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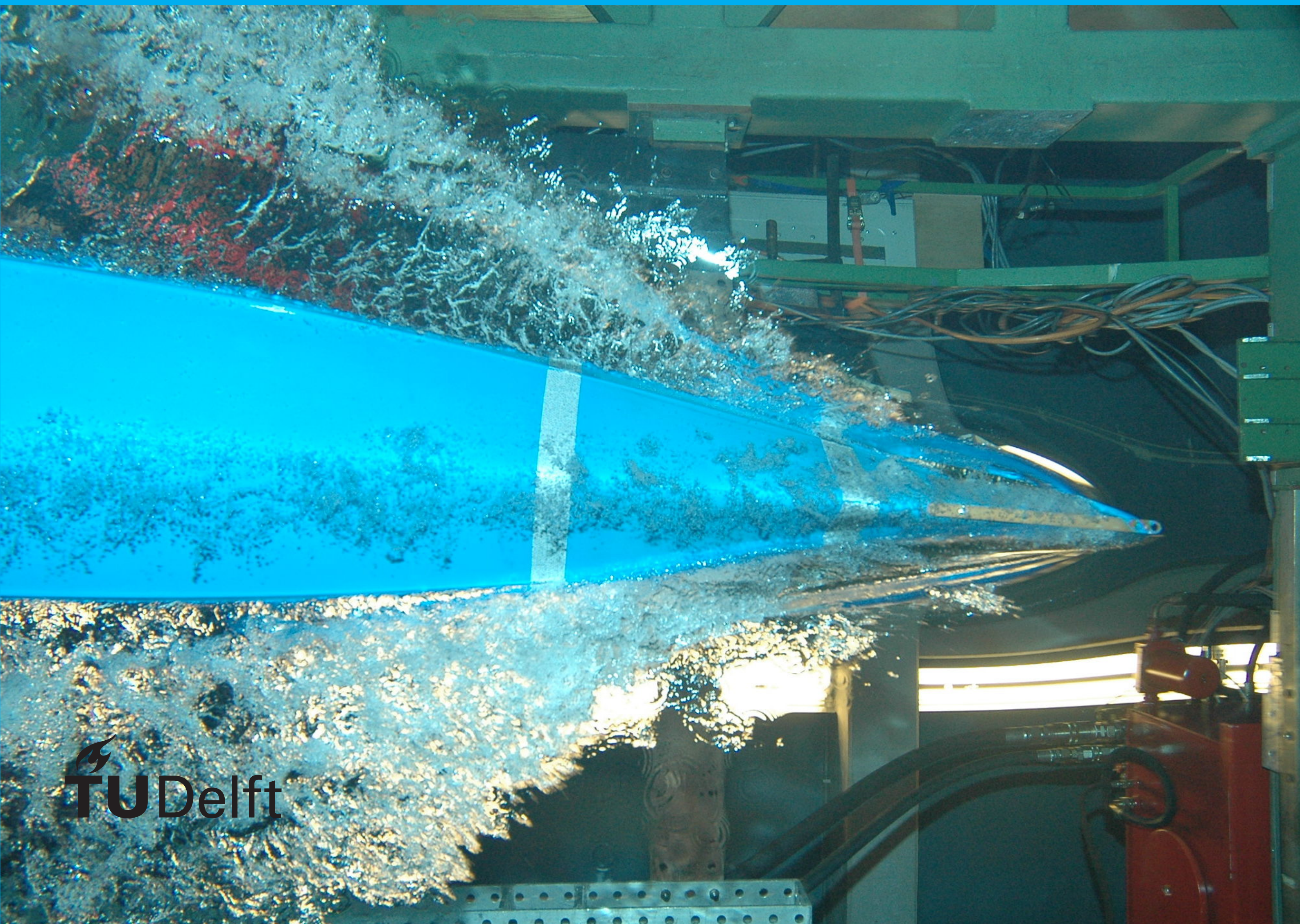
August 2021



Comparing different approaches to environmental contours for offshore wind turbine extreme response analysis

by

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TU Delft

Preface

The thesis is the final project of the Offshore and Dredging Engineering Master. It has been a valuable journey in my life.

I would like to express my appreciation to my supervisor, dr.ir. A. Jarquin Laguna and other members of the committee Prof.dr. S.J. Watson and Dr. ir. P. van der Male for their support and guidance. I am very grateful for the meeting and email time with them. Without their help, this work can not be completed.

Many thanks to my parents for their encouragement and support. Their encouragement gave me the courage to face and overcome difficulties in life. I would also like to thank all my friends both in Netherlands and in China. We encouraged each other during the corona time.

Finally, I would like to thank the decision, that is studying in TU Delft. The experience of the past two years has been the most exciting part of in my life. The past two years have taught me introspection and thinking to meet the challenges in my life firmly.

Zuhui Li
Delft, August 2021

Abstract

For marine structures subjected to combined wind and wave loads, predicting the long-term extreme response corresponding to a certain return period is an important aspect during the design stage. Generally, a full long-term analysis (FLTA) is recognized as a highly accurate method to determine the long-term extreme responses. FLTA integrates all the short-term extreme responses with their corresponding occurrence probability of environmental conditions. Therefore, this approach is very time-consuming and inefficient, especially for complex marine structures.

Therefore, the environmental contour method (ECM) is proposed as a more efficient alternative method for predicting the long-term extreme response of offshore structures. The traditional environmental contour is obtained using the joint distribution of mean wind speed, significant wave height, and spectral peak period. This method has been used extensively on marine structures subjected to wave loads with reasonable numerical accuracy. It decouples the response with the environmental variables and uses the largest most probable short-term response evaluated along with the environmental contour corresponding to a given return period or exceedance probability to represent the extreme response. However, for offshore wind turbines which are subjected to combined wind and wave loads, the ECM performs poorly on wind-induced responses (under wind only or combined wind and wave load conditions). This is due to the non-monotonic behavior of the wind-induced responses resulted from the control system of the wind turbine. The ECM will cause the deviation of the critical environmental conditions between the identified environmental contour and the realistic case. The modified environmental contour method (MECM) is proposed and developed to deal with such a system whose response changes discontinuously due to variations in the operating conditions with additional environmental contours taken into consideration.

It is seen that environmental contour plays an important role in the application of both the ECM and the MECM. A set of environmental conditions are selected along the target contour to perform short-term response analysis for the determination of the long-term extreme response. Traditionally, the environmental contour is established based on the inverse first-order reliability method (IFORM) by Rosenblatt transformation with response excluded as a variable. Since this traditional method involves the transformation of the standard normal variables and original physical space which is related to the FORM-approximation closely, a possible over-or underestimation of failure probability may be induced. Another method to obtain environmental contour is the inverse second-order reliability method (ISORM). The ISORM approximates the failure surface by a quadratic function at the design point in standard normal space instead of a linear function in the IFORM. The result of contour based on the ISORM always being conservative, which cannot be ensured by the traditional IFORM method. The highest density region method (HDRM) is to define the environmental contour as the boundary, along which the joint probability density function (PDF) of the environmental variables is a constant. This method solves the contour in the original physical space and can be used in high-dimension conditions.

