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Prediction of long-term extreme response of two-rotor floating wind turbine concept using the modified environmental contour method

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ABSTRACT

The modified environmental contour method (MECM) is assessed for the prediction of 50-year extreme response of a two-rotor floating wind turbine concept (2WT) deployed in two offshore sites in the northern North Sea (Norway 5) and the North Atlantic Ocean (Buoy Cabo Silleiro). The sites considered are in areas known for their floating wind development potential. The environmental contour method (ECM) is used to reduce the computational effort of full long-term analysis (FLTA) by only considering environmental conditions associated with a given return period. MECM is a modification of the ECM where additional environmental contours are included to account for discontinuous operation modes of dynamic structures. The results obtained in MECM are benchmarked against FLTA results and compared to ECM results. ECM leads to large underpredictions of responses governed by wind loads if compared to FLTA, as it is not capable of taking into account important operational modes of the 2WT. It is found that MECM, which includes the wind turbines cut-off contour, is able to reduce most response underpredictions within 15% difference compared to FLTA results. MECM may thus be considered as a sufficiently accurate and computationally efficient method for the long-term extreme analysis of 2WT concepts.

1. Introduction

Floating offshore wind turbine concepts (FOWTs) should be designed to withstand extreme environmental loading. The most accurate method for the prediction of long-term extreme responses is the full long-term analysis (FLTA). This approach directly integrates the probability distribution of all short-term extreme responses and their associated environmental conditions. However, FLTA is also computationally demanding due to the bulk response evaluation of all the relevant environmental conditions. In the last decade, more efficient methods able to evaluate extreme long-term responses with a sufficient level of accuracy have been investigated. The most widely used alternative to reduce the environmental cases to be evaluated is the environmental contour method (ECM) [1]. This method predicts the long-term extreme response by considering the short-term extreme distribution of only significant conditions lying on the environmental contour surface with the same return period as the long-term extreme response. However, the operational space of offshore wind turbines (OWTs) is highly discontinuous. The cut-in and cut-out wind speed limits, as well as full loading at rated conditions, entail a discontinuity of the environment-structural load relationship. ECM assumes the design load cases to lie nearby the environmental contour surface. Consequently, pure ECM is found to greatly under-estimate the long-term extreme responses of OWTs and FOWTs [2,3].

The modified environmental contour method (MECM), proposed by Li et al. [3], is a modification of the ECM that takes into account multiple contours in addition to the one associated with the ECM return period. The method allows for the employment of environmental contours in structures with a discontinuous environment-load condition.

MECM has been successfully employed to assess the long-term extreme response of a variety of offshore structures, including bottom-fixed OWTs [3], semi-submersible FOWTs [4], and combined wind turbine and wave energy converter systems (WECs) [5]. However, no MECM assessment for the analysis of multi-rotor floating wind turbine systems is to date available in the relevant literature. Knowledge of the validity of MECM results is of great practical utility given the significant reduction of the time needed for simulation and analysis.

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In this paper, the extreme long-term response of a spar-type two-rotor floating wind turbine concept (2WT) is analyzed by means of the MECM for two different offshore sites in the North Atlantic Ocean and the northern North Sea. The offshore sites considered in this work are in areas well known for their floating wind development potential [6]. The accuracy of MECM results is assessed by comparing them with results obtained from the complete FLTA and the more general ECM.

2. Overview of environmental long-term joint distributions

A detailed exposition of long-term joint distribution assessment can be found in Li et al. [7]. Long-term extreme response analysis is based upon the joint distribution of the environmental parameters of a particular offshore site. That is, for each specific environmental condition it is necessary to define the associated long-term probability of occurrence given a return period, e.g., 50 years. A large amount of data is normally necessary to estimate the environmental distributions. To get accurate joint distribution fittings it is suggested to use at least ten years datasets [8]. It is assumed that the short-term responses are sequential and stationary [7]. It is customary to define the joint distribution given by the average wind speed, U_w, the significant wave height, H_s, and the significant wave period, T_p, by means of a marginal distribution of U_w, a conditional distribution of H_s given U_w, and a conditional distribution of T_p given both H_s and T_p

$$f_{U_w,H_s,T_p}(u,h,t) = f_{U_w}(u) f_{H_s|U_w}(h|u) f_{T_p|U_w,H_s}(t|u,h) \tag{1}$$

where f denotes the probability density function operator (PDF). $f_{U_w,H_s,T_p}(u,h,t)$ is the joint PDF of environmental conditions at a specific offshore site. In other words, $f_{U_w,H_s,T_p}(u,h,t)$ gives the relative likelihood that a specific offshore site will experience a given environmental condition (u, h, t). Integration of the joint PDF over the environmental space yields unity by definition, $\int f_s(s)ds = 1$ [where s is the generalized environmental variable].

The average wind speed marginal distribution is found to be best fitted by means of a two-parameter Weibull distribution, which can be described as

$$f_{U_w}(u) = \left[\frac{\alpha_U}{\beta_U}\left(\frac{u}{\beta_U}\right)^{\alpha_U - 1}\right] exp\left[-\left(\frac{u}{\beta_U}\right)^{\alpha_U}\right] \tag{2}$$

where α_U and β_U are the fitting shape and scale parameters of the distribution, respectively. The conditional PDF of H_s given U_w is also fitted by means of a two-parameter Weibull distribution

$$f_{H_s|U_w}(h|u) = \left[\frac{\alpha_{HC}}{\beta_{HC}}\left(\frac{h}{\beta_{HC}}\right)^{\alpha_{HC} - 1}\right] exp\left[-\left(\frac{h}{\beta_{HC}}\right)^{\alpha_{HC}}\right] \tag{3}$$

where α_{HC} and β_{HC} are the fitting shape and scale parameters of the distribution, respectively. They are fitted by means of power functions

$$\alpha_{HC} = a_1 + a_2 u^{a_3} \tag{4}$$

$$\beta_{HC} = b_1 + b_2 u^{b_3} \tag{5}$$

where the constants a_1, a_2, a_3, b_1, b_2, b_3 are determined from data fitting. The conditional distribution of T_p given H_s and U_w is fitted by means of a lognormal distribution

$$f_{T_p|U_w,H_s}(t|u,h) = \frac{1}{\sqrt{2\pi}\sigma_{ln(T_p)} t} exp\left[-\frac{1}{2}\left(\frac{ln(t) - \mu_{ln(T_p)}}{\sigma_{ln(T_p)}}\right)^2\right] \tag{6}$$

where $\mu_{ln(T_p)}$ and $\sigma_{ln(T_p)}$ are the mean value and standard deviation defining the lognormal distribution. They are defined as

$$\mu_{ln(T_p)} = ln\left(\frac{\mu_{T_p}}{\sqrt{1 + \nu_{T_p}^2}}\right) \tag{7}$$

$$\sigma^2{}_{ln(T_p)} = \ln\left(\nu^2{}_{T_p} + 1\right) \tag{8}$$

$$\nu_{T_p} = \frac{\sigma_{T_p}}{\mu_{T_p}} \tag{9}$$

The mean value of T_p is computed as

$$\mu_{T_p} = \bar{t}(h)\left[1 + \theta\left(\frac{u - \bar{u}(h)}{\bar{u}(h)}\right)^\gamma\right] \tag{10}$$

where θ and γ are fitting coefficients, and $\bar{t}(h)$ and $\bar{u}(h)$ are the expected peak period and average wind speed fitted as power functions

$$\bar{t}(h) = e_1 + e_2 h^{e_3} \tag{11}$$

$$\bar{u}(h) = f_1 + f_2 h^{f_3} \tag{12}$$

where the constants e_1, e_2, e_3, f_1, f_2, f_3 are determined from data fitting. $\nu_{T_p}(h)$ may also be assumed only correlated with H_s. In this case the fitting can be described as follows

$$\nu_{T_p}(h) = k_1 + k_2 exp(hk_3) \tag{13}$$

where the constants k_1, k_2, k_3 are determined from data fitting. Empirical fitting parameters for the marginal distribution of U_w, the conditional distribution of H_s given U_w, and the conditional distribution of T_p given both U_w and H_s at different offshore sites can be found in Li et al. [7].

