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Response Extremes of Floating Offshore Wind Turbine Based on Inverse Reliability and Environmental Contour Method

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Abstract: Floating structures are subject to complex marine conditions. To ensure their safety, reliability analysis needs to be conducted during the design phase. However, because of the complexity of traditional full long-term analysis, the environmental contour method (ECM) based on the inverse reliability method, which can combine accuracy and efficiency, is extensively used. Due to the unique environment in the South China Sea, the probabilistic characteristics of three-dimensional (3D) environmental parameters of wind, wave and current are investigated. The ECs of the target sea are established via the ECM based on both the inverse first-order reliability method (IFORM) and inverse second-order reliability method (ISORM). It is found that the sea state forecasted by ISORM is more extreme and may lead to a more conservative design than IFORM. Furthermore, the wind–wave–current combination coefficient matrixes developed using the 3D ECs are proposed for the design of FOWTs in the South China Sea. The validity and practicality of the contours and matrixes are tested by using a floating offshore wind turbine (FOWT) as a numerical example. Then, the short-term response of the structure under the combined wind, wave and current conditions is calculated, providing a theoretical reference for the design of FOWTs.

Keywords: inverse first-order reliability method; inverse second-order reliability method; environmental contour method; floating offshore wind turbine; long-term response analysis

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1. Introduction

Floating structures suffer from harsh and complex environmental impacts during their service life. It is necessary to conduct a probabilistic reliability analysis of these structures. Usually, a comprehensive long-term response analysis of the structure should be carried out. However, because the calculation is cumbersome and very time-consuming, short-term response analysis approximation methods are used to simplify the calculation and improve the calculation efficiency.

The structural reliability analysis method based on probability and statistics theory was first proposed at the beginning of the 20th century. Winterstein [1] proposed the IFORM, which converts the joint probability distribution of environmental parameters into standard normal space and then converts the boundary in normal space back to the physical parameter space to obtain the EC. Kiureghia et al. [2] elaborated on the theoretical basis of the inverse reliability method; Li et al. [3] wrote a direct iteration program and then solved the inverse reliability analysis problem containing an unknown parameter; Xiang et al. [4] proposed an efficient method that can accurately predict structural fatigue through IFORM; Chai et al. [5] proposed the ISORM-based EC, and the results show that the ISORM contour is more conservative than IFORM.

The ECM, in conjunction with inverse reliability theory, is based on the long-term distribution of environmental parameters in the target sea area to predict environmental conditions under a specific RP (return period) and can intuitively reflect the combination of environmental parameters under extreme conditions. This method has become a common method for estimating the long-term extreme response of offshore structures and is widely used in design guidelines and standards, such as IEC [6], DNV GL-RP-C205 [7], etc. This method is generally drawn based on the joint distribution model of the environment and inverse reliability methods, including IFORM (Winterstein et al. [1]; Haver et al. [8]), Monte Carlo direct sampling method (Huseby et al. [9,10]), direct IFORM (Derbanne et al. [11]), and inverse second-order reliability method (Chai et al. [5]).

For ECs, it is crucial to accurately describe marine environmental conditions and establish the corresponding probabilistic models. For structural analysis under wave actions, Battjes et al. [12] and Longuet-Higgins et al. [13] proposed an analytical formula for the joint probability distribution of wave height and wave period; Haver [14] further studied a binary probability function with two parameters; Vanem [15] studied various joint distribution models, such as the conditional probability model of significant wave height and zero-crossing period, and the Copulas parameter family model; Bruserud et al. [16] found that when the wave height is greater than 8 m, its probability distribution characteristics obey a two-parameter Weibull distribution, while the current speed distribution under significant wave height conditions is more appropriately described by the Log-Normal distribution; Fontaine et al. [17] also used this method to derive the joint distribution extreme values of waves, winds and currents, for the design of offshore structures. In addition, the ECM is also used to analyze the complex response of offshore structures. Some researchers [17,18] applied ECM to calculate the N-year mooring extreme tension of an FPSO. Other researchers [19–21] applied ECM to calculate the related complex responses of bridges, such as long-span bridges and Hardanger bridges.

On this basis, the ECs for a sea area in the South China Sea via IFORM and ISORM are established, the difference between two methods of creating the contour is compared, and we determine the multiple load cases of combined conditions based on the design standards and the EC. Time-domain coupled analysis of an FOWT was carried out to provide a theoretical reference for the selection of environmental parameters in the design of floating structures in the South China Sea. The principles of IFORM and ISORM are briefly introduced in Section 2. In Section 3, the joint three-dimensional ECs of wind, wave and current in a specific sea area in the South China Sea are developed based on IFORM and ISORM, respectively. In Section 4, the environmental data extracted from the developed 3D contours are analyzed and compared, and a combination coefficient matrix of wind, wave and current in the South China Sea is proposed. Finally, the conclusions are drawn in Section 5.

2. Inverse Reliability Method for Floating Structures

In engineering applications, statistical models of waves generally assume that the ocean surface is a random wave field that traverses smoothly in a short time (such as 3–6 h) and is uniform in space. Stationary random waves can be seen as an ergodic random process, which can be seen as the result of the infinite superposition of micro-amplitude waves of different frequencies, amplitudes and random phases. Similarly, assuming that environmental parameters are stationary in the short term, their associated load effects can also be considered as stationary random processes, and the probability density function (PDF) can be combined to describe the random changes in environmental parameters in the long term. Assuming that the long-term changes in environmental parameters and the short-term loading process are also ergodic, the long-term response can be predicted based on some short-term response statistics.

2.1. Environmental Contour Method

The environmental contour method (ECM) is combined with the inverse reliability method [1] to establish a joint probability model of environmental parameters and analyze the contour (surface) in the environmental parameter space, which corresponds to the set of environmental parameters under a given RP. The form of the environment contour is determined by the dimensions of the relevant probability distribution of environmental parameters, which is a contour in the case of two parameters and a contour surface in the case of three or more parameters. In this method, short-term response extremes can be determined based on critical short-term environmental conditions on the EC of the same RP, and the long-term extremes can then be approximated.

Rosenblatt transformation is a method to convert the joint probability model of environmental variables into a multidimensional independent standard normal distribution based on conditional distribution, as follows [22]:

$$\begin{aligned} & u_1 = \Phi^{-1}\left(F_{S_1}(s_1)\right) \\ & u_2 = \Phi^{-1}\left(F_{S_2|S_1}(s_2 \mid s_1)\right) \\ & \cdots \\ & u_{n+1} = \Phi^{-1}\left(F_{\widetilde{Y}|S_1,S_2,\cdots,S_n}(y \mid s_1, s_2, \cdots, s_n)\right) = \Phi^{-1}\left(F_{\widetilde{Y}|\mathbf{S}}(y \mid \mathbf{s})\right) \end{aligned} \tag{1}$$

where $\mathbf{s} = (s_1, s_2, \cdots, s_n)$ represents n-dimensional environmental variables in the real physical parameter space, Y is the structural response variable, and $\mathbf{u} = (u_1, u_2, \cdots, u_{n+1})$ is the $(n + 1)$-dimensional independent standard normal distribution variable by the transformation.

2.2. Reliability Method

2.2.1. Inverse First-Order Reliability Method

IFORM is the inverse method of the first-order reliability method (FORM). This method approximately calculates the long-term response extreme value of a complex structure through short-term response analysis [23], such as the 3 h short-term response extreme value. It is assumed that the short-term sea state is a stationary random process, and the structural response extreme value is used as the analysis variable. Taking significant wave height H_s and spectral peak period T_p as an example, the cumulative distribution function (CDF) of R_{3h} is [24]:

$$F_{R_{3h}}(r) = \iint_{ht} F_{R_{3h}|H_sT_\mathrm{p}}(r|h,t) f_{H_sT_\mathrm{p}}(h,t)\,dtdh \tag{2}$$

where $F_{R_{3h|H_sT_\mathrm{p}}}(r|h,t)$ represents the CDF of the short-term response extreme value of the structure under a certain sea state (H_s, T_p), $F_{R_{3h}}(r)$ represents the probability that the short-term response extreme of the structure R_{3h} is less than the given response level r under any possible sea state, and $f_{H_sT_\mathrm{p}}(h,t)$ is the combination PDF of H_s and T_p.