Applying the environmental contour method and modified environmental contour method based on the IFORM, the ISORM, and the HDRM allows to predict the extreme response. The MECM results are much better than the results from the ECM according to safety requirements in the design stage. When applying the environmental contour method, the inverse second-order reliability method to obtain contour is recommended. The ISORM contour is more conservative than the traditional inverse first-order reliability method but the numerical analysis is more stable than the highest density region method in three dimensions, while when applying the modified environmental contour method, the traditional inverse first-order reliability is preferred because of its simplicity and time-efficiency in the calculation.

Contents

1

Introduction

1.1. Motivation

1.1.1. Background

For marine structures and offshore wind turbines (Figure 1.1) subjected to combined wind and wave loads, predicting the long-term extreme response corresponding to a certain return period is an important aspect during the design stage. The estimation of long-term extreme response can be considered as solving a reliability problem, which refers to the problem of ensuring safety during the life cycle of the structure. It means that for a certain extreme response, its corresponding probability of exceeding (can also be called the probability of failure) should always be lower than a certain failure upper limit to satisfy the reliability. On the other hand, if the exceedance probability or the return period is given, the extreme response corresponding to the exceedance probability or this return period can be found, such as once in 20 years or once in 50 years.

Figure 1.1: London Array offshore wind farm (London Array, 2014)

Generally, the full long-term analysis (FLTA) is considered to be the most accurate method to evaluate the extreme response of the structure. This method considers all the environmental conditions, so it is inefficient and impractical in application. Usually, its results are used as a benchmark for the accuracy of other methods. However, this method integrates all the short-term extreme responses with their corresponding occurrence probability of environmental conditions, therefore, it is time-consuming and inefficient. Only a few environmental conditions contribute to the extreme response of the structure.

In addition to estimating extreme response by combining the response under a single environmental load, a more direct way for simplification is to reduce the number of calculations, that is, obtain the result through fewer calculations of the environmental conditions required. The environmental contour method (ECM) is such a method and is developed as one of the approximate methods to improve the computational efficiency by reducing the number of required short-term analyses (Haver and Winterstein, 2009). This method has been used extensively on marine structures subjected to wave loads with reasonable numerical accuracy. It decouples the response with the environmental variables and uses the largest most probable short-term response evaluated along with the environmental contour corresponding to a given return period or exceedance probability to represent the extreme response. However, for offshore wind turbines which are subjected to combined wind and wave loads, ECM performs poorly on wind-induced responses (under wind only or combined wind and wave load conditions) (Li et al., 2013b). This is due to the non-monotonic behavior of the wind-induced responses resulted from the control system of the wind turbine. ECM will cause the deviation of the critical environmental conditions between identified environmental contour and the realistic case. Modified environmental contour method (MECM) is developed to deal with such system whose response changes discontinuously because of the change of the operational mode with additional environmental contours taken into consideration (Li et al., 2016). It is proved to be accurate for offshore wind turbine (Li et al., 2017), combined wind turbine and wave energy converter system (Li et al., 2018b) and integrated renewable energy device consisting of a floating wind turbine, a wave energy converter, and two tidal turbines (Li et al., 2019).

It is seen that environmental contour plays an important role in the application of both ECM and MECM. A set of environmental conditions are selected along the target contour to perform short-term response analysis for the determination of the long-term extreme response. Traditionally, the environmental contour is established based on the inverse first-order reliability method (IFORM) by Rosenblatt transformation (Rosenblatt, 1952) with response excluded as a variable (Winterstein et al., 1993). Since this traditional method involves the transformation of the standard normal variables and original physical space which is related to the FORM-approximation closely, a possible over-or underestimation of failure probability may be induced. Environmental contours were established based on IFORM pass-through points with a given marginal exceedance probability. Since there is no unique definition of exceedance probability for multivariate cases, the environmental contour can be defined in different ways. Apart from Rosenblatt transformation, exceedance probability can also be defined in terms of the total probability outside the contour (Mackay and Haselsteiner, 2021), for example, Inverse Second-Order Reliability Method (ISORM) (Chai and Leira, 2018) and highest density region method (HDRM) (Haselsteiner et al., 2017). ISORM approximates the failure surface by a quadratic function at the design point in standard normal space instead of a linear function in IFORM. The later definition tends to give conservative results compared with the former one.

1.1.2. Offshore wind turbine status

In the past few years, with the increasingly prominent problem of energy shortage and the global climate change caused by traditional fossil fuels, governments, and research institutions around the world have begun to pay more attention to the problem of energy. It is an urgent problem to look for stable renewable energy, alleviate the situation of an energy shortage, and reduce environmental pollution. Vigorously developing clean energy, such as wind energy, wave energy, tidal energy, geothermal energy, and solar energy, is also the consensus of all countries in the world.

Among the clean renewable energy mentioned above, wind energy has become one of the energy sources with the strongest growth momentum in recent years. Wind energy is a form of solar energy with great potential, and its reserves on the earth are also very abundant. It is estimated that 1% to 3% of the solar energy absorbed by the earth is converted into wind energy. The total amount is equivalent to 50 to 100 times that of all plants on the earth absorbed solar energy through photosynthesis and converted into chemical energy (National Geographic Society). Mankind has a long history of using wind energy. Before the popularization of electric power, people have developed different devices for wind utilization, for example, people used sails to propel the boat forward in BC or use wind power to lift water, irrigate, and grind grain. Nowadays, wind energy is mainly used to generate electricity. After the industrial revolution, equipment for generating electricity using wind energy appeared for the first time, and it has developed rapidly in recent decades, that is the wind turbine. As one of the power generation methods with the most mature technology, the most large-scale development conditions, and commercial development prospects in the field of new energy, wind energy has played an important role in the reform of energy structure, the development of new energy, and the maintenance of ecological balance.

In the past few years, wind energy is the fastest-growing form of energy. It can be predicted that in the next few decades, wind energy will play a key role in the proportion of energy supply. Since the first offshore wind farm-Vindeby Offshore Wind Farm (OWF), constructed in 1992 (Olsen and Dyre, 1993). The rapid increase of various offshore wind farm projects in Europe has made Europe a leader in the development of offshore wind power applications (Da et al., 2011). Until 2000, there were no offshore wind farms outside Europe (Zhao and Ren, 2015). Today, China and Europe lead the new installations of offshore wind turbines, accounting for more than 98% of new installations in 2020, shown in Figure 1.2.