3. Overview of long-term extreme methods

3.1. Full long-term analysis (FLTA)

The most accurate method to estimate the long-term extreme responses of offshore structures is the full long-term analysis (FLTA). FLTA is mostly used as a benchmark reference to more simplified methods. The method combines the short-term extreme response distribution associated with all the environmental conditions for a given return period and their corresponding probability of occurrence. The long-term distribution can be established by integrating the product of the short-term extreme response cumulative distribution functions (CDF) and the long-term PDF of the environmental conditions associated with a particular offshore site

$$F_X^{LT}(\xi) = \iiint F_{X|U_w,H_s,T_p}^{ST}(\xi|u,h,t) f_{U_w,H_s,T_p}(u,h,t) du dh dt \tag{14}$$

Equation (14) is the standard representation of the full long-term analysis [1]. X is a given response variable. F_X^{LT} and $F_{X|U_w,H_s,T_p}^{ST}$ are the long-term and short-term CDFs associated with the variable X. That is, they represent the probability that X will assume a value lesser or equal than ξ. The short-term extreme response probability distribution is often approximated by means of a Gumbel fit of the maxima of n realizations of random seeds [1]. It is customary to use Gumbel distributions to fit extreme data (also denoted as extreme value distribution - type I) [4]. The Gumbel distribution can be defined as:

$$F^{ST}(x) \approx e^{-e^{-(x-\mu)/\beta}} \tag{15}$$

where μ and β are, respectively, the location and scale parameters, which can be estimated by means of the method of moments [9]

$$\mu = \bar{x} - \gamma\beta \tag{16}$$

$$\beta = \sqrt{6}s_x \Big/ \pi \tag{17}$$

where γ is the Euler-Mascheroni constant ($\gamma \approx 0.57722$), $\bar{x}$ is the mean of the extreme values, and s_x is the standard deviation of the extreme values. If a reference time duration of 1-h is used, the full-long term extreme response can then be estimated by means of the inverse relationship

$$\xi^* = F_X^{LT^{-1}}(1 - 1\,/\,(N{*}365{*}24)) \tag{18}$$

where N is a given return period in years. From Equation (14) it is clear that FLTA entails the integration of a large number of environmental states. This method is thus extremely time-consuming. A great effort has been put by many researchers in designing more cost-effective methods to estimate extreme responses of offshore structures, such as the ECM [1] and MECM [3].

3.2. Environmental contour method (ECM)

ECM stems from the more general inverse first-order reliability method (IFORM) [10]. In contrast to IFORM, ECM does not consider the variability of the extreme response [4]. Consequently, the contour can be fully described in the environmental space. As already discussed, ECM assumes that the extreme response is found along a surface constructed within the environmental space (i.e., U_w, H_s, T_p) and associated with the desired return period, e.g., 50 years. The environmental condition along the contour surface which yields the largest short-term response is designated as design point. High empirical percentiles are used in order to take into account the omission of the short-term extreme response variability [4,11]. Percentiles values between 70% and 90% are normally used.

ECM is based on Rosemblatt transformation [12], whereby site-specific environmental PDFs are combined with the projection of a normal CDF into a gaussian space (U-space) associated with the desired return period. The U-space thus defined has the same number of dimensions of the environmental space. That is, the environmental space (U_w, H_s, T_p) is transformed into the U-space (U_1, U_2, U_3).

Fig. 1 depicts a graphical representation of the ECM procedure. The steps required to establish an EC may be described as follows. First, a desired return period N is defined, e.g., 50 years. The hourly exceedance probability, p_f, can then be defined as

$$p_f = \frac{1}{365.25{*}24{*}N} \tag{19}$$

The associated non-exceedance probability, $1 - p_f$, can then be used to compute the Gaussian variable, β, corresponding to the desired return period (Fig. 1a)

$$\beta = \Phi^{-1}(1 - p_f) \tag{20}$$

where Φ is the standard Gaussian CDF operator ($\mu = 0, \sigma = 1$). In the U-space, the distance of a point to the origin corresponds to the associated return period. Therefore, a sphere of radius β may be established to define all the environmental conditions associated with the return period N (Fig. 1b). The relationship between the environmental variables in the gaussian space (U_1, U_2, U_3) and the environmental variables in the physical space (U_w, H_s, T_p) can be described as follows

$$F(U_w) = \Phi(U_1) \tag{21}$$

$$F(H_s|U_w) = \Phi(U_2) \tag{22}$$

$$F(T_p|U_w, H_s) = \Phi(U_3) \tag{23}$$

That is, the probability computed from normal CDF is bound to the probability computed from the environmental CDF associated with the environmental variable considered, e.g., Weibull for the marginal distribution of U_w (Fig. 1c–d). For any given point in U-space, $(U_1{}^*, U_2{}^*, U_3{}^*)$, a corresponding point in the physical space can be thus established, $(U_w{}^*, H_s{}^*, T_p{}^*)$. As a consequence, the gaussian sphere in U-space can be transformed into a surface in physical space corresponding to the same return period N (Fig. 1e).

ECM entails much fewer environmental conditions compared with FLTA. Moreover, the design points are naturally lumped either in the maximum wind speed region or in the maximum wave height region. Therefore, often only a portion of the contour surface is of interest in long-term extreme analysis [7].

ECM is often not suitable to accurately analyze the long-term extreme response of systems whose environment-structural load relationship is not monotonically increasing. Structures such as FOWTs, for instance, feature many discontinuities of the response which are associated with sudden operational changes. It is clear that for such systems, the largest extreme response is likely to occur during normal operational conditions.