From the reliability theory, assuming that r_{crit} is the given critical response threshold, we consider that the structure would be secure when the response is below the failure boundary. So, $F_{R_{3h|H_sT_\mathrm{p}}}(r|h,t)$ can be rewritten as $\int_{r \le r_{crit}} f_{R_{3h}|H_s,T_p}(r|h,t)dr$:

$$F_{R_{3h}}(r) = \iint_{ht} \int_{r \le r_{crit}} f_{R_{3h}|H_s,T_p}(r|h,t) f_{H_s}(h) f_{T_p|H_s}(t)\,drdhdt \tag{3}$$

where $f_{R_{3h|H_sT_\mathrm{p}}}(r|h,t)$ is the PDF form of $F_{R_{3h|H_sT_\mathrm{p}}}(r|h,t)$, $f_{H_s}(h) f_{T_p|H_s}(t)$ is the one-dimensional density distribution and conditional density distribution form of $f_{H_sT_\mathrm{p}}(h,t)$.

The reliability method is widely applied to analyze the reliability index and failure probability of structures, so the structural limit state function can be transformed into the reliability form:

$$g_r(\mathbf{s}) = r - \widetilde{r} \tag{4}$$

where $\mathbf{s}$ is the random variables in the function $F_S(\mathbf{s})$, r represents the critical response to the structural failure, $\widetilde{r}$ is the response by the given loads $\mathbf{s}$. When $g_r(\mathbf{s}) < 0$, it indicates that the structure is in the failure state. In the case of the previous circumstance, the corresponding structural function can be expressed as:

$$g\left(R_{3h}, H_s, T_p; r_{crit}\right) = r_{crit} - R_{3h}\left(H_s, T_p\right) \tag{5}$$

Then, the structural failure probability can be estimated by:

$$p_f(r_{crit}) = \iiint_{g<0} f_{R_{3h}|H_sT_p}(r|h,t) f_{H_sT_p}(h,t)drdhdt \tag{6}$$

The Rosenblatt transformation is used to convert the parameters in Equation (5) by the first-order reliability method, and the environmental variables are transformed into a space consisting of independent and standard normal variables u_i (i.e., the U space). The process of the Rosenblatt transform is [22]:

$$\begin{array}{l} \Phi(u_1) = F_{H_s}(h) \\ \Phi(u_2) = F_{T_p|H_S}(t \mid h) \\ \Phi(u_3) = F_{R_{3h}|H_sT_p}(r \mid h,t) \end{array} \tag{7}$$

where $\Phi(\mathbf{u})$ is the standard normal distribution CDF. According to Equation (5), the transformed structural function is:

$$z = g\left(R_{3h}, H_s, T_p; r_{crit}\right) = g(u_3, u_1, u_2; r_{\text{crit}}) \tag{8}$$

Then, Equation (6) can be rewritten as the expression of standard normal variables in three dimensions:

$$p_f(r_{crit}) = \iiint_{\text{g}<0} \varphi(\mathbf{u})d\mathbf{u} \tag{9}$$

where $\varphi(\mathbf{u})$ is the PDF of the standard normal distribution. Rosenblatt transformation converts the probability model in the real physical parameter space into the **U** space; the design point is chosen as the closest point on the boundary to the origin, where coordinates in the **U** space can be expressed as $\hat{\mathbf{u}} = (\hat{u}_1, \hat{u}_2, \hat{u}_3)$. As shown in Figure 1, according to the FORM, the structural failure probability can be simply estimated as [24]:

$$\hat{p}_f(r_{crit}) = 1 - \Phi(\beta_f) \tag{10}$$

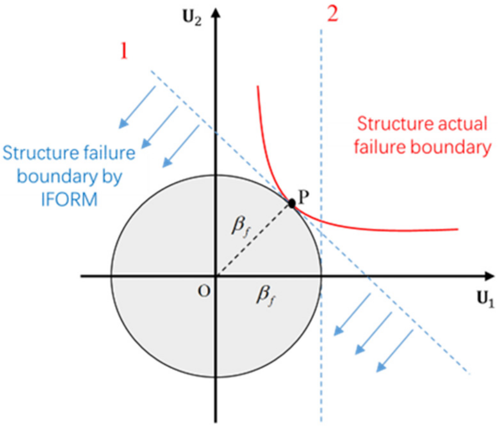


Figure 1. Actual linear and equivalent failure boundaries via FORM.

The distance β_f from the design point $\hat{\mathbf{u}}$ to the origin can be calculated by the following equation:

$$\beta_f = \sqrt{\sum_{i=1}^{3} \hat{u}_i^2} \tag{11}$$

The structural failure probability $p_f(r)$ is usually approximated by the annual exceedance probability. Usually, given an RP of N years, the total number of short-term sea states in the long term is judged, and the exceedance probability $p_f(r) = \frac{1}{\text{N}\times M}$ is defined as the RP in N years. M is the number of short-term sea states in one year.

After determining point $\hat{\mathbf{u}}$, delineate a sphere with the origin as the center and radius β_f in the $\mathbf{U}$ space, and perform the inverse Rosenblatt transformation to return the point (u_1, u_2, u_3) on the circular failure boundary to the physical parameter space and obtain the corresponding point set (h_s, t_p, r_{3h}). The maximum value $\hat{r}_{3h}$ of the response parameter in the dataset is the structural response extreme value, which can be obtained through retrieval. The corresponding point $\left(\hat{h}_s, \hat{t}_p, \hat{r}_{3h}\right)$ is the structural design point. This process is called the first-order inverse reliability process, or inverse FORM. The process is shown in Figure 2.

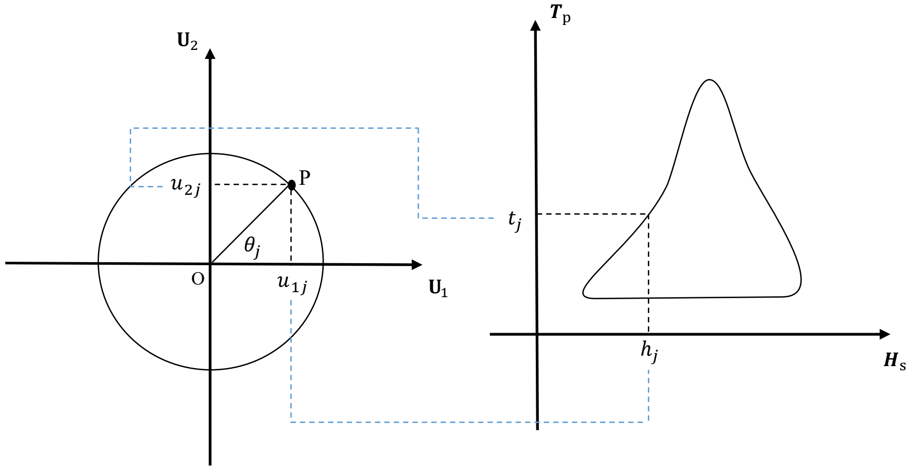


Figure 2. Schematic diagram of EC generated by inverse Rosenblatt transformation.

2.2.2. Inverse Second-Order Reliability Method

Since FORM will underestimate the true failure probability of the structure in some cases, SORM is an improved method that uses a specific second-order surface to approximate the failure surface at the design point. Regardless of the shape of the failure surface, because the approximate failure boundary is always convex, leading to the spherical safety domains being underestimated, the generated environment contours can always maintain a certain degree of conservatism.

According to Equations (6) and (9), it is necessary to solve the exceedance probability of the structure through the structural failure state to obtain the structural failure boundary. Different from the failure surface approximated by a linear function in the $\mathbf{U}$ space via FORM, SORM's approximate failure function $G_\mathbf{S}$ is a second-order function at the design point to approximate the failure boundary. The second-order failure boundary in the $\mathbf{U}$ space can be expressed as [5]:

$$G_\mathbf{S}(\mathbf{u}) = \sum_{i=1}^{m} a_i (u_i - \delta_i)^2 + \sum_{i=m+1}^{n+1} b_i u_i - c \tag{12}$$

Equation (12) represents the (n + 1)-dimensional variables, among which the nonlinear variables have m dimensions, and the remaining ($n + 1 - m$)-dimensional variables are expressed in linear form. In Equation (11), a_i, b_i, δ_i (i = 1, 2, …, n + 1) and c are the correlation coefficients in the quadratic failure function.