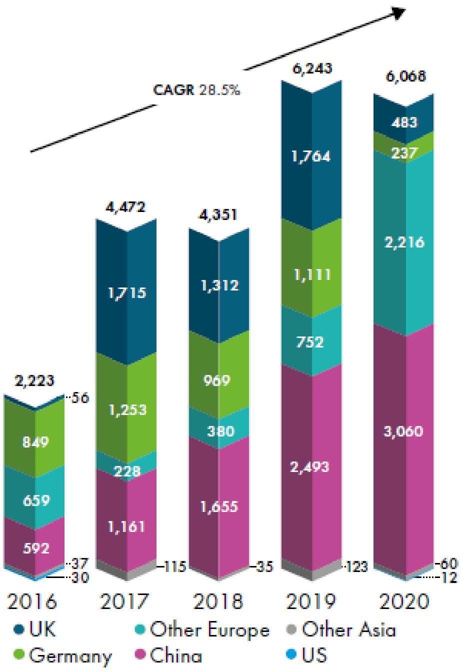


Figure 1.2: New offshore installation(MW) for different countries (GWE Council, 2021)

With the improvement of technology in recent years, the costs of offshore wind energy have fallen significantly, making it the cheapest large-scale source of renewable energy. The advantages of offshore wind farms are increasingly prominent. The offshore wind speed is usually higher than that onshore. Even a small increase in wind speed brings a large energy output, and the wind speed on the ocean is more stable, which makes the energy more and more reliable (Jeng, 2008). In addition, offshore wind with smaller wind shear and turbulence intensity is beneficial to ensure stable power generation and can reduce the overall fatigue load of the unit, which is beneficial to prolong the service life of the wind turbine (Esteban et al., 2011). Finally, sufficient sea area ensures the feasibility of large-scale wind farms, reduces visual and noise pollution. It helps to apply larger blades to increase single-unit power generation. This is also a way to reduce costs and increase the competitiveness of offshore wind energy (Herman et al., 2003).

Early research on offshore wind turbines is generally based on the existing onshore wind power technology. However, in the past ten years, the offshore wind power industry has continuously developed and improved offshore technology. The main difference from onshore wind turbines is the support structure of offshore wind turbines (Musial and Ram, 2010). According to the different forms of the support structure, it can be divided into two categories: bottom-fixed substructures and floating substructures, shown in Figure 1.3 and Figure 1.4.

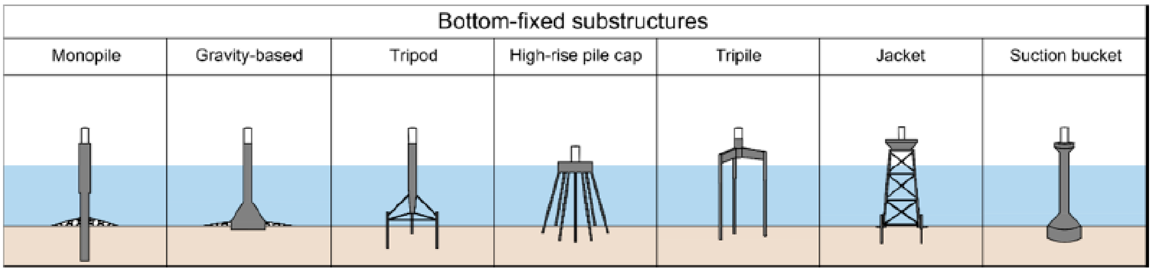


Figure 1.3: Different types of bottom-fixed substructures for offshore wind turbines (Mathern et al., 2021)

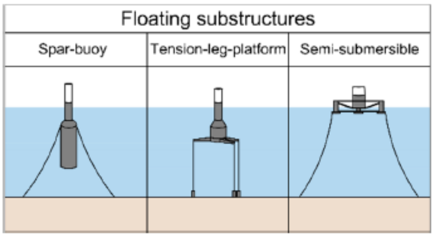


Figure 1.4: Different types of floating substructures for offshore wind turbines (Mathern et al., 2021)

1.2. Problem definition

Predicting the long-term extreme response can be considered as a reliability method and the environmental condition is modeled by a probability density function. Usually, not one environmental variable needs to be considered, but a combination of different variables. The joint probability density function can be considered as the combination of the marginal distribution of one variable and the conditional distribution of other variables, where Weibull distribution (Li et al., 2013a) and lognormal distribution are usually used (Vanem and Bitner-Gregersen, 2012). The process to obtain contour is the process to solve these probability distribution functions. The purpose of environmental contours is that the contour encloses the region of the environmental condition for the design purpose. The critical environment condition occurs on the boundary of this design region, that is the contour. In standard (Veritas, 2000), it suggests engineers evaluate the response along the environmental contour line instead of calculating all the combinations of the environmental condition in the region enclosed by the boundary line, and the calculated result is considered to be reliable, therefore, this is the purpose of the environmental contour.

Different definitions about environmental contour have been proposed differently, the contour line obtained through different definitions is different, therefore, the selected critical environmental conditions and the predicted extreme response will be different. The different definition of the environmental contour is one-sided exceedance probability, two-sided exceedance probability, and constant probability density. There are different approaches to obtain the environmental contour for a given type of contour line.

The traditional environmental contour method is based on the inverse first-order reliability method (IFORM) (Winterstein et al., 1993) through Rosenblatt transformation (Rosenblatt, 1952). The general equation can be simplified to convert the limit state function in physical space to standard normal space. This method excludes the response as a variable, but only considers the environmental variables.

An alternative method is the inverse second-order reliability method (ISORM) (Chai and Leira, 2018). It determines the failure surface by a quadratic function at the design point in U space, compared with that from the first-order reliability method in a linear function to represent the failure surface.

Another method described by Haselsteiner by separating the exceedance region from the failure region is the highest density region method (HDRM) (Haselsteiner et al., 2017). In this method, the environmental contour is defined as the boundary, along which the joint probability density function (PDF) of the environmental variables is a constant.

Environmental Contour Method is a valuable topic and it is active research. This method has been widely used in ship response analysis, but lack of information on research related to offshore renewable energy devices, i.e. offshore wind turbines, tidal turbines, wave energy converters, etc. The main objectives of this research are:

- Conclude the principles of the environmental contours obtained by the traditional IFORM, more conservative ISORM, and the HDRM.
- Predict the long-term extreme responses of monopile 5 MW wind turbine on the center of North Sea based on three different approaches of constructing environmental contours.
- Evaluate the effect of different contour establishment approaches on long-term extreme response analysis of offshore wind turbine.
- Explore which method is most recommended in practical applications.

1.3. Outline

Chapter 2 is the literature review of the present research. The different methods for long-term analysis are introduced, including full long-term analysis and some simplified methods, such as design sea state approach, subset simulation, and environmental contour method. Besides, different approaches to obtain environmental contour and its pros and cons are summarized.

Chapter 3 introduces the methodology relevant to the research. There are mainly two parts, The first one is about the principle for response analysis, including full long-term analysis, simplified full long-term analysis, environmental contour method, and modified environmental contour method. Another one is about the different approaches to obtain environmental contours, inverse first-order reliability method, inverse second-order reliability method and highest density region method included.

The outcome of this work is displayed and discussed in Chapter 4. It contains the definition of the joint probability density and the wind turbine model. Besides, the results based on different methods to predict the extreme response is presented. Besides, the prediction of the extreme response based on the different methods is compared and discussed.

Chapter 6 summarizes the conclusion and some recommendations. Limitations of this research and potential future research are listed and discussed as well. Finally, to support this work, numbers, figures, and characteristics of models and results are depicted in the appendices.

2
Literature Review

2.1. Introduction

Predicting the extreme response for a long term has always been an important step during the design stage no matter for marine structures or offshore wind turbines subjected to wave loads only, or wind loads only, or combined wave and wind loads. The prediction of long-term extreme response is based on the reliable probability, which can be considered as a reliability problem. It means that for a certain extreme response, its corresponding probability of exceeding (can also be called the probability of failure) should always be lower than a certain failure upper limit to satisfy the reliability. On the other hand, if the exceedance probability or the return period is given, the extreme response corresponding to the exceedance probability or this return period can be found, such as once in 20 years or once in 50 years.