3.3. Modified environmental contour method (MECM)

As previously discussed, ECM cannot be considered a reliable method to predict the extreme long-term response of structures with complex dynamics such as FOWTs. The MECM, proposed by Li et al. [3], is a modification of the ECM which takes into account multiple contours to incorporate non-monotonic behaviour. For instance, a contour surface with a maximum wind speed corresponding to the FOWT cut-off wind speed condition can be superimposed to the global 50-years contour surface to account for the discontinuous behaviour. In the same manner, additional contour surfaces are included accounting for cut-in and rated conditions. The additional contours have a different return period, as a different constraint is used to define the surface in U-space. Since the different contours use different return periods, extrapolation is needed to get consistent values to the original N-year period. The largest extreme response obtained from the environmental contours is the final MECM result. This can be written as [5]

$$\xi_1 = F_{X|U_w,H_s,T_p}^{ST(50yr)-1}(p_1|u_{contour1}, h_{contour1}, t_{contour1}) \tag{24}$$

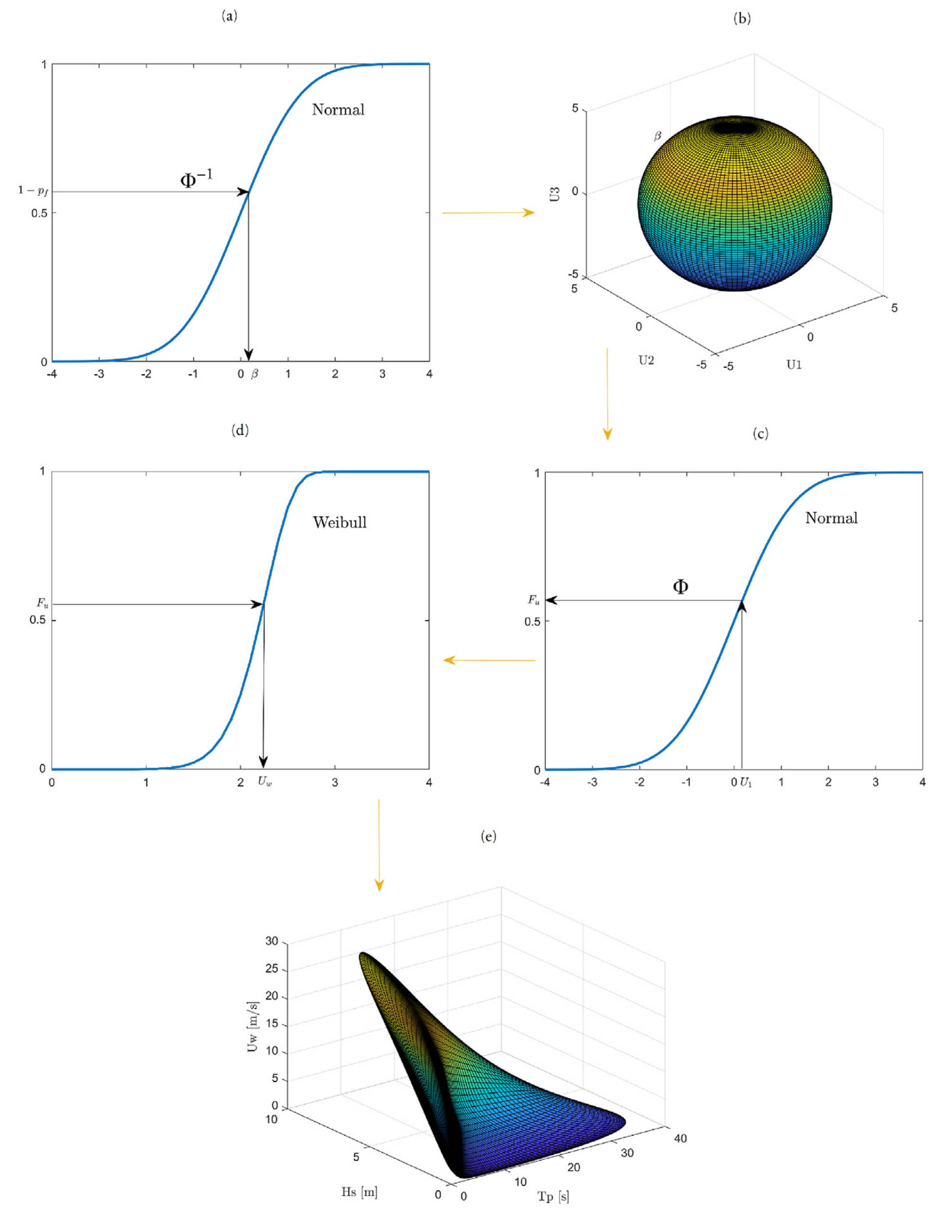

Fig. 1. Graphical representation of the Environmental Contour Method (ECM), based on Rosemblatt transformation [12]. Only the marginal (Weibull) distribution of U_w is shown, relative to a standard height of 10 m and site 14 (Table 3) [7].

$$\xi_2 = F^{ST(50yr)-1}_{X|U_w,H_s,T_p}(p_2|u_{contour2}, h_{contour2}, t_{contour2})$$
$$\ldots$$
$$\xi_{ECM} = F^{ST(ECM)-1}_{X|U_w,H_s,T_p}(p_1|u_{ECM}, h_{ECM}, t_{ECM})$$
$$\xi = max[\xi_1, \xi_2, \ldots, \xi_{ECM}]$$

where p_i (i = 1,2, …) is the empirical percentile level for the additional contour (commonly equal to 50%), while p_{ECM} is the empirical percentile used in ECM (commonly equal to 90%). The expected value of the additional contours is relative to a lower return period compared to the ECM. The extrapolated distributions equivalent to a 50-year return period are thus computed as

$$F^{ST(50yr)}_{X|U_w,H_s,T_p}(\xi) = F^{ST}_{X|U_w,H_s,T_p}(\xi|u_M, h_M, t_M)^{50/M} \tag{25}$$

where M is the return period of the additional contour. For a full methodological description of MECM refer to Li et al. [3].

4. Two-rotor spar-type floating wind turbine (2WT)

The present study focuses on the response of a spar-type two-rotor floating wind turbine concept (2WT) proposed by El Beshbichi et al. [13]. The system consists of two baseline NREL 5-MW wind turbines [14] mounted on a structure composed of horizontal arms connected to the main tower and supported by wires. The floating foundation used is a standard spar-buoy design. Fig. 2 shows the 2WT structural geometry. Major specifications of the 2WT concept are listed in Table 1. The table includes geometrical and inertial specifications, station-keeping specifications, hydrostatic specifications, and specifications related to the wind turbine design considered.

Three catenary mooring lines are used as station-keeping systems. The unstretched length of the lines is 902.2 m, while the