SORM uses, as an origin, the center of the circle and a sphere with a radius equal to the distance between the origin and the design point to approximate the failure surface, thus approximating the real safety zone as the area covered by the sphere. Therefore, Equation (12) describes a special second-order failure boundary, where $a_i = 1$, $b_i = 0$, $\delta_i = 0$ and $c = \beta_s$, so the structural failure probability of Equation (6) can be approximately expressed as:

$$p_f(r_{crit}) \approx \int_{\sum\limits_{i=1}^{n+1} u_i^2 \geq {\beta_s}^2} \varphi(\mathbf{u}) d\mathbf{u} \tag{13}$$

Similar to IFORM, the environment contour under selected RPs via ISROM is an inverse reliability problem, in which a given failure probability p_f and the environment parameters causing the structure failure probability p_f are obtained. Then, an n-dimensional sphere with a radius of β_s is created to apply the ISORM, and the radius β_s is calculated by:

$$\int_{\sum\limits_{i=1}^{n} u_i^2 \leq \beta_s^2} \varphi(\mathbf{u}) d\mathbf{u} = 1 - p_f \tag{14}$$

For standard normal variables in the $\mathbf{U}$ space, $\sum\limits_{i=1}^{n} u_i^2$ obeys the chi-square distribution χ^2 (chi-square) with n-dimensional degrees of freedom, so the radius β_s can be expressed as:

$$\chi_n^2\left(\beta_s^2\right) = 1 - p_f \tag{15}$$

where β_s denotes the reliability index by solving the inverse transformation of the chi-square distribution in Equation (15). For the significant H_s and T_p parameters in this study, the degree of freedom of the χ^2 distribution is n = 2; then, p_f is calculated using Equation (10).

3. Inverse Reliability Method and Joint Distribution of Environmental Parameters

3.1. Wave–Current–Wind 3D Environmental Contour

3.1.1. Environmental Models

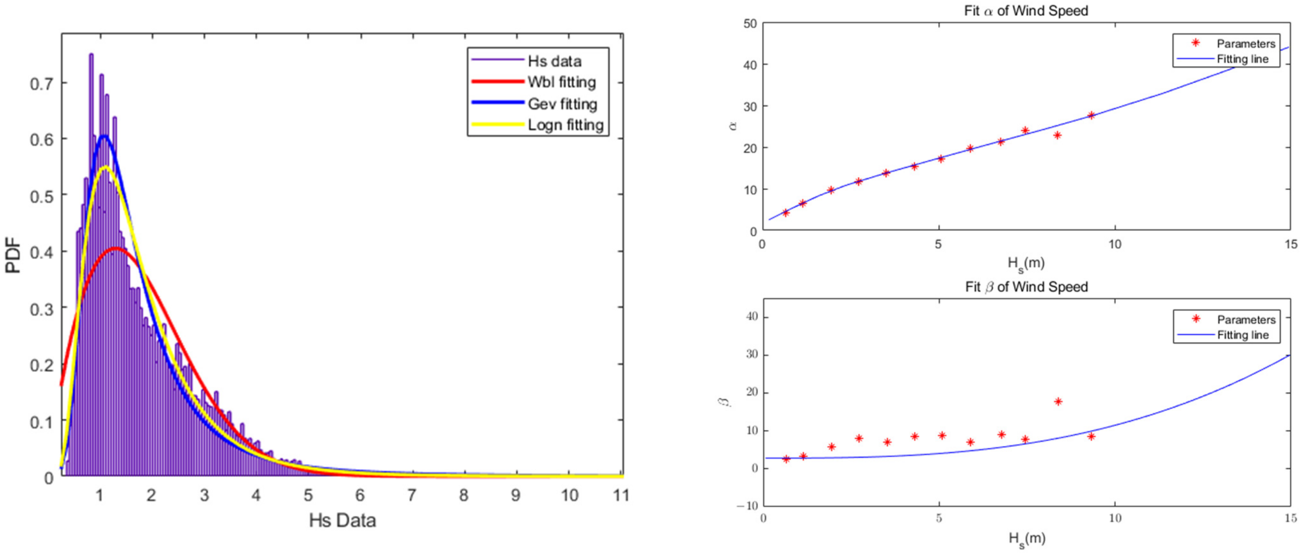
The joint distributions of H_s, V and U are analyzed by a structured joint probability model as:

$$f_{H_sVU}(h,v,u) = f_{H_s}(h) f_{V|H_s}(v|h) f_{U|H_s,V}(u|h,v) \tag{16}$$

The environmental data used in this study are from a site in the South China Sea. According to Equation (15), the probability model of H_s is established first, as shown in Figure 3a. A comparison of "Weibull (Wbl) fitting", "Generalized extreme value (Gev) fitting" and "Lognormal (Logn) fitting" shows the lognormal model has the best fitting results, especially at large wave heights. So, the lognormal distribution is the marginal distribution of $\boldsymbol{H_s}$. The Weibull distribution is selected as the conditional distribution of $\boldsymbol{V}$ under $\boldsymbol{H_s}$, and the Weibull distribution is selected as the conditional distribution of $\boldsymbol{U}$ under $\boldsymbol{V}$ and $\boldsymbol{H_s}$.

The method of group fitting is used for the statistical analysis of the conditional distribution of $\boldsymbol{V}$. Figure 3b shows V fitting under given $\boldsymbol{H_s}$; $\boldsymbol{V}$ is sorted from small to large according to the $\boldsymbol{H_s}$, where the wave group step size is 0.15 m. The maximum likelihood estimation (MLE) is used to fit the Weibull parameters of $\boldsymbol{V}$ in each group.

In the same way, for the conditional probability distribution of current speed $\boldsymbol{U}$, based on the grouping of $\boldsymbol{V}$, the joint distribution model of $\boldsymbol{V}$, $\boldsymbol{H_s}$ and $\boldsymbol{U}$ in this sea area can be determined according to Equation (15).



(**a**) Fitting of H_s data (**b**) Wind speed fitting under given H_s

Figure 3. Probability distribution fitting diagram.

3.1.2. 3D Environmental Contour

According to the constructed joint probability density model of V, H_s and U, the Rosenblatt transformation is used to transform it into the **U** space. Combined with the structural reliability method, it can be seen that the radius of the sphere β_f in the **U** space under the N-year RP based on FORM is:

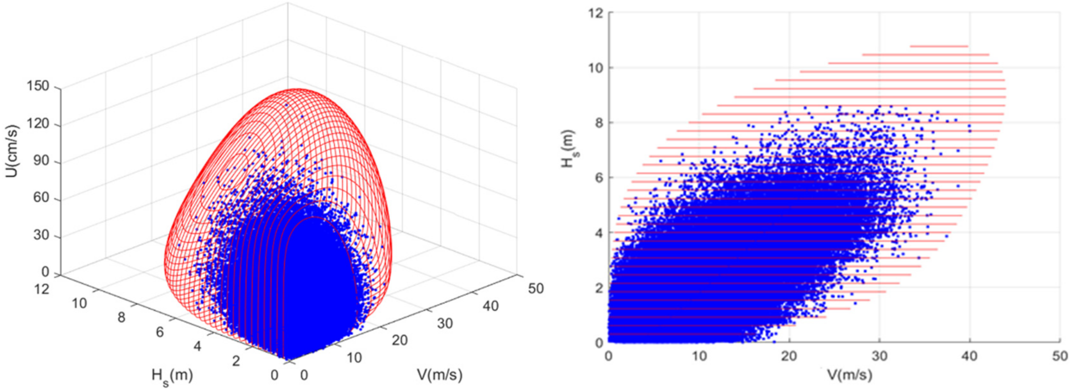
$$\beta_f = -\Phi^{-1}\left(p_f\right) = -\Phi^{-1}\left(\frac{1}{24 \times 365 \times N}\right) \tag{17}$$

For the design of FOWT, the extreme environment conditions are selected in the RP of 1 or 50 years in most cases [6,7,25,26]. To better guarantee the structural safety, set the RP to N as 50 years, and the corresponding β_f is 4.584. The 3D sphere in the **U** space is the structural failure boundary. After discretization of the sphere, the scatter point coordinate $u = [u_1, u_2, u_3]$ can be expressed as:

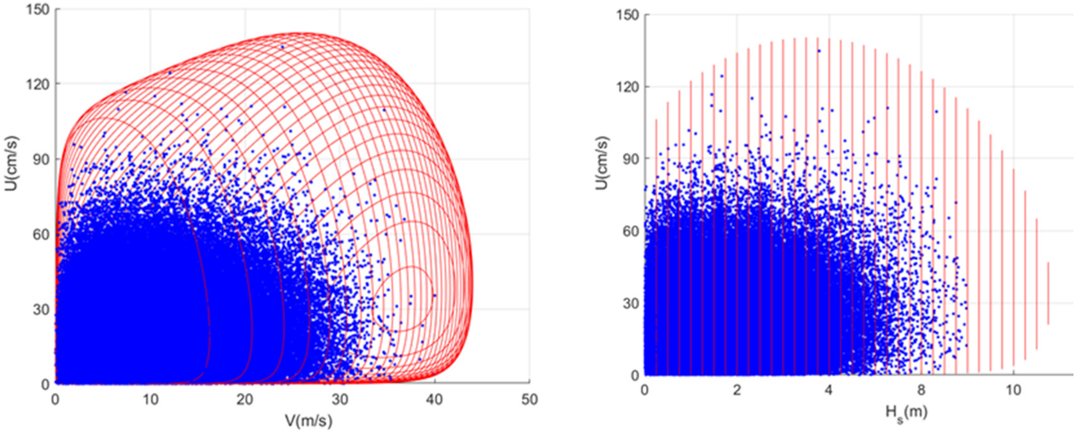
$$\begin{cases} u_{1i} = \beta_f \times \cos(\alpha_i) \\ u_{2i} = \beta_f \times \cos(\varphi_i) \\ u_{3i} = \beta_f \times \cos(\gamma_i) \end{cases} \qquad i = 1, \ldots, k \tag{18}$$

where α, φ, γ are the angles between the vector composed of the origin and each scatter point and the coordinate axes x, y, z, i and k represent the scatter point number and the number of scatter points.