By applying different methods, many scholars have conducted a lot of research on the prediction of long-term extreme response problems. In this literature review, different methods to evaluate long-term extreme responses are summarised, including the full long term analysis method and other simplified methods, such as design sea state approach (Naess and Moan, 2013), subset simulation (Au and Beck, 2001) and environmental contour method (Haver and Winterstein, 2009), introduced in section 2.2. A landmark method is the environmental contour method, different approaches to obtain the environmental contour and their advantages and disadvantages are evaluated in section 2.3. Finally, all the methods mentioned are summarised.

2.2. Long-term extreme response analysis

2.2.1. Full long term analysis

Full long term analysis (FLTA) is the most accurate method to predict extreme response, which can be focused on different positions of the wind turbine, such as the load on the blade (out-of-plane bending moment) (Agarwal and Manuel, 2009), the gear loads (Nejad et al., 2013) or the pitch moment on the mudline of a monopile support (Chen et al., 2020). This method considers all the environmental conditions, so it is computationally expensive in application. Usually, its results are used as a benchmark for the accuracy of other methods.

The advantage of this method is that it integrates all the environmental variables, so its results can be considered as the most representative straightforward method. It is accurate because this method takes into account the combination and contribution of all environmental variables, which results in a huge amount of simulations and is very time-consuming. Even worse, due to the irregularity of the wind and wave loads, for each environmental condition, a number of stochastic simulations are required, and then statistical methods are used to obtain the convergence result. The return period is related to the selection of the random number. Generally, the random number required for calculation is negatively correlated with the return period. The larger the return period, the fewer random seeds are needed for statistical analysis (for example, a return period of 50-year requires 20 random numbers, and a return period of 0.077 years requires 90 random numbers). The method to determine whether the results of curve fitting (the number of random seeds) is reliable enough is to test the upper and lower bounds of the 95% confidence interval. If it is less than 3%, the result of the fitting is considered to be reliable enough. For the division of the range and increment of environmental variables in the full long-term analysis, if the increment becomes smaller, there are more combinations of environmental variables included, and the number of simulations required and the calculation time will increase exponentially.

Extreme value analysis is common both in marine structure and offshore wind turbines, introduced in IEC 61400-1 (Turbines, 2005). The estimation of long-term extreme response can be considered as solving a probability problem, described in a simplified form in Equation 2.1 (Giske et al., 2017).

$$RE = 1 - P_f = \iint_{r<r_e} f_{R,E}\,(r,e)drde \tag{2.1}$$

where RE is the reliability, P_f is the failure probability, R and E is the response and the environmental variables, which is described by the joint probability distribution function (PDF) $f_{R,E}\,(r,e)$, r_e is the maximum response.

The principle of full long-term extreme response analysis is to obtain an extrapolated value by considering short-term load conditions for a given exceeding probability. Agarwal and Manuel (Agarwal and Manuel, 2009) give a detailed explanation about extrapolation methods and models. The peak-over-threshold method is applied to derive the short-term probability distributions of turbine loads and the inverse first-order reliability method is used to estimate long-term loads, which is compared with direct integration(FLTA). The response calculated by full long-term analysis is to integrate all the environmental variables and the corresponding probability distribution. Estimating the long-term extreme values can be based on different approaches, including short-term extremes, peak values, and the up-crossing rate (Naess and Moan, 2013). The full long-term analysis with short-term extreme values as an example can be expressed as:

$$F_R^{LT}\,(r_e) = \int F_{R|E}^{ST}\,(r_e\,|e)f_E\,(e)\,de \tag{2.2}$$

$$\int f_E\,(e)\,de = 1 \tag{2.3}$$

where $F_R^{LT}\,(r_e)$ is the long-term cumulative distribution function of the extreme response R and $F_{R|E}^{ST}\,(r_e\,|e)$ the short-term distribution function, *E* is the environmental conditions that satisfies Equation 2.4. Then the long-term extreme response r_e is predicted by Equation 2.5.

$$\int f_E\,(e)\,de = 1 \tag{2.4}$$

$$F_{R_{1h}}^{LT}\,(r_e) = 1 - P_f \tag{2.5}$$

2.2.2. Simplified method

Because of the inefficiency of the full long-term analysis, different simplified methods are proposed. In some studies, the long-term extreme response is estimated by considering the single environmental variables and add the single extremes together. When Baarholm et al. were studying the long-term stress of a ship, they combined single long-term extreme stresses caused by bending moments in both horizontal and vertical directions, the sum-of-squares method is used and considers the correlation among stresses. It is a more efficient way of calculation. Moreover, the accuracy of this method is also guaranteed by the correction coefficient. (Baarholm and Moan, 2002). For extreme analysis, this method has also been applied in other studies, such as in the study of stress and fatigue damage research for ships (Jiao, 1996) and bending moments research of ships (Wang and Moan, 1996).

Generally, the long-term analysis is important not only for the extreme response but also for estimating the fatigue damage. Dynamic analysis can be performed both for time-domain analysis and frequency-domain analysis. Over the years, a variety of methods have been proposed for long-term extreme analysis, combining frequency domain analysis (Grime and Langley, 2008) and time-domain simulation (Larsen and Olufsen, 1992)(Vázquez-Hernández et al., 2011). For fatigue damage, the most convenient way for analysis is frequency domain analysis. It is fast instead of a time-costly time-domain analysis. But time domain is still necessary because frequency domain analysis depends on extensive simplifications regarding nonlinearity and response statistics. Therefore, to make the predicted result more accurate, time-domain analysis is required.

In addition to estimating extreme response by combining the response under a single environmental load, a more direct way for simplification is to reduce the number of simulations. Obtain the result through fewer calculations of the environmental conditions required. Li et al. introduced a simplified full long-term analysis (SFLTA) when considering long-term extreme responses for a combined offshore renewable energy system (wave energy converter & offshore wind turbine) (Li et al., 2018b). The principle of this simplified method is to reduce the number of environmental conditions used for calculation but give the same results, expressed as:

$$1 - P_f = \int_{simplified} F_{R|E}\,(r_e\,|e)\, f_E\,(e)de \tag{2.6}$$

For the return period of 20-year or 50-year (high exceedance probability), attention should be paid to the tail part of the cumulative distribution function, which plays a significant role in the estimation of extreme response. It means that many combinations of environmental variables do not contribute to the extreme response. For these environmental conditions, replace the cumulative distribution function by 1 in long-term extreme analysis, The forecast results of the return period of T-year (e.g 20-year) extreme response will not be different significantly. Therefore, this means only the probability distribution of considered environmental conditions contributes to the long-term extreme response analysis, then Equation 2.6 can be rewritten as:

$$\begin{aligned} F_{R_{1h}}^{LT}\,(r_e) = & \sum_{(x_1,x_2,x_n)_{im}} F_{R_{1h}|X_1,X_2,X_n}^{ST}\,(r_e\,|x_1,x_2,x_n)\cdot f_{X_1,X_2,X_n}\,(x_1,x_2,x_n)\,\Delta x_1 \Delta x_2 \Delta x_n + \\ & \sum_{(x_1,x_2,x_n)_{ne}} 1\cdot f_{X_1,X_2,X_n}\,(x_1,x_2,x_n)\,\Delta x_1 \Delta x_2 \Delta x_n \end{aligned} \tag{2.7}$$

where $(x_1, x_2, x_n)_{im}$ is the important environmental conditions and $(x_1, x_2, x_n)_{ne}$ is the negligible environmental conditions.

