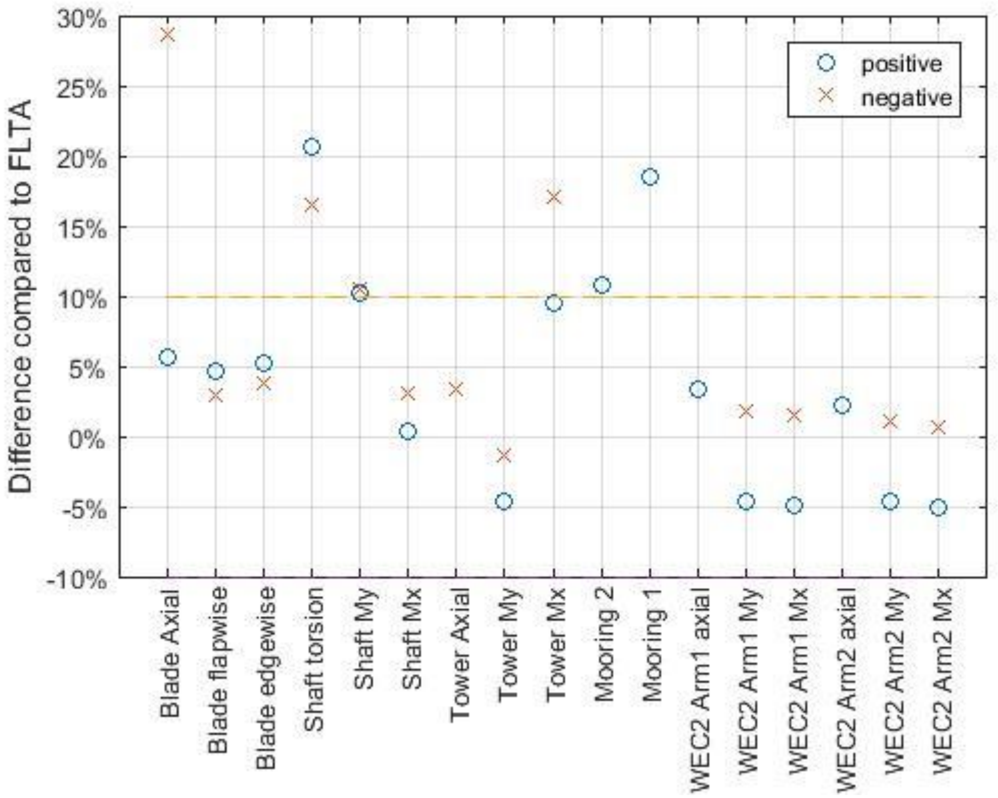

Figure 10. MECM percentage differences compared to FLTA for Site 14. For axial forces, "Positive" represents tension and "Negative" represents compression.