Inverse Rosenblatt transformation is used to convert the scatter points from the **U** space to the environmental parameter space, and a wind–wave–current 3D EC is constructed, as shown in Figure 4. The red lines are the IFORM contour, and the origin data are in blue. It can be seen from Figure 4a that the contour surface and scatter point configuration are well matched. Compared with existing contours [24,27,28], Figure 4b shows that the correlation between H_s and V is relatively high, as shown in Figure 4c,d; the correlation between both U and H_s and U and H_s is low, respectively.



(**a**) 3D view (**b**) Wind-wave view



(**c**) Wind–current view (**d**) Wave–current view

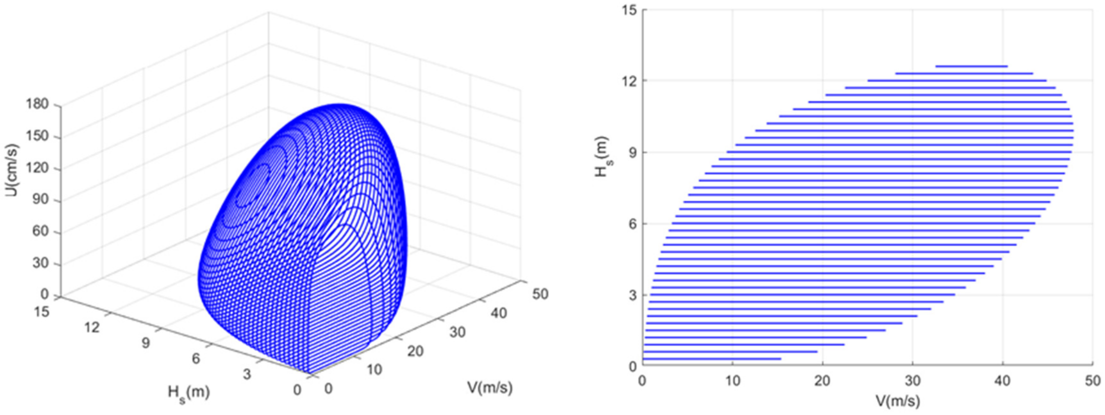
Figure 4. 3D environment contour using IFORM.

Using SORM, the relationship between the sphere radius β_s in the **U** space and the failure probability of N-year RP obeys the χ_n^2 distribution, and β_s can also be solved by the inverse function of the χ_n^2 distribution as follows:

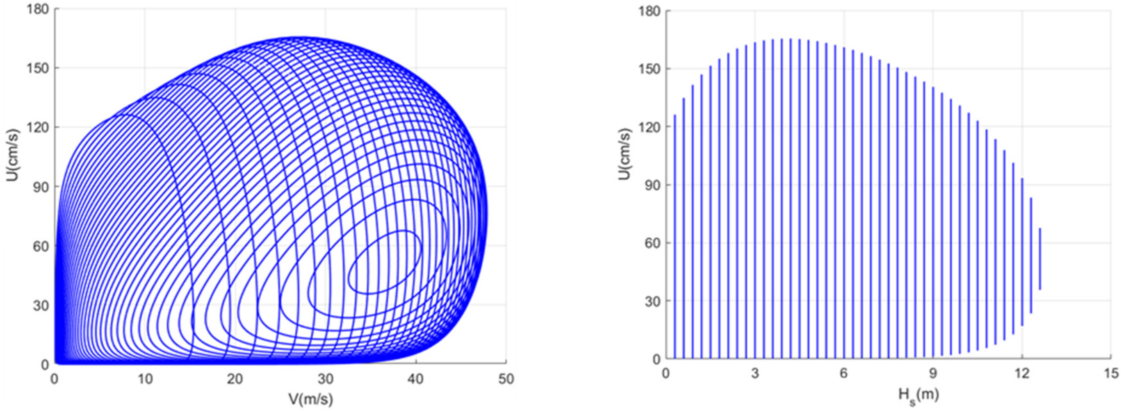
$$\chi_n^2\left(\beta_s^2\right) = 1 - p_f = 1 - \frac{1}{24 \times 365 \times N} \tag{19}$$

For the 3D environmental parameter problem, the degree of freedom of the χ_n^2 distribution is $n = 3$, and the spherical radius $\beta_s = 5.382$ under the 50-year RP can be obtained. Based on the β_s, the structural failure boundary is delineated, and the inverse Rosenblatt transform is used to convert the boundary data into a 3D environmental parameter space; then, a 3D contour is established, as shown in Figure 5, the bule lines are the ISORM contour.

Figure 6 compares the differences between IFORM and ISORM contours. It can be seen that the spatial shapes of IFORM and ISORM contours are similar, but the ISORM contour has a wider range than the IFORM contour; that is, the extreme values calculated by using ISORM are larger than IFORM, and the reliable radius β_s of ISORM (5.382) in **U** space is larger than β_f of IFORM (4.584). Therefore, ISORM is more conservative than IFORM.



(**a**) 3D view (**b**) Wind-wave view



(**c**) Wind–current view (**d**) Wave–current view

Figure 5. 3D environment contour using ISORM.

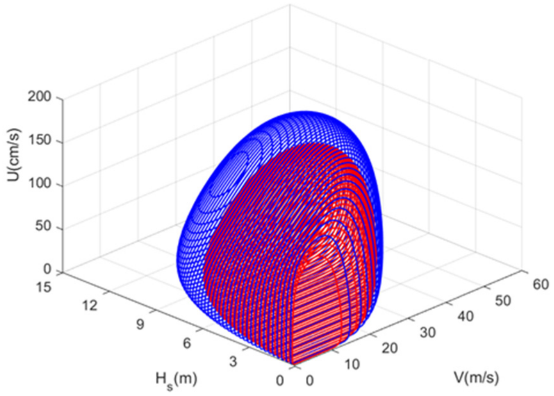


Figure 6. Comparison of IFORM (red) and ISORM (blue) 3D environment contours.

4. Response Extremes under Combined Environmental Conditions

In the design of FOWT, the RP of the environment condition is generally defined as 50 years. When considering the combinations of extreme conditions corresponding to different environmental parameters, the existing design standards recommend different approaches to combine the environments; i.e., CCS recommends a combination of 50-year RP wind, 50-year RP wave and 50-year RP current [25], and DNV Supplementary recommends a combination of 50-year RP wind, 1-year RP wave and 1-year RP current [7]. This is because, apparently, using the combination of 50–50–50 may cause a more conservative design than 50–1–1. Therefore, if overly conservative design conditions are adopted, reliability and costs in the design cannot achieve a good balance. This section considers the environmental conditions of wind, waves and currents, and we obtain multiple combinations of them according to the design standards and the ECs, conduct a time-domain dynamic coupled analysis of an FOWT, and evaluate the response of the platform under given environmental conditions.

4.1. On the Combination of Wave–Wind–Current

Based on the South China Sea 50-year RP 3D ECs in Figures 4 and 5, the extreme values of each parameter on the contour surface are shown in red, as shown in Table 1.

Table 1. Extreme environmental parameters by 3D ECs.