The environmental conditions can be divided into important ones and negligible ones. But how to select the considered environmental conditions is usually difficult when applying this method. The best way is to concentrate on environmental conditions with special significance, such as the cut-out wind speed, the rated wind speed of the wind turbine, etc. Similar approaches to reduce unimportant environmental conditions have also been applied in previous studies, for a monopile wind turbine (Chen et al., 2020), for a jacket-type offshore wind turbine subjected to combined wave and wind loads (Li et al., 2013b), and a marine structure subjected to wave loads only.(Videiro and Moan, 1999).

Another simplified method applied to extreme response prediction is the short-term approach (also called design sea state approach) (Naess and Moan, 2013)(Dnv, 2014). This method is developed for the offshore structure subjected to wave loads only. It contains two variables-significant wave height H_s and spectral peak period T_p. The sea state with a return period of n-year H_s and associated T_p is identified. The response obtained through this combination of H_s and T_p is worked as the n-year extreme response.

Although this method is time-saving for calculating, it also has disadvantages. First of all, it only considers the relevant parameters of wave loads, which is not suitable for the presence of wind loads. Secondly, the dynamic response is not only affected by the load intensity, but also by the load cycle. Therefore, the critical environmental condition may be a smaller H_s with a heavy T_p. Finally, this method weakens the contribution of small storms to the response, but if it occurs with high enough frequency, the result cannot be ignored.

The concept of subset simulation (Au and Beck, 2001) has been been used for extreme analysis. Subset simulation is a method used in reliability engineering to calculate the probability of small failure events encountered. When considering the long-term extreme response of offshore structures, the return period of 20 or 50 years can be regarded as such a rare event. The basic idea is to express the small failure probability as the product of the larger conditional probability by introducing intermediate failure events. Based on this method, some extended methods have been developed to predict long-term extreme responses, such as combining importance sampling with subset simulation (Low and Huang, 2017). The role of important sampling is to reduce the sampling variability caused by long-term uncertainty, thereby effectively improving the efficiency of calculation. This method calculates an unbiased result and the corresponding error, which has been proved to be reliable.

The environmental contour method (ECM) (Haver and Winterstein, 2009) is another alternative and efficient method, which is a landmark method. As a simplified method of analyzing the structural response, it is widely used to determine the final design load of marine structures (Dnv, 2014). This method has been approved to be accurate on the extreme value forecast of the marine structures with saving a lot of calculation time because this method can estimate a reasonable result based on several environmental conditions. A certain return period (20-year or 50-year) is required when applying the environmental contour method. This contour is composed of different environmental variables, such as spectral peak period, significant wave height, mean wind speed. Then, the response is calculated within the certain points.

The principle of environmental contour method can be expressed in Equation 2.8, where u_{ECM}, h_{ECM} and t_{ECM} is the environmental condition with the largest extreme response on the contour, called 'design point'. In this method, the short-term extreme distribution $F^{ST}_{R_{1h}|U_w,H_s,T_p}\ (r_e\ |u_{ECM}, h_{ECM}, t_{ECM})$ with environmental condition at design point in a return period is used to apply environmental contour method.

$$F_{R_{1h,50y}}\ (r_e\ |u, h, t) \approx F^{ST}_{R_{1h}|U_w,H_s,T_p}\ (r_e\ |u_{ECM}, h_{ECM}, t_{ECM}) \tag{2.8}$$

Traditional environmental contour method is based on inverse first order reliability method (IFORM) (Winterstein et al., 1993), which has been applied in extreme response analysis in different offshore structures design subjected to wind and wave loads, such as deepwater floating structures (Veritas, 2010), offshore ships (DNV, 2015), offshore wind turbine (Turbines—Part, 2009), tidal turbines (Veritas, 2008).

The advantage of the environmental method is that this method excludes the response as a variable, but only considers the environmental conditions. Only some points on the contour line (combination of the environmental condition) need to be simulated. However, this is also the disadvantage of this method. Because it decouples the response and the environmental variables, therefore reducing one dimension. Usually, a high fractile (70% to 90%) needs to be considered to compensate for missing response parameters when calculating the response. Besides, multiple factors on the average value can also be used, or increase the number of environmental contours.

Another shortcoming for the environmental contour method is the extreme response predicted by the selected environmental point on the contour line does not close to that from the full long-term analysis, especially for an offshore wind turbine in some research (Li et al., 2017). Therefore, the most strict approach is when dealing with a new case, such as a new offshore structure or a new site, it should be calibrated and verified through a full long-term analysis, increasing a lot of work. But there is no doubt that this method is of great significance, and the approximated results obtained by the environmental contour method have been widely used in extreme response prediction of offshore structures.

Studies (Saranyasoontorn and Manuel, 2005) have shown that unconventional offshore structures that are not suitable for the environmental contour method refer to that the structural response is not monotonous subjected to the load with the environmental variables change, for example, offshore wind turbines have different operating modes at different wind speeds, for example, the cut-in speed is typically 3 to 5 m/s. At the rated wind speed, the turbine can generate electricity at its maximum, or rated, capacity. The rated speed is usually in the range of 11 to 16 mph. At the cut-out wind speed, the turbine shuts down to avoid damage. Because of the non-monotonic behavior of the structure caused the wind load, in the case that the response is wind-dominated, the predicted extreme response from the environmental contour method is usually lower than the actual case.

The environmental condition predicted by the environmental contour method is beyond the operating range of wind turbines, however, the maximum extreme response usually occurs within the operating range. Therefore, the calculation result of this method leads to a large error. If the response is wind-dominated, the selected environmental condition is the most serve case, however, it is likely the maximum extreme response does not occur at this point. In this case, the traditional environmental contour method is not suitable. To solve this question, there are two options.

The first one is to consider the response as a variable, that is, accounting for extreme variability. In the early research, this method has been developed in some studies, such as long term extreme response of blade root moment (Saranyasoontorn and Manuel, 2004)(Agarwal and Manuel, 2009) and shear force and bending moment at the mudline (Saranyasoontorn and Manuel, 2005).

These studies have improved the extreme value forecast to a certain extent, and are closer to the results from the full long-term analysis. However, there are still large errors in the results, and it is difficult to find the probability distribution function of the response parameter when considering it as a variable. It requires experimentation or time-domain simulation, which is expensive and time-consuming, and experiments or simulations are required for each combination of environmental parameters. This method does not fundamentally solve the problem.

The root cause of the difference is the non-monotonic behavior of the wind turbine under wind load. When applying the environmental contour method, it is assumed that the variability of the extreme response can be ignored, which means that there should not exist overly conspicuous non-monotonic behavior. However, the actual situation is contrary to the assumptions. Therefore, the environmental contour method could not be applied directly on the wind-dominated offshore wind turbine, which promotes the development of another simplification method, that is the modified environmental contour method (Li et al., 2016).