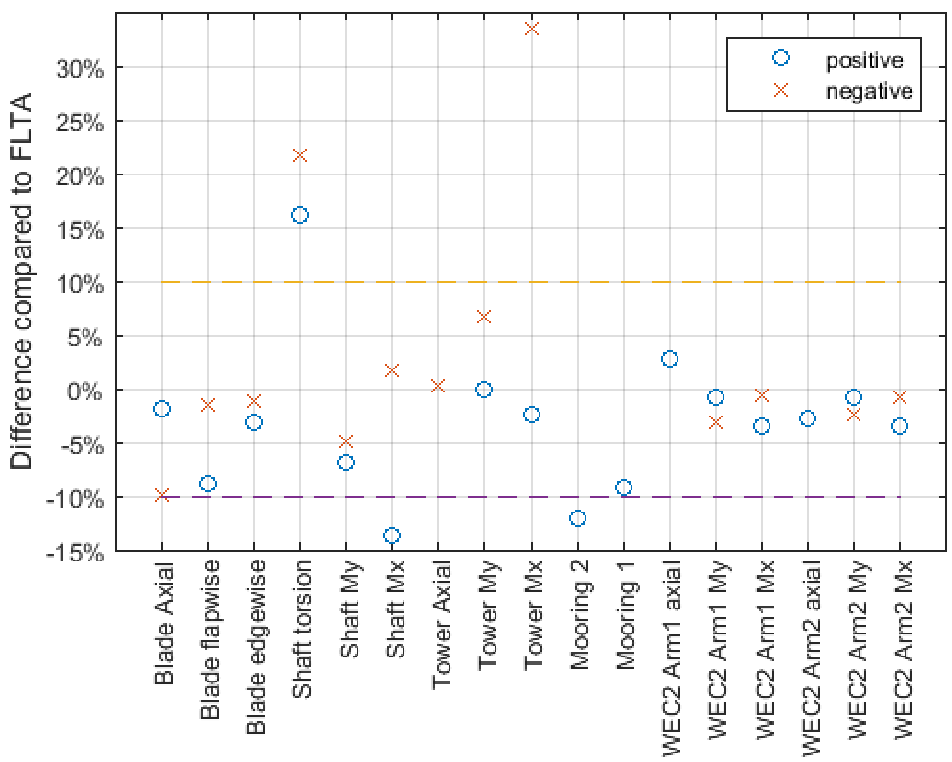

Figure 11. MECM percentage differences compared to FLTA for Site 15. For axial forces, “Positive” represents tension and “Negative” represents compression.

Figures 9 and 10 show the percentage differences of the extreme structural responses predicted by MECN and FLTA. Compared to Figures 3 and 4, it can be seen that MECM improves the prediction for the responses that are wind-dominated, which includes the blade, shaft and tower responses. The large under-estimations of ECM are reduced to around 10%. Overall, the MECM is able to provide predictions of the long-term extremes close to the FLTA results with a maximum percentage difference of 10% for all the responses. In this study, the improvement of the MECM can reduce the under-prediction of ECM by around 30% in average.

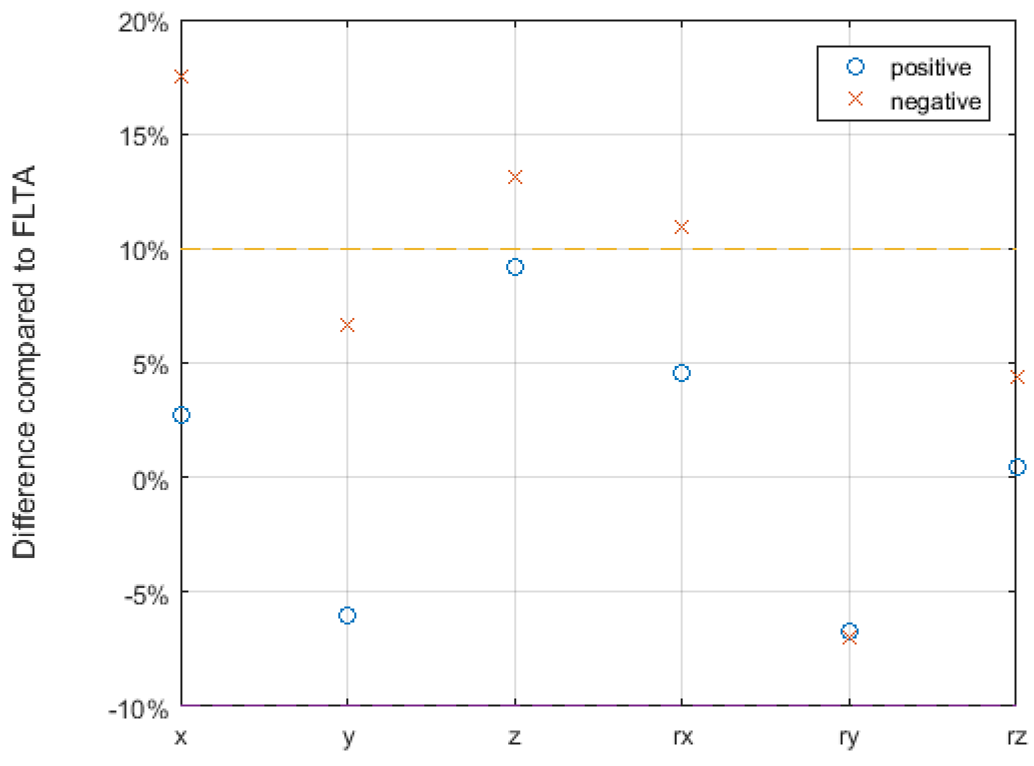

Figure 12. MECM percentage differences for extreme motion responses compared to FLTA for Site 14.