	V (m/s)	H_s (m)	U (cm/s)
IFORM	42.70	10.50	141.96
ISORM	47.85	12.60	165.45

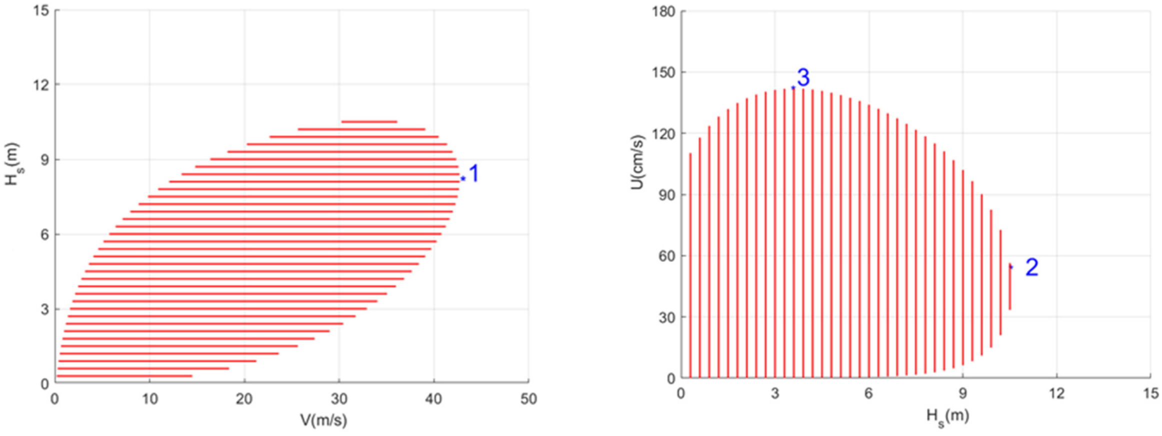
The traditional design method is to use a combination of the extreme values of 50-year RP wind, 50-year RP wave and 50-year RP current directly, that is, the combination of sea conditions in Table 1. However, the probability that the extreme values of wind, wave and current occur simultaneously is rarely seen, so using the combination of each extreme value will undoubtedly be conservative. Alternatively, the ECM can fully consider the correlation and joint probability distribution between each parameter to obtain the combined design conditions. The ECs can be used to analyze the sea condition parameters in different leading conditions. Leading conditions are defined as the combination of wind, wave and current extreme values by multiplying given combination factors (in the range of 0–1). Six types of leading conditions are investigated, which consists of single-parameter leading conditions (wind led, wave led, current led) and two parameter leading conditions (wind–wave led, wind–current led, wave–current led).

The single-parameter leading conditions include wind, wave and current, which are denoted as condition point No. 1, 2 and 3 in Figure 7, respectively. Figure 7a,b show the leading condition points No. 1, 2 and 3 by using IFORM contour, and Figure 7c,d show those by using ISORM contour.

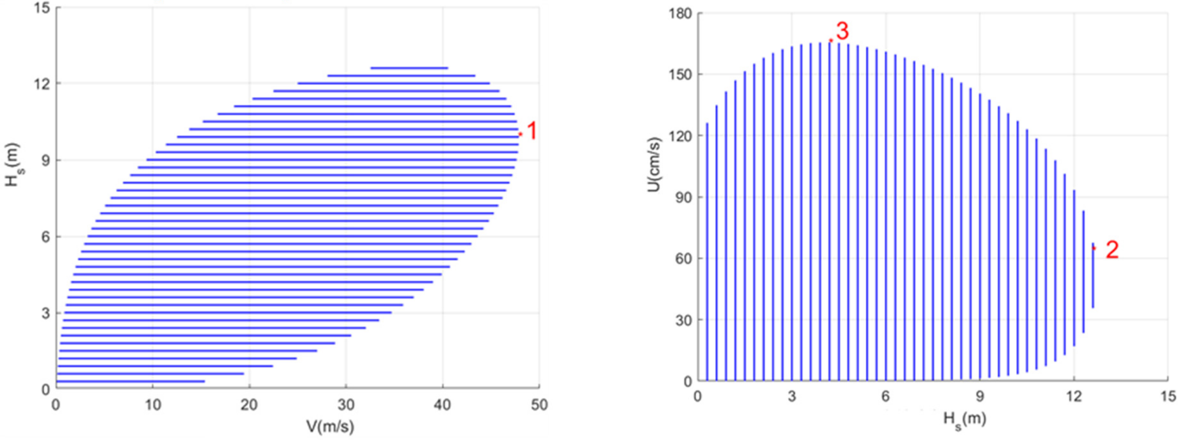
The two parameter leading conditions include wind–wave led, wind–current led and wave–current led, which are denoted as condition points No. 4, 5, and 6. For the 3D contours, a straight line with a slope of 1 was drawn on the corresponding two-dimensional perspective view, and the intersection point with the contour surface is the leading condition point. In order to facilitate observation, the contour is normalized. Figure 8 shows the two parameter leading conditions on the contour of IFORM and ISORM.

Further, after normalizing the contour and recording the corresponding coordinates and combination factors, the combined coefficient matrix under different leading conditions can be obtained, as shown in Table 2. The data in Table 2 were standardized and retained to two decimal places.

It can be found that when the wind mainly led, the wave combination coefficients are close to 1, or when the wind–wave led, the current combination coefficients of IFORM and ISORM contours are both smaller. In other words, when the V or H_s is close to the 50-year extreme state, U does not reach half of its extreme condition; that is, U in the target sea area is not highly correlated with V or H_s.

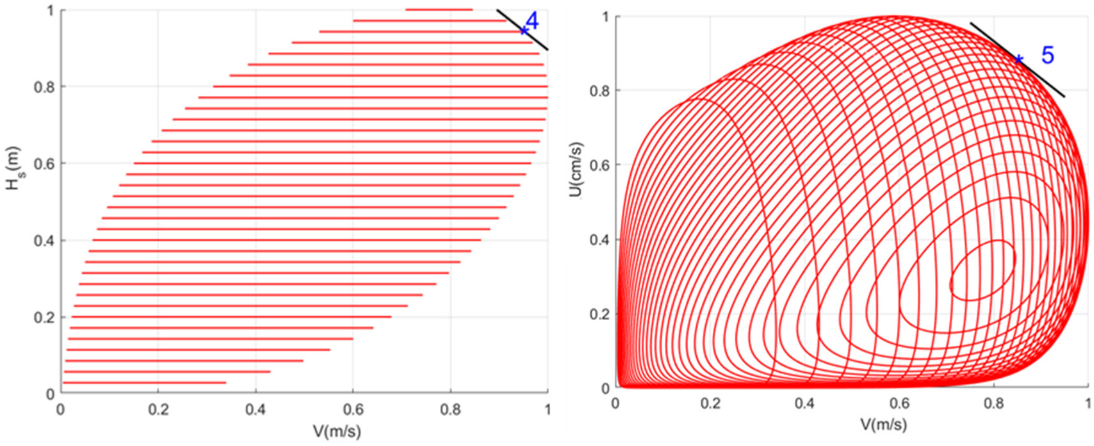


(**a**) Wind speed leading condition via IFORM (**b**) Wave and current leading condition via IFORM



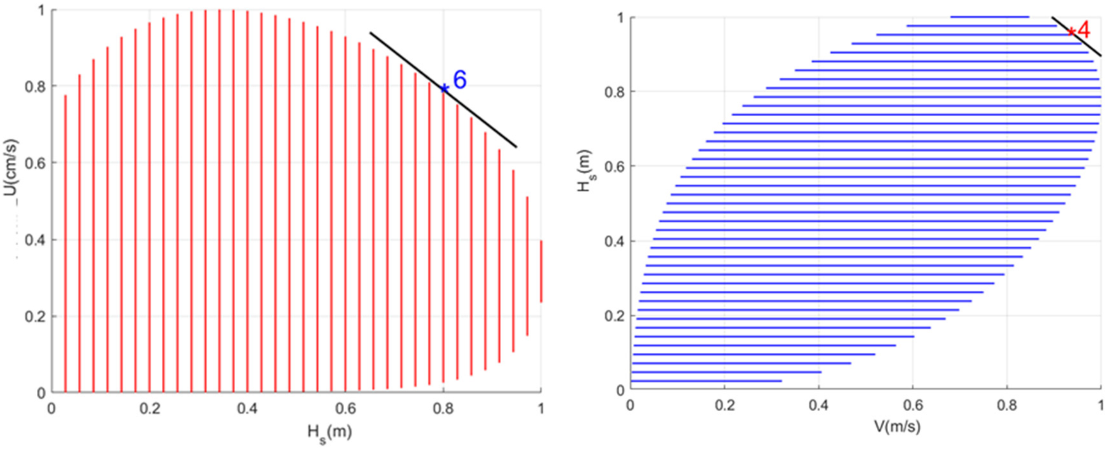
(**c**) Wind speed leading condition via ISORM (**d**) Wave and current leading condition via ISORM

Figure 7. Leading conditions by single parameter.