The modified environmental contour method aims to solve the problem that the extreme response predicted by the environmental conditions selected based on the traditional environmental contour method is different from the actual situation. If this problem is solved, this method can be applied again. In principle, without changing the operating state, the environmental contour method should still be applied to the environmental conditions in each monotonic area. By introducing more contour lines corresponding to critical environmental conditions. It is found that the extrapolated result of the new contour surface greatly improves the prediction of certain responses that the environmental contour method fails.

The modified environmental contour method is essential that in addition to the original environmental contour, a newly added contour with a smaller return period is used to find a point. Through appropriate extrapolation to consider the impact of changes in response, the improved environmental contour method can find the exact design point from the inverse first-order reliability method. The selection of this new contour requires a full understanding of the characteristics of the system. Therefore, for an unknown system, multiple environmental contours need to be made to obtain forecast results similar to the inverse first-order reliability method. Take the extreme response for the return period of 50 years as an example. The principle of the modified environmental contour method can be described as follows.

Consider the N-year the extreme responses, it contains $N \cdot 365.25 \cdot 24$ numbers of 1-hour interval. Each 1-hour unit of time is assumed to be independent, then the 1-hour cumulative distribution function of the return period of N year is:

$$F_{R_{1h,Ny}}(r_e) = F^{LT}_{R_{1h}}(r_e)^{N \cdot 365.25 \cdot 24} \tag{2.9}$$

The 50-year 1-hour extreme response cumulative distribution function can be extrapolated from the N-year 1-hour extreme cumulative distribution function:

$$F_{R_{1h,50y}}(r_e) = \left(F_{R_{1h}}^{LT}(r_e)^{N\cdot 365.25\cdot 24}\right)^{\frac{50}{N}} = \left(F_{R_{1h,Ny}}(r_e)\right)^{\frac{50}{N}} \tag{2.10}$$

$$F_{R_{1h,50y}}(r_e) \approx F_{R_{1h,50y}}(r_e\,|u_N,\ h_N, t_N) = \left[F^{ST}_{R_{1h|U_w,H_S,T_p}}(r_e\,|u_N, h_N, t_N)\right]^{\frac{50}{N}} \tag{2.11}$$

where $F_{R_{1h,50y}}(r_e\,|u_N,\ h_N, t_N)$ is the 50-year 1-hour extreme response cumulative distribution function. The principle of this method is to obtain $F_{R_{1h,50y}}(r_e)$ by extrapolating $F_{R_{1h,Ny}}(r_e)$ and the N-year environmental contour is approximated by $F^{ST}_{R_{1h|U_w,H_S,T_p}}(r_e\,|u_N, h_N, t_N)$.

The modified environmental contour method is widely used in bottom-fixed offshore wind turbines (Li et al., 2016), semi-submersible wind turbines (Li et al., 2017), combined wind turbine and wave energy converter system (Li et al., 2018b) (Li et al., 2018a), etc. with good accuracy in predicting extreme responses. In addition to the offshore wind turbine, the modified environmental contour method can be applied on any systems that the operational mode change with the environmental variables or the cases that the extreme responses are non-monotonic with the environmental variables, such as the structure with the control system. It is the method without correction coefficient to obtain the more accurate value. That is the advantage of this method. It is suitable for any case because it considers the variability of the response and the non-monotonic behavior of the structure.

However, this method has its disadvantage as well. On the one hand, the principle of this method is to calculate the response for a return period by a smaller return period N-year. The smaller the return period, the more random seeds are required. Therefore, the procedure of the modified environmental contour method is more computationally expensive than the traditional environmental contour method, but it is still efficient than full long-term analysis. On the other hand, not only the disadvantage of the modified environmental contour method but also the environmental contour method. That is the influence of wind turbulence intensity on the extreme response was not strictly considered, that is, the turbulence intensity was not taken as an environmental variable into consideration, or assume the turbulence intensity as a certain constant. When applying this method, the only environmental variables considered are mean wind speed U_w, significant wave height H_s and spectral peak period T_p. Usually, turbulence intensity T_i is set to be a constant as 15% (Li et al., 2016). However, as one of the important characteristics of wind, turbulence intensity follows the probability distribution function of a given wind speed in actual environmental conditions (Risø). Since the turbulence intensity is closely related to the fatigue damage (Hansen and Larsen, 2005), and it has been proved that turbulence intensity has a greater impact on the fatigue of the wind turbine than the wind shear index (Ernst and Seume, 2012).

To meet the reliability and safety requirements, the design requirements of the International Electrotechnical Commission's IEC (Standard, 2005) or DNV (Veritas, 2004) standards should be consulted in the design stage. IEC 61400 standard writes the turbulence intensity is considered as a function of wind speed. In the actual environment, the turbulence intensity, as a variable, follows the probability distribution function relevant to the wind speed. Therefore, a probability density function can be constructed to determine the correlation of wind speed and turbulence intensity when predicting the extreme response of the wind turbine for a given exceedance probability.

Extended environmental contour method (Chen et al., 2020) has been developed to solve this problem. Considering turbulence intensity as an additional environmental variable can significantly reduce the non-conservative property of the traditional environmental contour method in predicting wind-dominated responses. The modified environmental contour method generally has better prediction accuracy for extreme responses than the traditional environmental contour method. However, turbulence intensity is set to be 15% too conservative. Considering turbulence intensity as an environmental variable will greatly reduce the extreme response forecast value than the modified environmental contour method subjected to the combined wind and waves or under the environmental conditions dominated by the wind. In a word, the extended environmental contour method reduces the conservativeness compared with the modified environmental contour method. The disadvantage is that the measured data of wind is needed to build the probability density function, which increases large quantities of work.

2.3. Different approaches to obtain contours

2.3.1. The role of the environmental contour

As mentioned in Equation 3.4, predicting the long-term extreme response can be considered as a reliability method, which has been discussed in some studies (Bitner-Gregersen et al., 2002), and the environmental condition is modeled by a probability density function. Usually, not only one environmental variable need to be considered, but a combination of different variables E_i. The joint probability density function can be considered as the combination of the marginal distribution of one variable and the conditional distribution of other variables, Weibull distribution (Li et al., 2013a) and lognormal distribution are usually used (Vanem and Bitner-Gregersen, 2012). The process to obtain contour is the process to solve these probability distribution functions. The purpose of environmental contours is that the contour encloses the region of the environmental condition for the design purpose. The critical environment condition occurs on the boundary of this design region, that is the contour. In standard (Veritas, 2000), it suggests engineers evaluate the response along the environmental contour line instead of calculating all the combinations of the environmental condition in the region enclosed by the boundary line, and the calculated result is considered to be reliable, therefore, this is the purpose of the environmental contour.

2.3.2. Different definitions of environmental contour

Different definitions about environmental contour have been proposed differently, the contour line obtained through different definitions is different, therefore, the selected critical environmental conditions and the predicted extreme response will be different (Armstrong et al., 2015). The different definition of the environmental contour is shown in Figure 2.1.