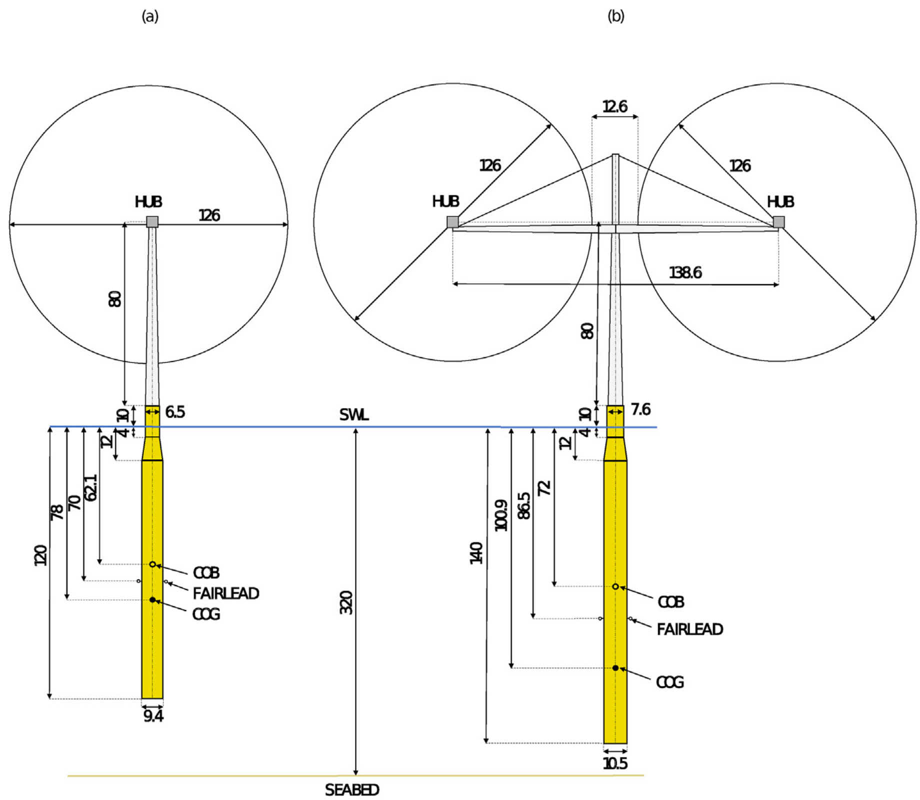

Fig. 2. a) OC3 geometry [m] [14]. b) 2WT configuration [m] [13].

Table 1
Major specifications of the 2WT concept [13,18].

Draft	m	140
Depth to CoG (full system)	m	100.9
Depth to fairlead	m	86.5
Diameter	m	7.6 to 10.5 (tapered)
Water Displacement	m^3	11.7×10^3
Platform Mass (including ballast)	kg	10.6×10^6
Tower Mass	kg	537×10^3
Rotor Mass (per unit)	kg	110×10^3
Nacelle Mass (per unit)	kg	240×10^3
Platform Roll Moment of Inertia about CoG	kgm^2	1.13×10^{10}
Platform Pitch Moment of Inertia about CoG	kgm^2	1.13×10^{10}
Platform Yaw Moment of Inertia about Centerline	kgm^2	1.7×10^8
Number of mooring lines	–	3
Angle between adjacent mooring lines	deg	120
Unstretched line length	m	902.2
Radius to fairlead	m	5.78
Line diameter	m	0.09
Line mass density	kg/m	200
Yaw Spring Mooring Stiffness	Nm/rad	9.8×10^7
Heave Hydrostatic restoring stiffness	N/m	4.56×10^5
Roll Hydrostatic restoring stiffness	Nm/rad	3.42×10^9
Pitch Hydrostatic restoring stiffness	Nm/rad	3.42×10^9
Surge added linear damping	$N/(m/s)$	1×10^5
Sway added linear damping	$N/(m/s)$	1×10^5
Heave added linear damping	$N/(m/s)$	1.3×10^5
Yaw added linear damping	$Nm/(rad/s)$	1.3×10^7
Rotor Diameter	m	126
Hub Height	m	90
Cut-In, Rated, Cut-Out Wind Speed	m/s	3, 11.4, 25
Cut-In, Rated Rotor Speed	rpm	6.9, 12.1

static vertical length is 250 m. The mooring line mass density used is equal to 200 kg/m, and a constant yaw stiffness equal to 9.8×10^7 Nm/rad is used. A proportional-integrative (PI) rotor-collective blade pitch control strategy on the generator speed is linearly coupled with a proportional rotor-collective blade pitch control on the 2WT platform yaw motion [13]. The coupled control strategy aims at mitigating the platform yaw response by reducing the thrust on the hub surging due to the positive yaw dynamics.

The numerical simulations rely on an in-house code for the simplified dynamics of multi-rotor FOWTs concepts [13,15]. The tool is developed in Modelica, within the open-source platform OpenModelica [16]. Fig. 3 depicts a flowchart describing the simulation tool structure. The system is assumed as a single rigid body, i.e., six equations of motion (EoMs) are used to solve the system dynamics. The linear hydrodynamic solver WADAM within SESAM-HydroD is used to solve the first-order frequency-domain hydrodynamic problem [17]. The frequency-domain added mass, $A(\omega)$, radiation damping, $B(\omega)$, and incident wave loads per unit wave amplitude, $X(\omega)$, can then be obtained for the given floating platform. Radiation damping is approximated by means of a state-space representation [15]. A pre-processor is used to obtain operational quantities from input information, such as the radiation damping state-space matrices (A, B, C, D), the linear hydrodynamic loads from incident waves, $F_w(t)$, included as realizations from look-up Inverse Fourier Transformations (IFT), and the added mass matrix computed at infinite frequency, A_∞. The characteristic wave height, H_s, characteristic wave period, T_p, and seed number, S_h, are also used to define the hydrodynamic state of the system. Station-keeping loads given by mooring lines are modeled as quasi-static load-displacement relationships [18].

The aerodynamic loads are assumed as concentrated at the hub. The aerodynamic thrust loads, T, act at the hub locations. In order to obtain the aerodynamic state of the system, the aerodynamic torque is used to solve the rotor equivalent EoM, included in the aerodynamic module. The aerodynamic loads are computed by mapping the quasi-static aerodynamic thrust and torque coefficients. Turbulent wind realizations, (U, V, W), are computed by means of the NREL pre-processor TurbSim [19]. TurbSim input information are the mean wind speed at the hub height, U_{hub}, and the seed number, S_t. The thrust loads can be defined as

$$F = \frac{1}{2}\rho_{air} C_t(\lambda, \beta) A {U_{rel}}^2 \tag{26}$$

where ρ_{air} is the air density, C_t is the steady-state thrust coefficient, λ is the tip speed ratio, β is the rotor-collective blade pitch angle, A is the rotor plane area, and U_{rel} is the relative speed between local wind and hub. The torque loads are defined as

$$T = \frac{1}{2}\rho_{air} R C_q(\lambda, \beta) A {U_{rel}}^2 \tag{27}$$

where R is the rotor radius, and C_q is the steady-state torque coefficient. System response parameters considered in the present study are listed in Table 2. Due to limitations in the present modeling strategy, only the global rigid body motion responses are considered in the evaluation of long-term extremes. However, rigid motion responses may be used as indicators for structural responses.