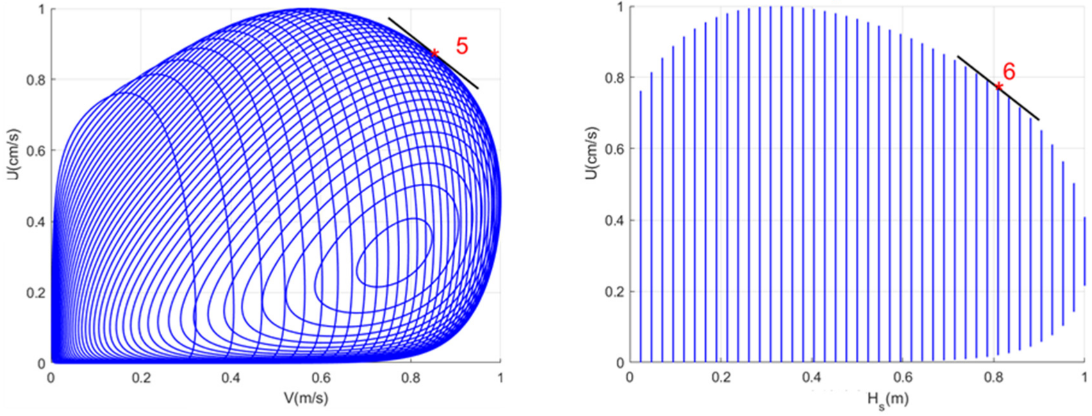


(**a**) Wind–wave leading condition via IFORM (**b**) Wind–current leading condition via IFORM

Figure 8. *Cont.*



(**c**) Wave–current leading condition via IFORM (**d**) Wind–wave leading condition via ISORM



(**e**) Wind–current leading condition via ISORM (**f**) Wave–current leading condition via ISORM

Figure 8. Leading conditions by two parameters.

Table 2. Wind–wave–current combination coefficient matrix.

	IFORM			ISORM		
Leading Conditions	**Wind**	**Wave**	**Current**	**Wind**	**Wave**	**Current**
Wind	1.00	0.77	0.45	1.00	0.79	0.46
Wave	0.76	1.00	0.37	0.84	1.00	0.39
Current	0.59	0.34	1.00	0.57	0.33	1.00
Wind–wave	0.95	0.94	0.43	0.94	0.95	0.43
Wind–current	0.84	0.65	0.89	0.85	0.66	0.87
Wave–current	0.84	0.80	0.78	0.85	0.81	0.77

4.2. Environmental Conditions in Combined Design Conditions

Based on the combination coefficients under different leading conditions in Table 2, the combinations of extreme conditions can be obtained; in order to facilitate the time-domain analysis, the specific value of the sea conditions are summarized in Tables 3 and 4. COMB1–COMB6 represents six groups of extreme conditions with different leading parameters, and the data are all kept to two decimal places.

Table 3. Combination of different conditions via IFORM contour.

Load Cases	**Leading Conditions**	**V (m/s)**	**H_s (m)**	**U (cm/s)**
COMB1	Wind	42.70	8.10	63.57
COMB2	Wave	34.21	10.50	52.95
COMB3	Current	25.06	3.60	141.96
COMB4	Wind–wave	40.57	9.87	61.04
COMB5	Wind-current	35.87	6.83	126.34
COMB6	Wave-current	35.87	8.40	110.73

Table 4. Combination of different conditions via ISORM contour.

Load Cases	**Leading Conditions**	**V (m/s)**	**H_s (m)**	**U (cm/s)**
COMB1	Wind	47.85	9.90	76.35
COMB2	Wave	40.23	12.60	63.98
COMB3	Current	27.47	4.20	165.45
COMB4	Wind–wave	44.98	11.97	71.14
COMB5	Wind-current	40.67	8.32	143.94
COMB6	Wave-current	40.67	10.21	127.40

Apparently, the sea conditions determined via the ISORM contour of the target sea area are conservative and may results in an uneconomical design. Therefore, the combined conditions of the IFORM contour are used for subsequent research.

According to the recommendations of CCS [25], the mooring system of the FOWT should be designed considering that wind, wave and current all reach the extreme values of N-years (usually 1-year or 50-year) RP, which are the COMB1–COMB3 conditions in Tables 3 and 4. However, three parameters infrequently reach the extreme value at the same time, so it is more common that one of the parameters reaches an extreme value. Some standards [6,7,26] also mention these situations and recommend the combined coefficient matrix as (1,0.5,0.5) (V, H_s, U). Further, DNV [7] mentions that the ECM should be applied to obtain the combination of conditions, which is the COMB4–COMB6.

4.3. Response Analyses of Floating Offshore Wind Turbine

4.3.1. Load Cases

Dynamic coupled analysis of an FOWT is conducted to calculate the structure's response subject to wind, wave and current in Sesam DeepC. The environmental dynamic loads include first- and second-order wave forces, wind and current forces, the penitential damping forces, the viscous damping forces and the mooring and cable forces, which lead to a complex non-linear dynamic system [29]. Therefore, the time-domain analysis needs to be carried out to acquire the short-term responses of the FOWT in these sea conditions.

A three-column semi-submersible FOWT in the South China Sea was used as an example. The mooring system of the platform consists of nine identical mooring lines. Three mooring lines are distributed on each of the three columns. Overall, it has a 3 × 3 symmetrical layout, and the nine mooring lines are named clockwise (as 1–9). The first line is the lower line in the load incidence direction, as shown in Figure 9, and its main particulars are listed in Table 5. The non-linear time-domain dynamic response of the platform is calculated using the coupled model in Figure 10a, and the heave RAOs are shown in Figure 10b.

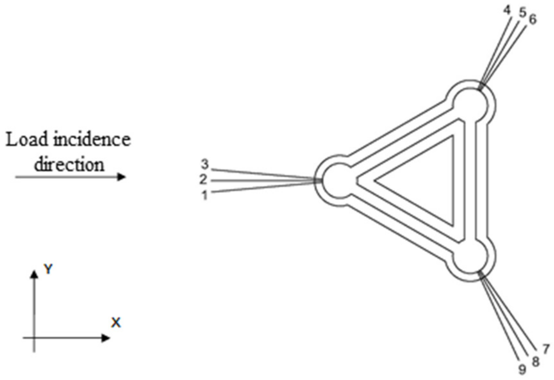
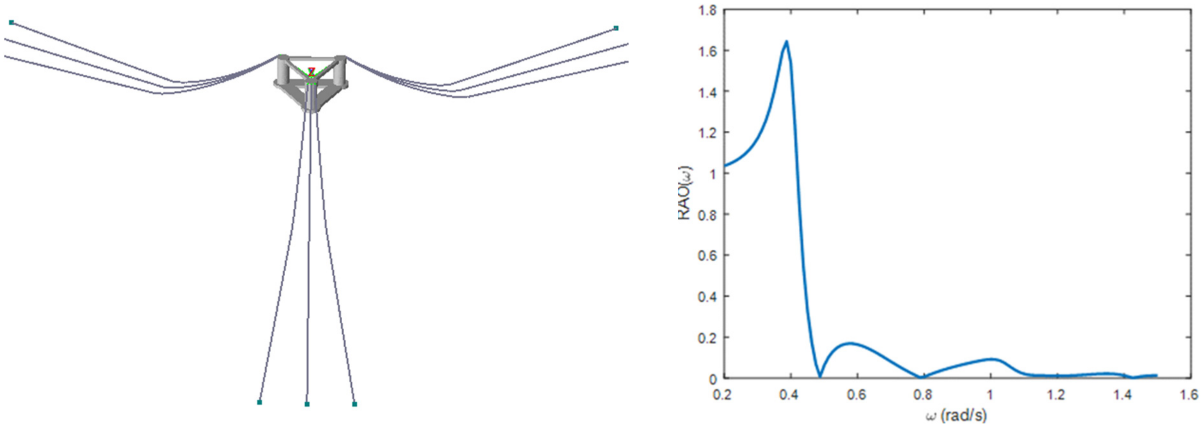


Figure 9. Mooring diagram of FOWT.

Table 5. Main scale parameters of FOWT.

Design Parameters	Date	Unit
Column side length	13	m
Column center distance	60	m
Column height	29.5	m
Pontoon height	3.5	m
Pontoon width	14.5	m
Draft	18	m
Displacement	15,200	t
Molded Depth	33	m
Depth of water	65	m
Mooring radius	450	m



(**a**) Coupled model of the moored platform (**b**) Heave RAO of the platform

Figure 10. Coupled analysis model and heave RAO of the platform.

In this example, for the safety of the platform, the environmental loads are considered as the same incident direction, which rarely happens and could cause larger responses from the structure. Depending on that, the wind, waves and currents are conservatively assumed to be in the 0-degree incident direction, that is, the x direction, which is also the inline direction of the No. 2 mooring line. Combined with the EC and FOWT design standards, different combination conditions SS1–SS12 are selected, as shown in Table 6.

Table 6. Combined conditions based on IFORM contour.