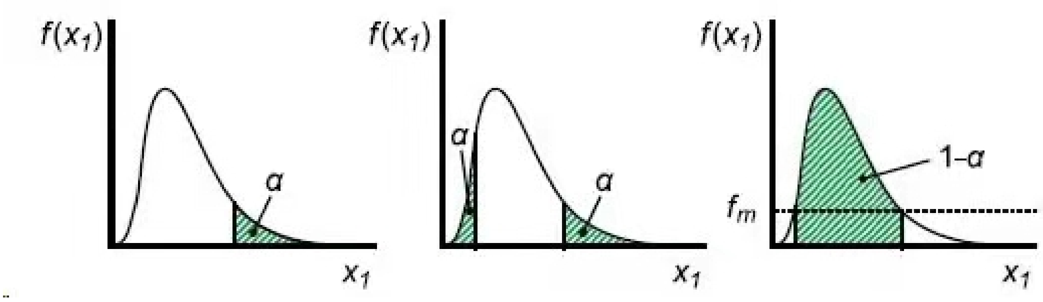


Figure 2.1: Different definitions of environmental contour (Haselsteiner et al., 2017)

The left one shown in Figure 2.1 is the one-sided exceedance probability, and it is the most original definition. The definition of the contour is all the variables satisfy the requirement in one side, shown in Equation 2.13.

$$P\,(X_1 < x_1, X_2 < x_2 ... X_n < x_n) = 1 - \alpha \tag{2.12}$$

where α is the exceedance probability.

The second definition is the double-sided exceedance probability (Jonathan et al., 2014), shown in the middle figure of the Figure 2.1. This concept is proposed because sometimes for an offshore structure, we have to consider not only the highest value of the variable but also the lowest value. For example, the spectral peak period is a very important environmental variable when researching the extreme response. Sometimes we need to pay attention to the lowest value of the peak period. This is because the natural frequency of the structure may be higher or lower than the average value of the period. It can be expressed in Equation 2.12.

$$P\,(X_1 > x_{1u}, X_2 > x_{2u} ... X_n > x_{nu}) = \alpha \;\cup\; P\,(X_1 < x_{1l}, X_2 < x_{2l} ... X_n < x_{nl}) = \alpha \tag{2.13}$$

The third definition of the contour is to find a contour with a constant probability density f_m along the contour, which enclosed the design region. The region enclosed is called the highest density region (Hyndman, 1996). Different scholars have carried out extensive research and explanation on this concept. For example, the contour line with constant probability density proposed by Haver (Haver, 1987), but this is a one-sided exceedance case. Leira (Leira, 2008) transform the variable from physical space to a standard normalized space when applying this method. Although the definition of the highest density region is used, the transformation makes the probability along the contour line not constant. The definition described by Veritas is to obtain the constant probability density (Veritas, 2000). However, its disadvantage is the probability enclosed by this contour is not clear.

2.3.3. Different approaches to obtain environmental contour

There are different approaches to obtain the environmental contour for a given type of contour line. The traditional environmental contour method is based on the inverse first-order reliability method (IFORM) (Winterstein et al., 1993). The general equation can be simplified to convert the limit state function $g(X) = 0$ in physical space to $g(U) = 0$ in U space. The space containing all the original environmental variables X is called X space (physical space). All the variable X can be transformed from the X space to the standard normal space U space, and the variable in U space obeys the standard normal distribution. Perform a first-order approximation at the design point u_{design}, u_{design} is the point with the maximum probability density on the limit state function $g(U) = 0$, and in U space, u_{design} is the closest point to the origin. The distance $r = |u_{design}|$ is called reliability index. The reliability of the approximate linear limit state function is $\Phi(r) = 1 - P_f$, where Φ is the cumulative distribution function of the standard normal distribution.

The environmental contour method determines the environmental contour based on inverse first-order reliability method through Rosenblatt transformation (Rosenblatt, 1952). This method excludes the response as a variable, but only considers the environmental variables. The response is calculated by Equation 2.14

$$r_e \approx {F^{ST}_{R_{1h}|U_w,H_s,T_p}}^{-1}(p\,|u_d, h_d, t_d) \tag{2.14}$$

This method to obtain the environmental contour is the most traditional method, which has been widely used in the research, such as the extreme load prediction on the blade (Saranyasoontorn and Manuel, 2004), the design of a monopile offshore wind turbine (Myers et al., 2015), the platform response evaluation (Baarholm et al., 2010) and the predicting for the extreme sea state (Eckert-Gallup et al., 2016).

The advantage of this method is the principle of this method is relatively simple and has been widely used. However, the prediction based on this method is usually low than the actual condition. Quantile here is used to compensate for the omission of structure response excluded as a variable. An empirical value of 90% is applied for the prediction of the extreme response in the environmental contour method. Its relevant recommendations for quantile value are introduced in some studies (Haver and Winterstein, 2009). Multiple factors or increase the number of environmental contours can also be used in some studies (Muliawan et al., 2013).

An alternative method is the inverse second-order reliability method (ISORM) (Chai and Leira, 2018). It determines the failure surface by a quadratic function at the design point in U space, compared with that from the first-order reliability method in a linear function to represent the failure surface. The approximation of the FORM results in a larger space, causing an overestimated failure probability for a convex failure surface, shown in the left figure of **??**. On the contrary, the FORM approximates a lower boundary, causing an underestimated failure probability for a concave failure surface in U space.

In practical application, the shape of the failure surface is unknown in advance. Therefore, if it is a concave one, the environmental contour obtained from the inverse first-order reliability method would be not accurate enough (Haselsteiner et al., 2017). The inverse second-order reliability method, as a more conservative approach, is proposed to optimize this shortcoming. It is another way to establish environmental contour. It is also an inverse problem of estimating the exceedance probability with a return period like IFORM. First, the exceedance failure P_f is assumed to be known, then find the expression that imposed on the environmental variables. The principle for establishing contours by inverse second-order reliability method can be expressed by:

$$1 - P_f = \int_{\sum_{j=1}^{n} u_{j,ECM}^2 \leqslant r_i^2} \psi_U(u)\, du \tag{2.15}$$

where n means the dimension of environmental variables, a n-dimension sphere with radius r_i. ψ means the standard multivariate normal PDF.

Since for the standard normal variables in U space, *h*as a χ^2 distribution with *n* degrees of freedom, r_i can be determined by Equation 2.16 with a inverse process of χ^2 distribution.

$$\chi^2\left(r_i^2\right) = 1 - P_f \tag{2.16}$$

The contour obtained by the inverse second-order reliability method shares a similar shape compared with that from the inverse first-order reliability method, and both methods transform U space into physical space through Rosenblatt transformation (Rosenblatt, 1952). However, the difference is that the contour based on the inverse second-order reliability method limits environmental parameters more conservatively than that of the inverse first-order reliability method. This is because ISORM approximates the failure space by a quadratic function in U space. No matter what kind of shape the failure surface is, the design point and the failure domain will always be overestimated. For design, this overestimation leads to the result of contour based on ISORM always being conservative and safety has been fully guaranteed, which cannot be ensured by the traditional IFORM method.

Both the two methods to obtain the environmental contour mentioned above are implemented through Rosenblatt transformation from standard normal space to original physical space, studies have shown that Rosenblatt transformation may over-or underestimation of failure probability may be induced (Huseby et al., 2013). Therefore, the Monte Carlo method (MCM) which has been applied in structural reliability analysis (Zhang et al., 2010) (Naess et al., 2009) is proposed as a more precise approach to interpreting the environmental contour (Huseby et al., 2013). The direct Monte Carlo method allows the definition of environmental contour in original space directly (Huseby et al., 2015). That avoids the difference due to the transformation.