5. Environment

The geographical sites and their environmental characteristics used in this work are based on information from Li et al. [7]. The sites considered are referred to as site 3 and site 14 and are located

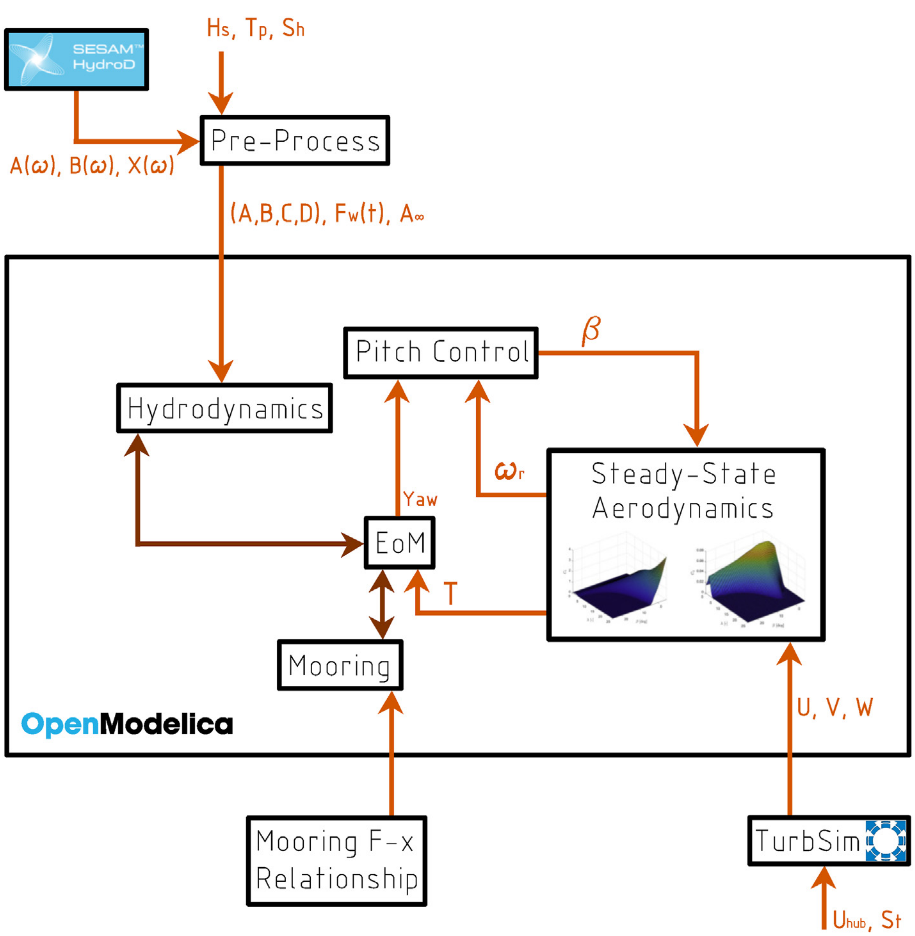

Fig. 3. Flowchart describing the simulation tool structure used in the analysis.

Table 2
Response parameters in consideration for long-term extreme analysis of the 2WT system.

No.		Response
q_1	m	Surge
q_3	m	Heave
q_5	deg	Pitch
q_6	deg	Yaw
T_1	kN	Upstream Farilead #1 Tension
T_2	kN	Upstream Farilead #2 Tension
T_3	kN	Downstream Fairlead Tension
$\dot{q}_1$	m/s	Surge velocity
$\dot{q}_3$	m/s	Heave velocity
$\dot{q}_5$	deg/s	Pitch velocity
$\dot{q}_6$	deg/s	Yaw velocity
$\ddot{q}_1$	m/s^2	Surge acceleration
$\ddot{q}_3$	m/s^2	Heave acceleration
$\ddot{q}_5$	deg/s^2	Pitch acceleration
$\ddot{q}_6$	deg/s^2	Yaw acceleration

Table 3
Characteristic values of site 3 and site 14.

		Site 3	Site 14
Location		Atlantic	North Sea
Water depth	m	449	202
Distance to shore	km	40	30
50-year U_w at 10 m	m/s	28.37	33.49
50-year H_s	m	10.19	10.96
Mean value of T_p	s	11.84	11.06

Table 4
Meteorological conditions used for simulations of wind speed profiles in Turbsim.

Turbulence model	Kaimal
IEC standard	IEC 61400-1-ED3
Turbulence type	Normal
Turbulence characteristics	B
Hub height [m]	90

in the North Atlantic Ocean and the northern North Sea, respectively. The geographical location of the offshore sites used in the present study is shown in Fig. 4. Locations are selected from wind and wave resource assessment performed within the EU-funded project MARINA Platform [20]. Offshore sites selected are locations well known for their floating offshore wind development potential [6,21]. Site 14 is first selected due to harsh long-term environmental conditions, while site 3 is selected as a reference site in Southern European waters. Both sites are sufficiently deep to host deep drafted platforms such as the spar-type 2WT platform. Table 3 shows the characteristic values of the offshore sites used in this study. Table 4 shows the basic information of the meteorological conditions used to compute turbulent wind profile realizations. The environmental cases in FLTA are initially limited to the ones listed in Table 5. The bin sizes are chosen from recommendations in the standard DNVGL-RP-0286 [22], which gives a total of 8160 environmental conditions. The simulation time is approximately 25 min for each case. In this work, the number of environmental conditions is reduced by selecting only the conditions with a return period of fewer than 1000 years. This ensures that conditions with low exceedance probability are considered while unimportant conditions are omitted. Fig. 5 shows the selected conditions relative to the 50-year contour surface of site 14 and adjusted for the hub height wind speed. Based on this method, a total of 1205 environmental conditions are selected (about 85% fewer conditions).

Fig. 4. Location of sites used in the present study [7,20].

As previously described, the present application of MECM makes use of two environmental contours. The first is associated with the standard ECM 50-years return period, while the second is associated with the wind turbines' cut-out wind speed, i.e., 25 m/s. Fig. 6 shows the ECM contour and the additional contour represented by the cut-off wind speed for site 3 and site 14. The latter is often referred to as the 'cut-off contour.' For site 14, the cut-off contour is created with a return period corresponding to approximately 105 h, while 680 h is used for site 3.

Table 6 shows a comparison of the number of cases and cumulative computational time needed to perform long-term analysis by means of the FLTA, the ECM, and the MECM. As it is clear, FLTA requires a large amount of environmental cases. The contour methods presently proposed significantly reduce the computational effort for long-term analysis. Total computational time is reduced of about 91.6% if ECM is considered, and of about 86% if MECM is considered.

6. Results and discussion

Fig. 7 shows the FLTA 1-h exceedance probability for platform surge, heave, pitch, and yaw platform motions computed for site 3 and site 14. The dashed line represents the 50-years return period threshold. Moreover, Table 7 summarizes the 50-year extreme responses obtained from FLTA. Results show how the responses

Table 5
FLTA environmental conditions.

		Min	Max	Bin
U_w	m	4	50	2
H_s	m	1	20	1
T_p	s	2	34	2

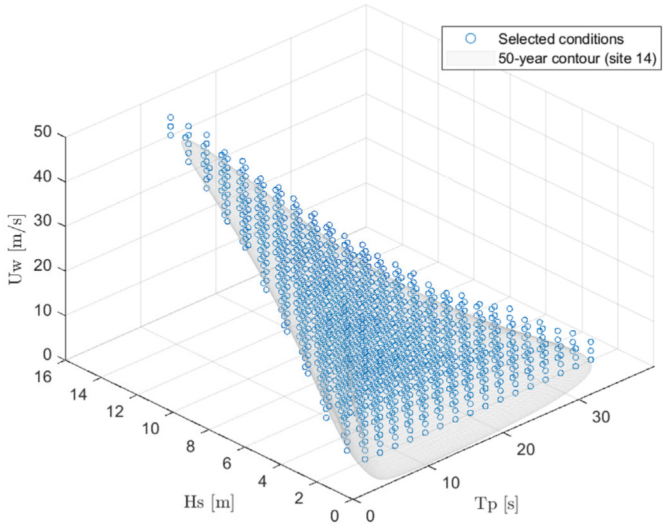

Fig. 5. Environmental conditions used for FLTA. The 50-year contour surface of site 14 is included to visualize the threshold of the selected conditions.

predicted are very close for both sites. This indicates that the responses are not affected significantly by the harsher wind conditions of site 14. Heave motion is significantly reduced in site 3, with a 50-years extreme of about 3.6 m against 6.2 m in site 14. As heave is wave-dominated, it is reasonable to assume that the wave-induced loads, associated with lower frequencies for site 3 if compared to site 14 (Table 3), are more prone to dynamically amplify heave motion.