Load Cases	V (m/s)	H_s (m)	U (m/s)
SS1	42.70	8.10	0.64
SS2	34.21	10.50	0.53
SS3	25.06	3.60	1.42
SS4	40.57	9.87	0.61
SS5	35.87	6.83	1.26
SS6	35.87	8.40	1.11
SS7	42.70	10.50	1.42
SS8	33.80	7.20	1.02
SS9	42.70	7.20	1.02
SS10	33.80	10.50	1.02
SS11	33.80	7.20	1.42
SS12	10.50	1.50	0.50

According to Table 6, the wind speed of SS1–SS11 exceeds the cut-out wind speed of 25 m/s; that is, the wind turbine blade is in a shutdown state, and SS12 is the rated condition. At this time, the wind turbine blade can generate electricity normally, so each group of conditions in Table 7 is:

Table 7. Extreme responses of the moored FOWT in different combination conditions.

Load Cases	Responses		
	Pitch (°)	Offset (m)	Mooring Force (kN)
SS1	6.68	8.39	2226.19
SS2	7.20	8.87	2586.68
SS3	2.93	5.10	1646.12
SS4	7.94	9.14	2633.80
SS5	5.94	7.29	2002.70
SS6	6.80	8.14	2253.49
SS7	10.30	11.60	3751.61
SS8	5.78	6.51	1842.27
SS9	6.57	8.29	2239.37
SS10	8.33	9.68	2772.10
SS11	6.21	7.45	2062.73
SS12	3.58	4.80	1646.13

SS1–SS6 are the six leading conditions based on IFORM contour in Section 3.1.2;

SS7 is a working condition where extreme values of wind, waves and currents all reach the extreme values of the 50-year RP;

SS8 is a working condition where the extreme values of wind, waves and currents all reach the extreme values of the 1-year RP;

SS9–SS11 are different combinations of 50-year RP extreme values and 1-year RP extreme values of wind, waves and currents: SS9 conditions are 50-year RP wind + 1-year RP wave + 1-year RP current, and SS10 is 1-year RP wind + 50-year RP wave + 1-year RP current, SS11 is 1-year RP wind + 1-year RP wave + 50-year RP current.

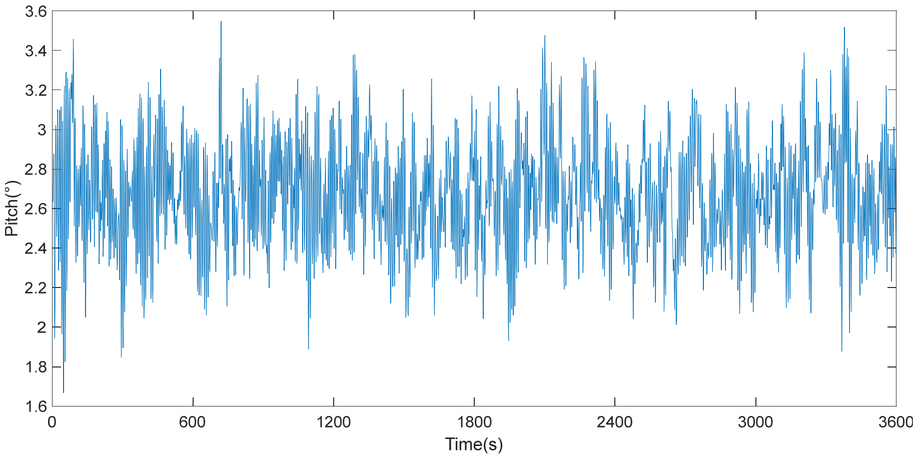
SS12 is the rated wind, wave and current conditions and is superimposed on the top dynamic wind load at the corresponding wind speed.

4.3.2. Time-Domain Analysis

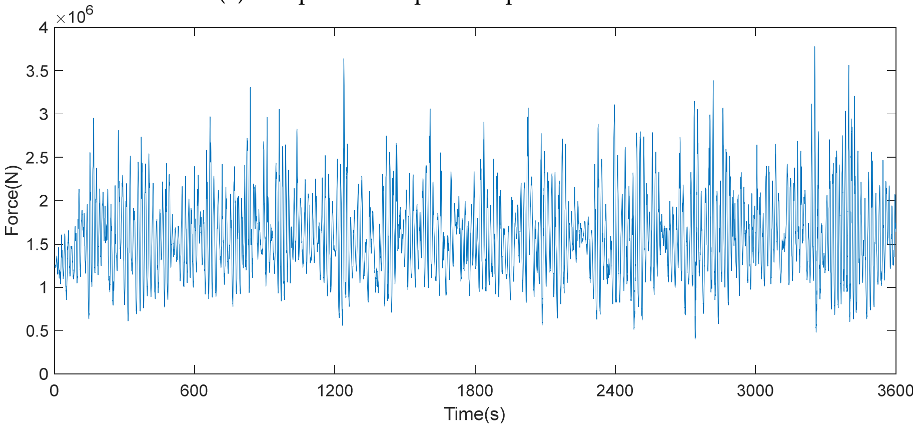
Through time-domain analysis and coupling calculation, the extreme response results of the platform were obtained. Table 7 shows the calculation results of each group of conditions, and the results were retained to two digits.

For the design of FOWTs, the pitch and roll angles are generally limited based on the evaluation standards of an inclination angle of 5° in rated conditions and an inclination angle of 10° in extreme conditions.

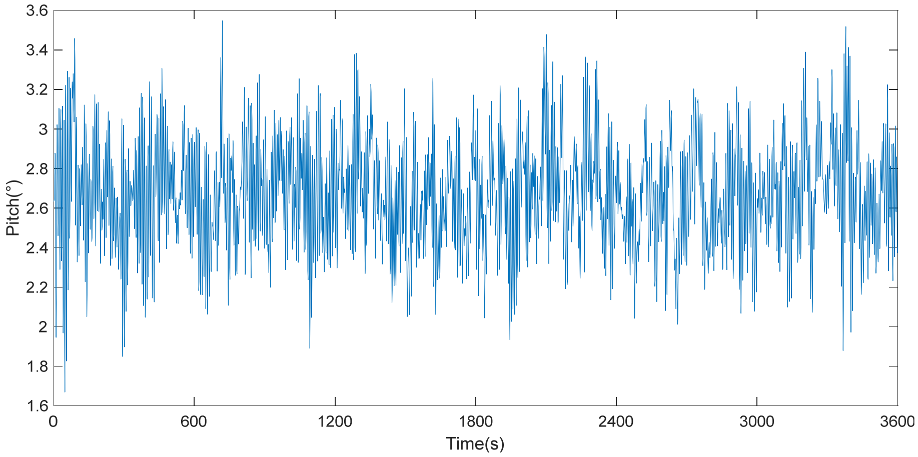
The calculation results in Figure 11a show that the platform pitch angle (3.58°) in rated condition SS12 is less than 5°, which meets the design requirement.



(**a**) The platform's pitch response in case SS12



(**b**) Mooring tension of Mooring line #2 in case SS1



(**c**) The platform's pitch response in case SS7

Figure 11. Dynamic responses of the FOWT platform.

Compared with the responses of SS1 and SS9, both of which are led by 50-year RP wind, the topside wind loads are added to both of them, and the extreme responses meet the requirements of the design standards. Figure 11b shows the tension forces in SS1, responses calculated from SS1 that, selected by the contour, reach larger values than the combinations of 50-year RP wind, 1-year RP wave and current. This indicates that the environmental combinations of contours may be more conservative than the combinations of different RPs. Similarly, the wave-led conditions and the current-led conditions are compared, showing that when wave or current conditions lead, the combinations of contours are of economic efficiency.

As for the most extreme conditions, SS7, which is the most frequently selected working condition as well, the pitch of the platform is over 10°, which implies that the conservative estimate of SS7 may be too large. The tension forces are demonstrated in Figure 11c; the minimum breakage load (MBL) of the mooring line is 12,690 kN, and the maximum tension of mooring line #2 in case SS7 is within the safe range.

In summary, different combined conditions have direct impacts on the structural response, thereby affecting the structural design. The combined conditions recommended in the design standards may provide more dangerous sea conditions, such as the 50-year RP wind, 50-year RP wave and 50-year RP current condition (SS7), which will be more conservative for structures that can withstand higher risks or during survival conditions. Similarly, based on the structural design standards, the designed sea conditions determined by the ECM, which analyzed and the reliability and conservatism of the design conditions, can achieve a better balance between structural safety and cost. Therefore, it is more important to select appropriate conditions based on engineering requirements, metocean conditions and structural properties.