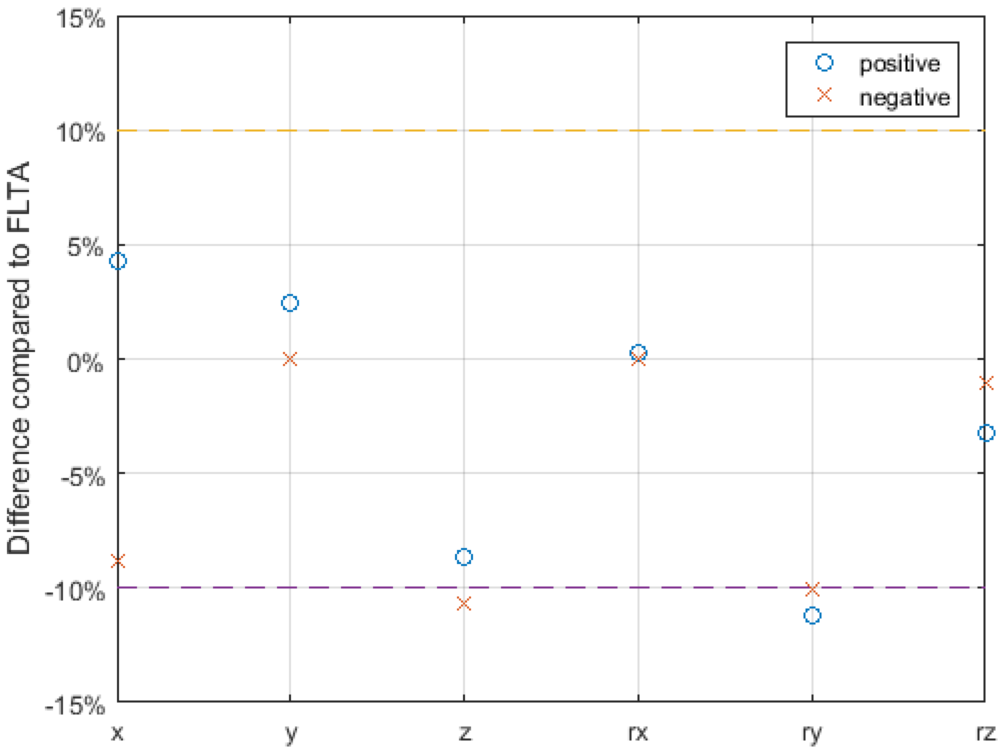

Figure 13. MECM percentage differences for extreme motion responses compared to FLTA for Site 15.

Figures 11 and 12 show the percentage differences of the extreme motion responses predicted by MECN and FLTA for site 14 and 15 respectively. As explained in Section 4.2, the heave response (z) can already be well-predicted by ECM. Similar to the structural responses, the MECM improves the long-term extreme prediction for the other responses as well by reducing the difference between FLTA and MECM results to be within 10%.

4.4 Environmental conditions found by ECM and MECM (design sea states)

The ECM and MECM identify the most important environmental condition (design sea states) on each contour for each extreme structural and motion response and the short-term extreme of these environmental conditions are used to calculate the long-term results. In the previous studies on the application of ECM and MECM to bottom-fixed and semisubmersible wind turbines, it is found that the "tip" region of the contours corresponding to the highest mean wind speed and significant wave heights usually contains the design sea states for structural responses of wind turbines.

Figures 14 to 17 show the design sea states as estimated for this study. For ECM (50-year contour), the same trend can be found for both Sites 14 and 15 that all the design sea states are located near the tip area where mean wind speed and significant wave heights are the highest. However, for MECM, some design sea states are located away from the high wind and wave area as shown in Figure 15 and 16. These design sea states corresponds to the structural responses of blade flap-wise bending moment, tower bending moment, and shaft responses. The reason for their different location is explained in Figure 18, which shows the relation of the expected short-term extreme responses and the mean wind speed. It can be seen that their peak is located around 12 to 16 m/s, which is closer to the rated wind speed (11.4 m/s) of the wind turbine. Thus their design sea states are also further away from the tip region of the environmental contours.