As previously stated, ECM takes into account the 50-years contour surface, while MECM considers both the 50-years contour and the contour corresponding to the wind turbines cut-off condition, that is, 25 m/s. It is challenging to locate the important conditions on the contour efficiently. The aim is to cover enough environmental conditions without compromising accuracy and efficiency. This may be achieved, for instance, by searching only areas of the contour in which the extreme response is expected to be located [5]. However, for conceptual systems as the 2WT, there is little evidence for dominant environmental regions. As such, the whole contour is included in the present study. Fig. 8 and Fig. 9 show the selected conditions on the 50-years environmental contour surfaces for sites 3 and 14, respectively. Fig. 10 and Fig. 11 show the selected conditions on the cut-off environmental contour surfaces for both sites. The design points obtained in the study are highlighted with filled black circles. Each design point is associated with one response variable, even though overlap of design points can occur. It can be noted how the design points found from the 50-year contour are generally located in the regions corresponding to rated wind speed, wave period close to the platform natural periods, maximum wind speed, and cut-off wind speed. For the cut-off contours, the design points are generally located at the wind-wave peak or close to rated wind conditions. Common percentiles used in previous studies of long-term extreme responses of floating wind turbine concepts are 90% for ECM and 50% for additional contours for MECM [3–5]. Same percentiles values are thus used in this work.

Fig. 12 compares the results of ECM and MECM as percentage difference with respect to the FLTA results for site 3 (a) and site 14 (b). Negative values indicate underprediction, while positive values indicate overprediction. Response underprediction is clearly the major issue in using simplified methods such as the ECM. Overpredictions above 90%, exclusively associated with platform heave motion in site 3 (about 150% overprediction), are omitted for figure clarity. All MECM results lay within 15% difference compared to FLTA results. Table 8 and Table 9 list the resulting long-term extremes obtained from the 50-years contour (ECM) and cut-off contour for sites 3 and 14, relative to previously described percentiles. FLTA results are also presented to illustrate the value deviations. The color grade indicates deviation from FLTA results. Red grading indicates underprediction higher than about 30% compared to FLTA, while green grading indicates overprediction. ECM performs inadequately for a wide range of the responses considered. The most notable underpredictions are relative to surge motion, and yaw motion, velocity, and acceleration. ECM underpredicts yaw motion of about 50% if compared to FLTA. Underpredictions of the extremes can be explained by considering the

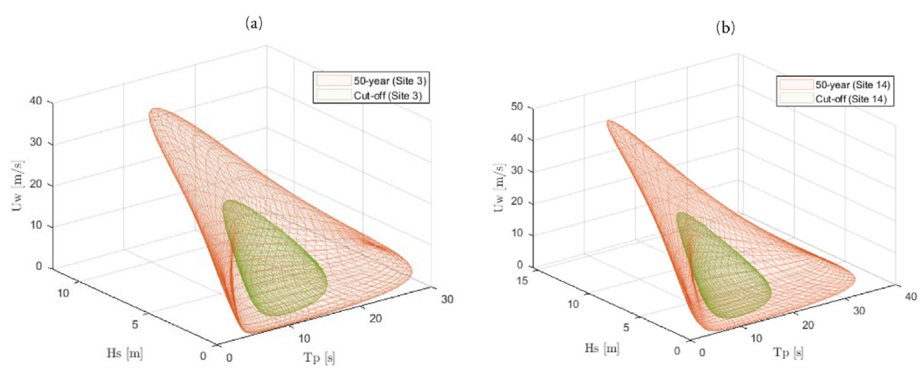

Fig. 6. Environmental contours associated with the ECM 50-years return period and with the wind turbine cut-off wind speed. a) Site 3. b) Site 14 [7].

Table 6
Comparison of number of cases and cumulative computational time needed to perform long-term analysis (CPU time needed for a single case is 25 min circa).

		N_{cases}		T_{sim} [min]	Variation *w.r.t.* FLTA
FLTA		1205		30125	
MECM	50-years	101	170	4250	−86%
	cut-off	69			
ECM	50-years	101	101	2525	−91.6%

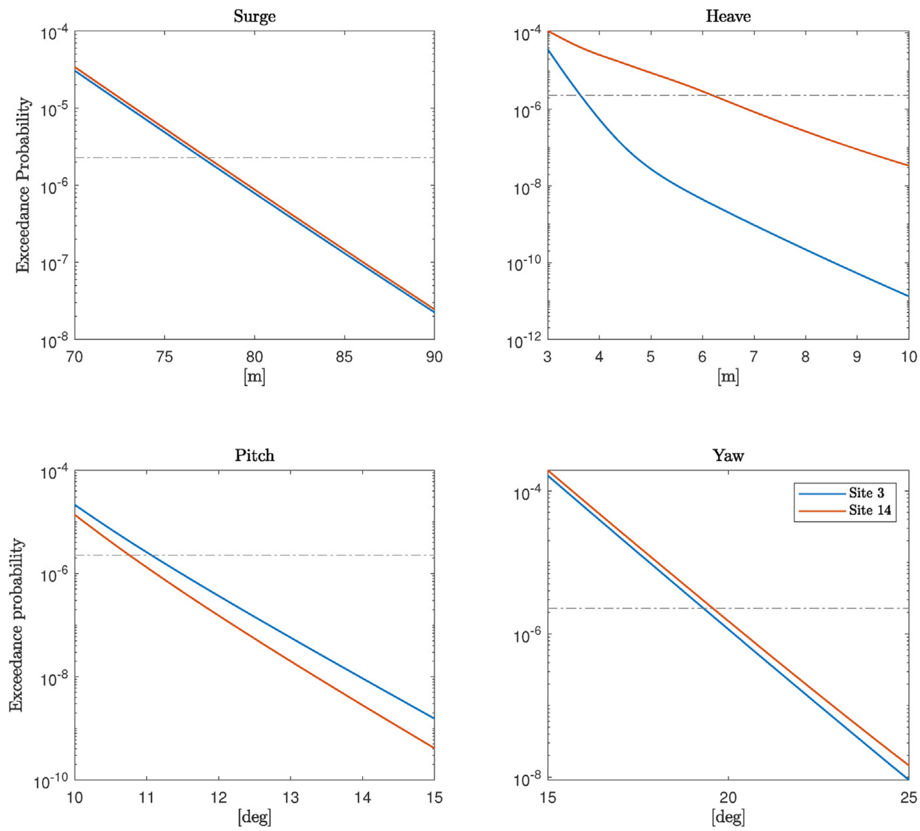

Fig. 7. Full long-term extreme exceedance probability of platform surge, heave, pitch, and yaw motions computed for site 3 and site 14. The dashed line represents the exceedance probability associated with 50-years return period.