5. Conclusions

The response extremes of an FOWT based on inverse reliability methods and ECM were investigated in this study. The joint probability of wind, wave and current at a site in the South China Sea was investigated to establish three-dimensional ECs by using IFORM and ISORM; comparisons between the wind–wave–current 3D contours by using IFORM and ISORM showed that IFORM is more suitable for FOWTs; using the 3D ECs, the combination factors associated with wind, wave and current were proposed in the South China Sea for six leading combination conditions; and the combined environmental conditions obtained by the inverse reliability methods and the proposed combination factors were further applied to a floating wind turbine platform. The main conclusions are drawn as follows:

(1) Based on the statistical analysis of environmental parameters in the South China Sea, it was found that the Weibull–Log-Normal–Weibull probability distribution model can better describe the long-term joint distribution characteristics of wind–wave–current in the South China Sea.

(2) By comparing the wind–wave–current ECs by using IFORM and ISORM, the ECs constructed by using IFORM and ISORM had a similar shape, the contour from ISORM covered a larger space volume, and the corresponding reliability index was larger, indicating that ISORM is more conservative than IFORM.

(3) ECM is based on the distribution characteristics of wind, wave and current in a sea site, and it can effectively describe the characteristics of environmental conditions. The characteristics of extreme sea conditions appropriately reduce the degree of conservatism in the design of FOWTs, and the EC method can be used for the optimal design of FOWTs.

(4) The inverse reliability analysis of environmental conditions and ECM is based on metocean data from a site in the South China Sea. The proposed wind–wave–current combination coefficients in the design and analysis of FOWTs can provide a more accurate environmental data design basis for the floating platform and the mooring system.

In future work, combinations of the environmental loads should be used to consider different incident directions of wind, wave and current, and the associated extreme responses of the FOWT platform need further research, as the ECM depends on the joint distribution models of environmental data. Moreover, the method can be extended to other sea areas by obtaining the probability distribution characteristics of the environmental parameters of the sea area. Further work will include collecting more metocean data to develop universal wind–wave–current combination coefficients for the design of FOWTs.

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Nomenclature

EC	Environmental Contour
ECM	Environmental Contour Method
IFORM	Inverse First-Order Reliability Method
ISORM	Inverse Second-Order Reliability Method
FOWT	Floating Offshore Wind Turbine
CDF	Cumulative Distribution Function
PDF	Probability Density Function
3D	Three-Dimensional
MLE	Maximum Likelihood Estimation
S_i	Environmental Variable in Physical Space
u_i	Standard Normal Variable in Normal Space
H_s	Significant Wave Height
T_p	Spectral Peak Period
V	Mean Wind Speed
U	Surface Current Speed
RP	Return Period
U space	The space of u_i by Rosenblatt transform
Φ	Standard Normal Distribution
χ_n^2	Chi-Square Distribution
R_{3h}	3 h Response Extreme of The Structure
r_{crit}	Critical Response Threshold
β_f	Reliability Index (Φ^{-1})
β_s	Reliability Index ($(\chi_n^2)^{-1}$)

References

1. Winterstein, S.R.; Ude, T.C.; Cornell, C.A.; Bjerager, P.; Haver, S. Environmental parameters for extreme response Inverse FORM with omission factors. In Proceedings of the ICOSSAR-93, Innsbruck, Austria, 9–13 August 1993; pp. 551–557.
2. Der Kiureghian, A.; Zhang, Y.; Li, C.C. Inverse reliability problem. *J. Eng. Mech.* **1994**, *120*, 1154–1159. [CrossRef]
3. Li, H.; Foschi, R.O. An inverse reliability method and its application. *Struct. Saf.* **1998**, *20*, 257–270. [CrossRef]
4. Xiang, Y.B.; Liu, Y.M. Application of inverse first-order reliability method for probabilistic fatigue life prediction. *Probabilistic Eng. Mech.* **2011**, *26*, 148–156. [CrossRef]
5. Chai, W.; Leira, B.J. Environmental contours based on inverse SORM. *Mar. Struct.* **2018**, *60*, 34–51. [CrossRef]
6. International Electrotechnical Commission (IEC). *Marine Energy—Wave, Tidal and Other Water Current Converters*; International Electrotechnical Commission: Geneva, Switzerland, 2016.

7. DNV, G.L. DNVGL-RP-C205. Environmental Conditions and Environmental Loads. 2019. Available online: https://www.dnv.com/oilgas/download/dnv-rp-c205-environmental-conditions-and-environmental-loads/ (accessed on 3 September 2019).
8. Haver, S.; Winterstein, S.R. Environmental Contour Lines: A Method for Estimating Long Term Extremes by a Short Term Analysis. *Trans.—Soc. Nav. Archit. Mar. Eng.* **2009**, *116*, 116–127.
9. Huseby, A.B.; Vanem, E.; Natvig, B. A new approach to environmental contours for ocean engineering applications based on direct Monte Carlo simulations. *Ocean Eng.* **2013**, *60*, 124–135. [CrossRef]
10. Huseby, A.B.; Vanem, E.; Natvig, B. Alternative environmental contours for structural reliability analysis. *Struct. Saf.* **2015**, *54*, 32–45. [CrossRef]
11. Derbanne, Q.; de Hauteclocque, G. A new approach for environmental contour and multivariate de-clustering. In Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering, Glasgow, UK, 9–14 June 2019; American Society of Mechanical Engineers: New York, NY, USA; p. V003T02A030.
12. Battjes, J.A. Long-term wave height distributions at seven stations around the British Isles. *Dtsch. Hydrogr. Z.* **1972**, *25*, 179–189. [CrossRef]
13. Longuet-Higgins, M.S. On the joint distribution of the periods and amplitudes of sea waves. *J. Geophys. Res.* **1975**, *80*, 2688–2694. [CrossRef]
14. Haver, S. Wave climate off northern Norway. *Appl. Ocean Res.* **1985**, *7*, 85–92. [CrossRef]
15. Vanem, E. Joint statistical models for significant wave height and wave period in a changing climate. *Mar. Struct.* **2016**, *49*, 180–205. [CrossRef]
16. Bruserud, K.; Haver, S.; Myrhaug, D. Joint description of waves and currents applied in a simplified load case. *Mar. Struct.* **2018**, *58*, 416–433. [CrossRef]
17. Fontaine, E.; Orsero, P.; Ledoux, A.; Nerzic, R.; Prevosto, M.; Quiniou, V. Reliability analysis and Response Based Design of a moored FPSO in West Africa. *Struct. Saf.* **2013**, *41*, 82–96. [CrossRef]
18. Vázquez-Hernández, A.O.; Ellwanger, G.B.; Sagrilo, L.V.S. Long-term response analysis of FPSO mooring systems. *Appl. Ocean Res.* **2011**, *33*, 375–383. [CrossRef]
19. Giske, F.-I.G.; Kvale, K.A.; Leira, B.J. Long-term extreme response analysis of a long-span pontoon bridge. *Mar. Struct.* **2018**, *58*, 154–171. [CrossRef]
20. Lystad, T.M.; Fenerci, A.; Øiseth, O. Buffeting response of long-span bridges considering uncertain turbulence parameters using the environmental contour method. *Eng. Struct.* **2020**, *213*, 110575. [CrossRef]
21. Castellon, D.F.; Fenerci, A.; Øiseth, O.; Petersen, Ø.W. Investigations of the long-term extreme buffeting response of long-span bridges using importance sampling Monte Carlo simulations. *Eng. Struct.* **2022**, *273*, 14986.
22. Rosenblatt, M. Remarks on a Multivariate Transformation. *Ann. Math. Statist.* **1952**, *23*, 470–472. [CrossRef]
23. Gong, H.N.; Xie, B.T.; Wang, J.R. Long-term prediction of extreme response of deepwater floating platform based on environmental contour method. *Ocean Eng.* **2021**, *39*, 28–38. (In Chinese)
24. Giske, F.I.G.; Leira, B.J.; Øiseth, O. Full long-term extreme response analysis of marine structures using inverse FORM. *Probabilistic Eng. Mech.* **2017**, *50*, 1–8. [CrossRef]
25. CCS. *CCS GD29-2021. Guide for Floating Offshore Wind Turbine*; China Classification Society: Beijing, China, 2021. (In Chinese)
26. ABS. *Guide for Building and Classing—Floating Offshore Wind Turbines*; American Bureau of Shipping: Spring, TX, USA, 2024.
27. Liao, Z.K.; Zhao, Y.L.; Dong, S. Estimating Design Loads for Floating Structures Using Environmental Contours. *J. Mar. Sci. Appl.* **2022**, *21*, 114–127. [CrossRef]
28. Mackay, E.; Hauteclocque, G.D. Model-free environmental contours in higher dimensions. *Ocean. Eng.* **2023**, *273*, 113959. [CrossRef]
29. Wang, J.R.; He, K.; Xie, B.T.; He, C.L.; Wu, W.B. A coupled analysis approach for a moored floating structure subject to internal solitary waves and surface waves. *Ocean Eng.* **2024**, *306*, 118029118029. [CrossRef]