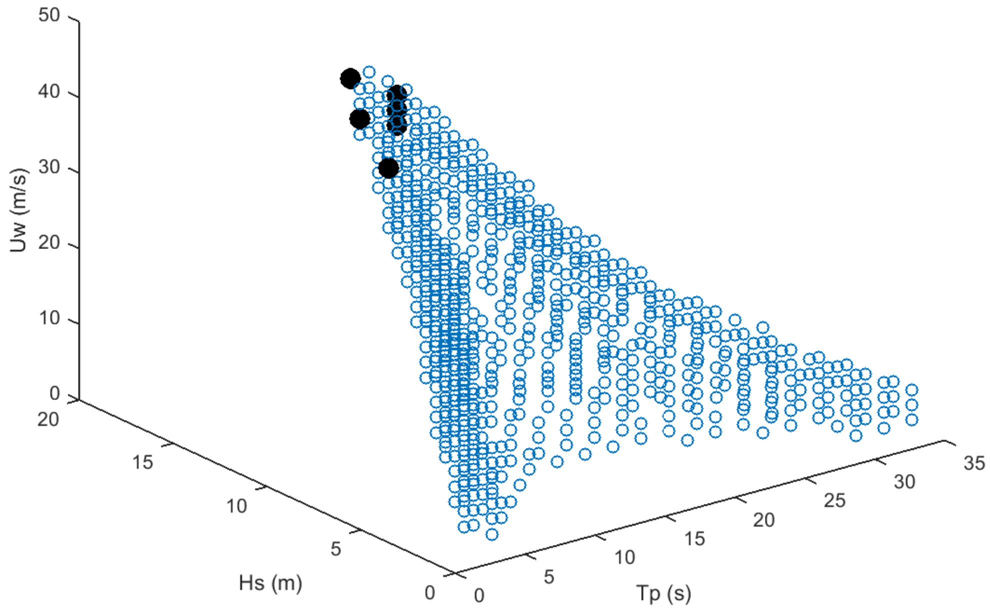

Figure 14. Design sea states on the 50-year contour of site 14 for ECM and MECM. For this contour, ECM and MECM have the same design sea states. The blue circles represent all the environmental conditions on the contour and the black dots are the design sea states. It should be noted that some design sea states corresponds to several responses.

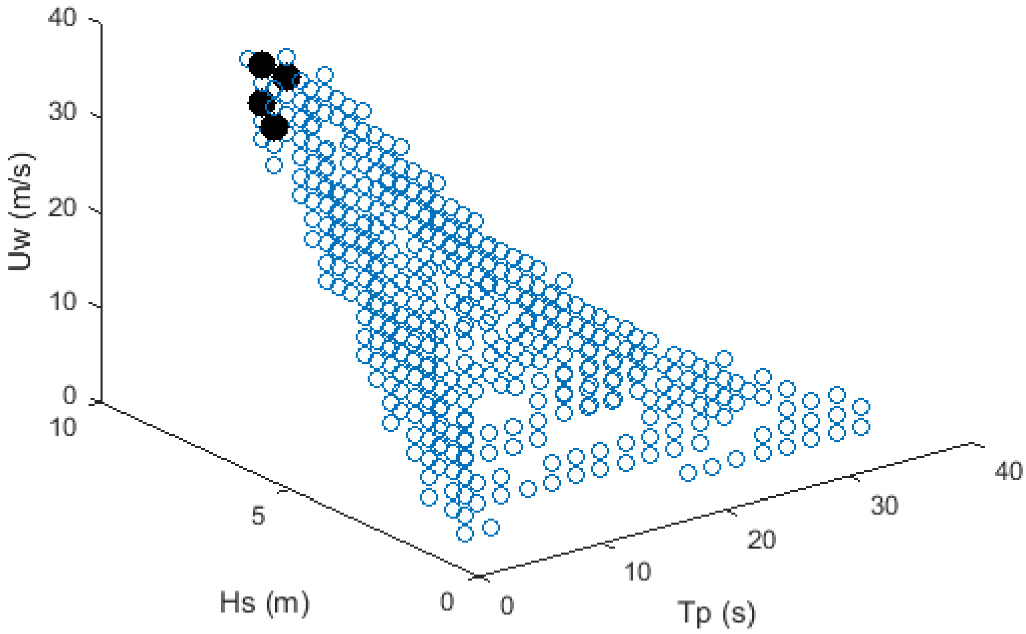

Figure 15. Design sea states on the 50-year contour of site 15 for ECM and MECM. The blue circles represent all the environmental conditions on the contour and the black dots are the design sea states. It should be noted that some design sea states corresponds to several responses.