omittance of the wind turbine parking operational mode by using a simple ECM approach. The greatest deviations are relative to responses dominated by wind loading. From Fig. 12, it can be noted how MECM either significantly improves or predicts the same results as ECM. In particular, long-term extreme prediction of platform yaw motion is significantly improved. Yaw motion, which in previous work is found to be one of the major dynamic modes of the 2WT concept, can be related to the transversal distribution of thrust loads and to wind turbulence intensity [13]. Since platform yaw motion is wind dominated, the inclusion of the cut-off contour in MECM aids the detection of long-term extremes near the cut-off wind condition. The significant over predictions for heave motion, surge, heave, and pitch velocities and accelerations - higher than 25% compared to FLTA responses - can be explained by considering that the relative extreme responses are already very close to the results obtained from FLTA. A percentile of 90% may thus be considered as too conservative [5].

Table 7
50-years long-term extreme responses obtained from FLTA for site 3 and site 14.

Response		Site 3	Site 14
q_1	m	77.06	77.37
q_3	m	3.64	6.20
q_5	deg	11.06	10.76
q_6	deg	19.31	19.57
T_1	kN	5122	5148
T_2	kN	4897	4902
T_3	kN	2827	2831
$\dot{q}_1$	m/s	5.03	5.72
$\dot{q}_3$	m/s	0.90	1.24
$\dot{q}_5$	deg/s	2.10	2.30
$\dot{q}_6$	deg/s	4.19	4.52
$\ddot{q}_1$	m/s^2	2.67	3.05
$\ddot{q}_3$	m/s^2	0.52	0.59
$\ddot{q}_5$	deg/s^2	1.09	1.26
$\ddot{q}_6$	deg/s^2	1.52	1.53

7. Conclusions

In this paper, the modified environmental contour method

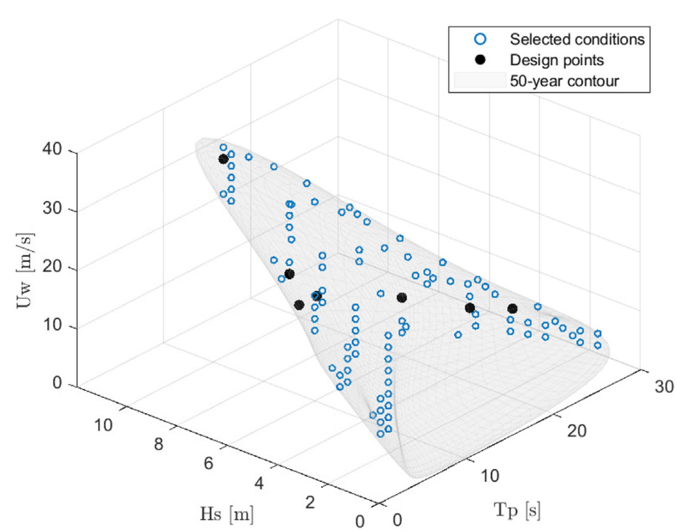

Fig. 8. Discretized conditions for 50-years contour surface for site 3. The blue circles are the selected conditions, while the filled black circles are the design points.

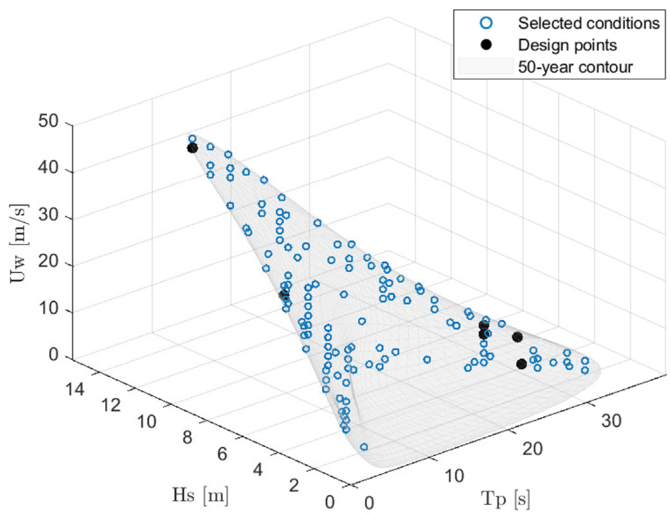

Fig. 9. Discretized conditions for 50-years contour surface for site 14. The blue circles are the selected conditions, while the filled black circles are the design points.

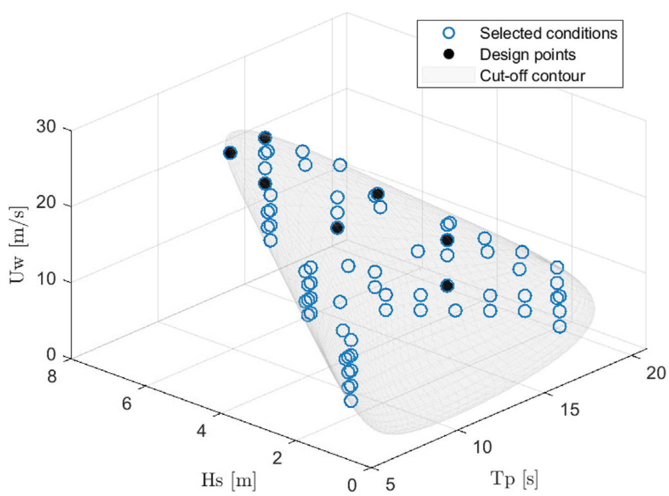

Fig. 10. Discretized conditions for cut-off contour surface for site 3. The blue circles are the selected conditions, while the filled black circles are the design points.

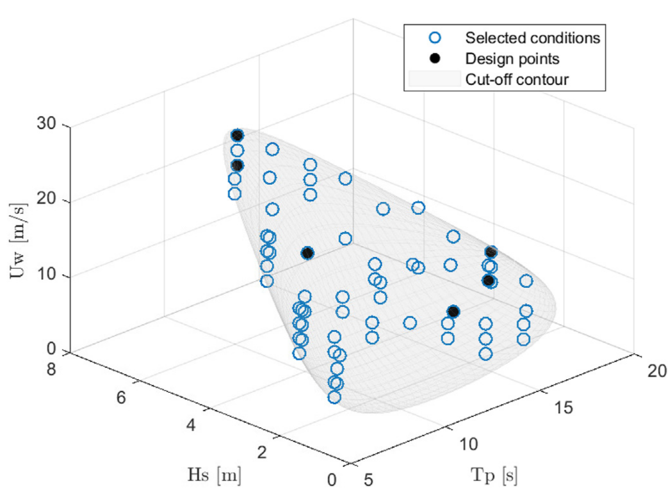

Fig. 11. Discretized conditions for cut-off contour surface for site 14. The bluue circles are the selected conditions, while the filled black circles are the design points.