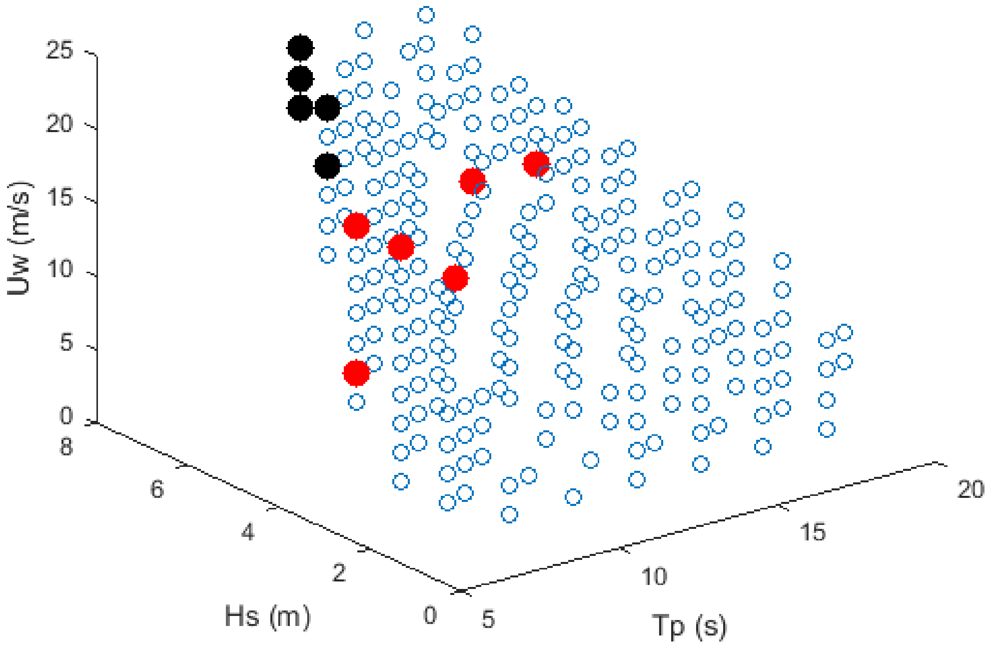

Figure 16. Design sea states on the cut-out wind speed contour of site 14 for MECM. The blue circles represent all the environmental conditions on the contour and the black dots are the design sea states near the tip (high Uw and Hs region). The red dots are the design sea states that are further away from the tip. It should be noted that some design sea states corresponds to several responses.

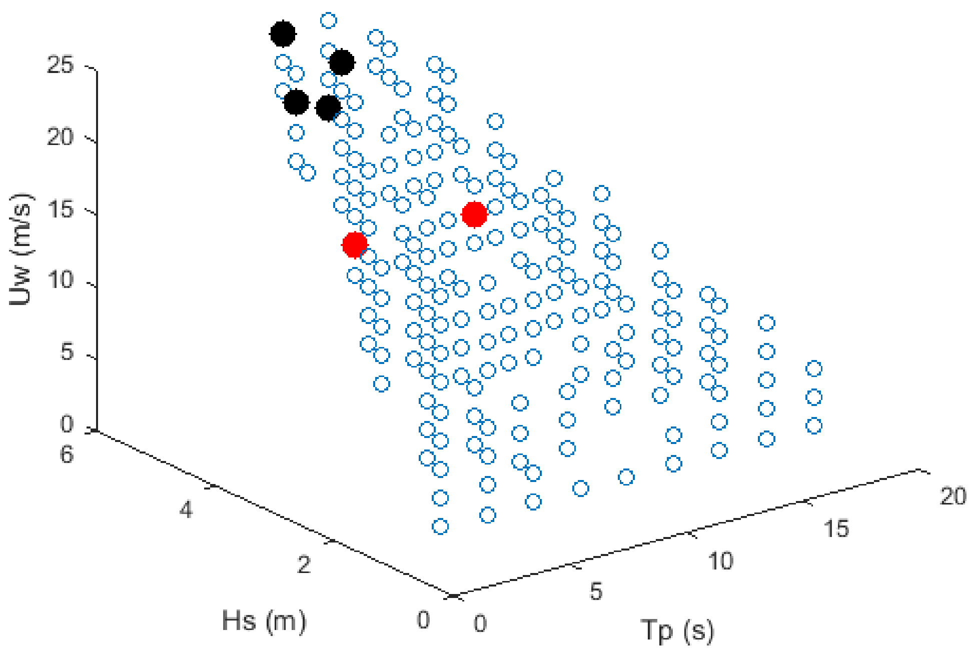

Figure 17. Design sea states on the cut-out wind speed contour of site 15 for MECM. The blue circles represent all the environmental conditions on the contour and the black dots are the design sea states near the tip (high Uw and Hs region). The red dots are the design sea states that are further away from the tip. It should be noted that some design sea states corresponds to several responses.