(MECM) is used to predict the 50-year extreme response of a two-rotor floating wind turbine concept (2WT) deployed in two different offshore sites. The standard contour method (ECM) is much faster than the complete full long-term analysis (FLTA) but performs poorly if the loads acting on the system are not monotonically increasing with the environmental state. The analysis considered the environmental conditions describing two specific offshore sites located in the North Sea and the North Atlantic Ocean, known to be suitable for floating offshore deployment. FLTA and ECM were carried out and used as a benchmark to assess the performance of MECM. MECM takes into account two environmental contours, that is, the baseline 50-years return period contour used in ECM and an additional cut-off wind speed contour. ECM leads to significant underprediction of the system responses dominated by wind loading. In particular, underestimation of platform yaw motion, a typical dynamic mode of the 2WT system, is about 50%, while the underestimation associated with platform surge motion is about 30%. It is found that MECM significantly improves the accuracy of wind-dominated results while predicting the same accuracy for wave-dominated results. ECM over-estimates wave-dominated results, such as surge, heave, and pitch velocities and accelerations. Over-estimation can be associated with the high fractile level employed (90%), as results are already very close to the ones obtained in FLTA. Most MECM responses are within 15% difference with respect to FLTA results. Therefore, MECM may be assumed suited to be employed for the analysis of two-rotor FOWTs without the risk of underestimating long-term extreme responses. The conclusions offered in this study can be summarized as follows:

- MECM can predict the long-term extreme response of multi-rotor floating wind turbine concepts within a maximum underestimation of about 15% compared to FLTA results.
- MECM wind-dominated results are especially more accurate if compared to those obtained by means of the standard ECM, while maintaining the same level of accuracy for wave-dominated results.
- MECM over-estimation of wave-dominated results can be associated with the high fractile level (90%) employed in the ECM environmental contour, as results are already very close to the ones obtained in FLTA.

The numerical simulations relied upon a simplified model assuming concentrated aerodynamic loads at the hubs. The model maps steady-state aerodynamic coefficients characteristic of the wind turbine employed. Therefore, this method is not able to cover more complex dynamic effects. For instance, the aerodynamic interaction effect between the rotors is not considered. Skewed effects are also not considered, such as the skewed conditions related to significant yaw motion. The results obtained in this study give useful indications about the applicability of MECM for multi-rotor floating systems and sufficiently accurate wave-dominated responses. However, wind-dominated responses may be significantly affected by the aforementioned assumptions. Future work will include the expansion of the analysis by means of a more sophisticated model including a blade-element momentum (BEM) implementation for multi-rotor FOWTs and structural dynamics.

CRediT authorship contribution statement

Omar El Beshbichi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Henrik Rødstøl:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – review & editing, Visualization. **Yihan Xing:** Conceptualization, Methodology, Software, Formal

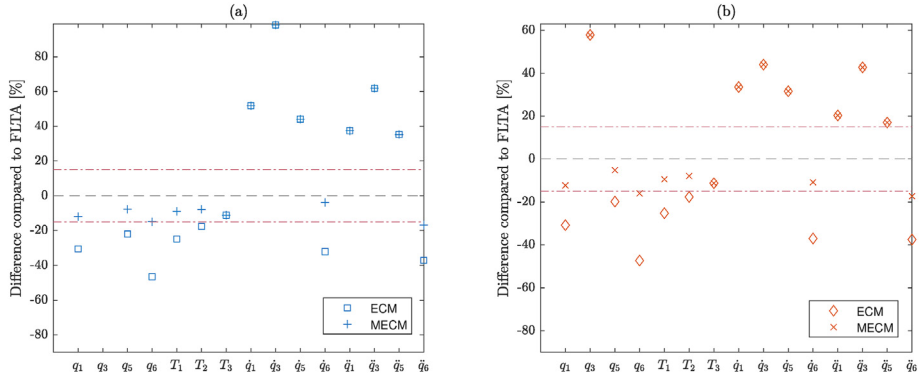

Fig. 12. Percentage deviation of ECM and MECM results to FLTA results for site 3 (a) and site 14 (b). The 50-years contour uses a 90% percentile, while the cut-off contour uses a 50% percentile.

Table 8
Predicted 50-year extreme responses with ECM and MECM for site 3. Percentiles used are 90% for the 50-years contour and 50% for the cut-off contour. The color grade indicates deviation from FLTA results. Red grading indicates underprediction higher than about 30% compared to FLTA. Green grading indicates overprediction.

Response	FLTA	ECM (90%)	Cut-off (50%)	MECM	
q_1	77.06	53.49	67.82	67.82	m
q_3	3.64	9.78	2.71	9.78	m
q_5	11.06	8.62	10.22	10.22	deg
q_6	19.31	10.35	16.49	16.49	deg
T_1	5122	3847	4676	4676	kN
T_2	4897	4035	4596	4596	kN
T_3	2827	2512	2386	2512	kN
$\dot{q}_1$	5.03	7.63	4.28	7.63	m/s
$\dot{q}_3$	0.90	1.78	0.53	1.78	m/s
$\dot{q}_5$	2.10	3.02	1.71	3.02	deg/s
$\dot{q}_6$	4.19	2.84	4.04	4.04	deg/s
$\ddot{q}_1$	2.67	3.66	3.09	3.66	m/s^2
$\ddot{q}_3$	0.52	0.84	0.43	0.84	m/s^2
$\ddot{q}_5$	1.09	1.47	1.31	1.47	deg/s^2
$\ddot{q}_6$	1.52	0.95	1.26	1.26	deg/s^2

Table 9
Predicted 50-year extreme responses with ECM and MECM for site 14. Percentiles used are 90% for the 50-years contour and 50% for the cut-off contour. The color grade indicates deviation from FLTA results. Red grading indicates underprediction higher than about 30% compared to FLTA. Green grading indicates overprediction.

Response	FLTA	ECM (90%)	Cut-off (50%)	MECM	
q_1	77.37	53.53	67.81	67.81	m
q_3	6.20	9.79	2.75	9.79	m
q_5	10.76	8.63	10.20	10.20	deg
q_6	19.57	10.32	16.43	16.43	deg
T_1	5148	3847	4662	4662	kN
T_2	4902	4035	4514	4514	kN
T_3	2832	2511	2307	2511	kN
$\dot{q}_1$	5.72	7.64	4.28	7.28	m/s
$\dot{q}_3$	1.24	1.79	0.58	1.79	m/s
$\dot{q}_5$	2.30	3.03	1.71	3.03	deg/s
$\dot{q}_6$	4.52	2.84	4.02	4.02	deg/s
$\ddot{q}_1$	3.05	3.67	3.09	3.67	m/s^2
$\ddot{q}_3$	0.59	0.84	0.43	0.84	m/s^2
$\ddot{q}_5$	1.26	1.47	1.31	1.47	deg/s^2
$\ddot{q}_6$	1.53	0.96	1.26	1.26	deg/s^2

analysis, Investigation, Writing – review & editing, Supervision. **Muk Chen Ong:** Conceptualization, Formal analysis, Investigation, Writing – review & editing, Resources, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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