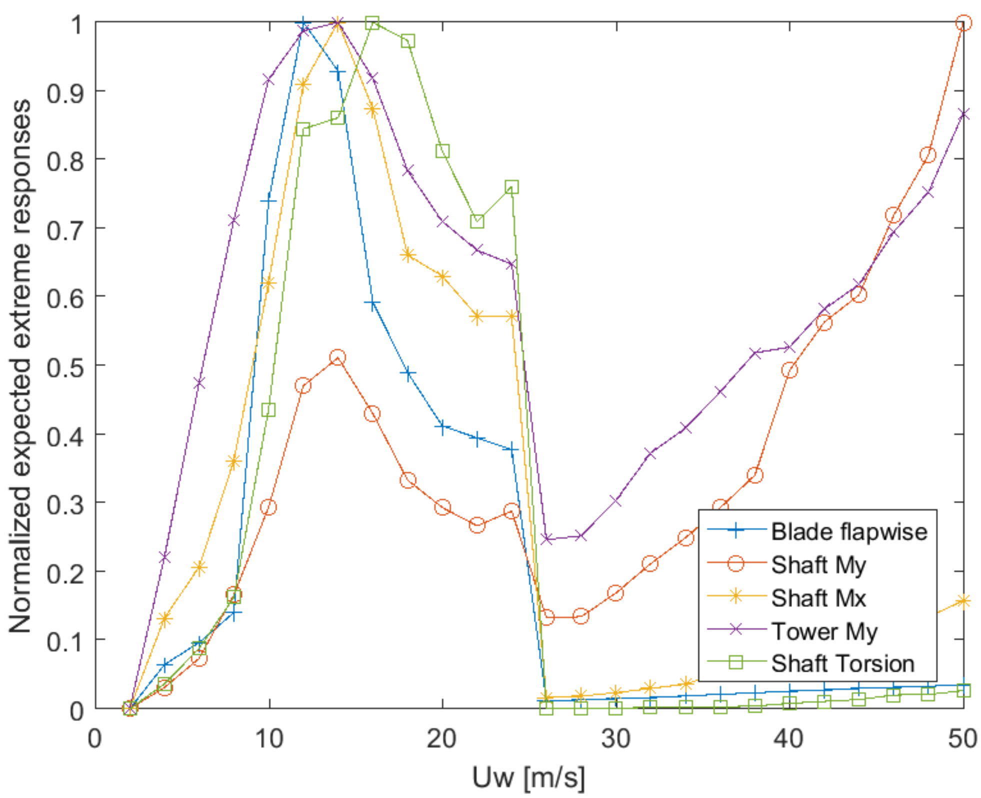

Figure 18. Extreme responses (blade flapwise, tower and shaft bending moments) vs mean wind speed. The y-axis is the normalized value of the expected extreme responses for the corresponding mean wind speed (Uw) and its most probable sea state (Hs and Tp) for site 14.

5. Conclusions

In this paper, different methods for predicting long-term extreme responses considering the wind and wave conditions at two given European offshore sites are carried out and structural response quantities are calculated, compared and presented. A full long term analysis (FLTA) was performed and regarded as the reference method, and its results are compared with the results of environmental contour methods (ECM and the MECM). The efficiency of ECM and MECM for predicting the long-term extreme structural and motion responses of the combined concept SFC was examined by comparing the results of the ECM and MECM with those of the FLTA,. The original ECM was found to work well for wave-dominated responses (e.g. mooring lines and WEC) but greatly under-predict the long-term extremes of the wind-dominated responses (e.g. of blades, shaft, tower). MECM can effectively and efficiently improve the performance for wind-dominated response by introducing another environmental contour (corresponding to the cut-out wind speed) inside the original one with 50-year return period. The long-term extreme response prediction of MECM is very close to the reference results of the FLTA, i.e. with under-predictions less than 10%.

It is also found that the design sea states (most important environmental conditions) for ECM/MECM are generally located at the “tip” of the environmental contour where mean wind speed and significant wave height for most responses. However, the responses of the blades and shaft have design sea states further away from the tip of the cut-out wind speed contour. Thus, it is necessary to check a larger area of the environmental contour of the cut-out wind speed instead of just the tip region.

In general, it was found that the MECM can efficiently provide accurate the long-term extreme structural and motion responses for the combined WT and WEC system considered in this study.

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