When applying the Monte Carlo method, the first step is to generate a lot of the sea state for the given probability density function based on Monte Carlo simulation. Then, select another parameter θ to define a line in two-dimension space or a surface in three-dimension space. In this way, the whole variable space is divided into two parts. One is the space that contains most of the variable points, another one is space that contains the cases corresponding to the exceedance probability (the number is $\alpha \cdot n$), where n represents the total number of the environmental condition. The environmental contour is obtained by integrating a range of parameter θ, such as, $\theta \in [0, 2\pi)$. Then connect all the integrated lines to obtain the environmental contour. Many research has been developed about the Monte Carlo method, such as a comparison study with the traditional inverse first-order reliability method (Vanem and Bitner-Gregersen, 2015), study on several statistical modeling approaches for the joint distribution of ocean wave parameters (Vanem, 2016) and its flexibility (Huseby et al., 2014).

The advantage of this method is firstly it avoids the transformation from U space to physical space, but calculate the response in the original physical space directly, therefore, avoid the error in the process of transformation. Moreover, the Monte Carlo method can construct the environmental contour more flexibly, which means standard parameterized models of environmental variables are not necessary. It can weaken the effect of the change of the wave state caused by climate, included in some studies. (Vanem and Bitner-Gregersen, 2012). Finally, the calculation speed of the Monte Carlo method is extremely fast. Although the limitation of the original method is not the calculation time, the faster calculation speed is always gratifying. In fact, this method is faster than most of the known engineering applications. Although the Monte Carlo method overcomes the problems caused by the Rosenblatt transformation, the environmental state is required to be simulated. Another disadvantage is that this method cannot generate concave contours by the limitation of its definition.

Another method described by Jonathan et al. is to obtain the contour with constant exceedance probability (Jonathan et al., 2014). It is defined as:

$$P\left(X_1 > x_1, X_2 > x_2\right) = \alpha \tag{2.17}$$

The definition of the method is based on two environmental variables. The difference from the previous method is that for the definition of the exceedance probability area, this method has a boundary defined by a finite length for each variable, not a tangent line that divides the entire space into half. Therefore, this method separates the failure region and exceedance region. It means the definition of the contour is separated from the limit state function. When applying this method, a reference point is selected firstly, denote as r_0, then a line passing through this reference point is defined with an angle between the line and the horizontal axis theta θ. Finally, select a point on the line to ensure $P_r = \alpha$. The range of θ is $\theta \in [0, 2\pi)$, integrate θ in the whole space, then the contour is obtained.

The advantage of this method is that it applies to all contour estimation condition variables that are large and it quantifies the uncertain contour position. Besides, it is suitable in different spaces, such as standard normal variables, U space and the original physical variable space, X space. Moreover, this method can be applied to n (n > 2) dimensions, which is difficult to apply the inverse first-order reliability method in high dimension space, and the failure probability can be estimated directly instead of defining a 'design point' like in IFORM. In a word, this method describes a more general method about environmental statistics, instead of concentrating on a certain specific question and it has been demonstrated that conditional probability model has been combined with this method successfully (Jonathan et al., 2010).

However, this method determines several regions with the exceedance probability. Although one of these several exceedance areas is considered to be overlapped the failure region, its definition is not the case ($P\left(X_1 > x_1, X_2 > x_2\right) = \alpha$). Therefore, if the definition of the contour is independent of the failure area, it is appropriate to define the exceedance region as a single region, instead of several regions.

The concept of separating the exceedance region from the failure region is developed by Haselsteiner (Haselsteiner et al., 2017). That is the highest density region method. In this method, the environmental contour is defined as the boundary, along which the joint probability density function (PDF) of the environmental variables is a constant. And the total probability enclosed by the boundary is 1-P_f. The principle of this method can be described in Equation 2.18.

$$\int_{f_E(e) \geqslant f_H} f_E\left(e\right) de = 1 - P_f \tag{2.18}$$

The highest density region (R) is defined in Equation 2.19 and the contour (C) is defined in Equation 2.20.

$$R\left(f_H\right) = \{f_E\left(e\right) \geqslant f_H\} \tag{2.19}$$

$$C\left(f_H\right) = \{f_E\left(e\right) = f_H\} \tag{2.20}$$

Two characteristics are met when applying HDRM: The probability density of the grid inside the region is at least as large as that outside. The region occupies the smallest volume in physical space for a given probability density f_H. The highest density contour can be solved by numerical integration method (Wright, 1986) or Monte Carlo method (Hyndman, 1996). The Monte Carlo method is used in high-dimension cases, which means various environmental variables. The numerical integration method is usually used in the low-dimension case.

The highest density region method tends to give the conservative result. This method solves the contour in the original physical space and can be used in high-dimension conditions. The contour can be obtained as long as the probability model is known (Eckert-Gallup and Martin, 2016). It is considered an attractive approach to obtain contour.

2.4. Conclusion

The long-term analysis is important for the structure's response research, such as fatigue damage and extreme response. It can be considered a reliable method for dealing with the probability density function. The most accurate method is the full long-term analysis, but it is very time-consuming and inefficient. Therefore, many simplified methods have been proposed. For fatigue damage, frequency domain analysis is the most common method, it is faster for calculation than time-domain analysis. For extreme response, the assumption and simplification make frequency domain analysis with a higher error. Therefore, the simplified method in the time domain is necessary.

Different methods have been proposed to simplify the full long-term analysis of the extreme response. There are mainly two principles. On the one hand, estimate extreme response by combining the extremes under every single environmental load. On the other hand, reduce the number of environmental conditions used for integration. Different application has been developed on reducing the number of environmental conditions used. The simplified full long-term analysis (SFLTA) divides the environmental conditions into the important part and negligible part. It reduces the number of environmental conditions required, but how to find the important environmental conditions is difficult. It depends on the operation mode of the system.

The design sea state approach is simple and quick to calculate. However, it just considers the effect of wave loads and weakens the contribution of small storms to the response. Combining importance sampling with subset simulation reduces the sampling variability caused by long-term uncertainty, thereby effectively improving the efficiency of calculation. This method calculates an unbiased result and the acceptable error.

The environmental contour method is a landmark method, it is widely used to determine the final design load of marine structures. The traditional environmental contour method is based on the inverse first-order reliability method. It excludes the response as a variable but only considers the environmental conditions. A high fractile (70% to 90%) needs to be considered to compensate for missing response parameters when calculating the response. However, it is not suitable for the condition that the response is non-monotonic subjected to the load.

The modified environmental contour method can be applied on any systems that the operational mode change with the environmental variables or the cases that the extreme responses are non-monotonic with the environmental variables, such as the structure with the control system. The extended environmental contour method considers turbulence intensity as an additional environmental variable that can significantly reduce the non-conservative property of the traditional environmental contour method in predicting wind-dominated responses. However, the measured data of wind is needed to build the probability density function, which increases large quantities of work. The purpose of environmental contours is that the contour encloses the region of the environmental condition for the design purpose. The critical environment condition occurs on the boundary of this design region.

The inverse first-order reliability method (IFORM) is the most traditional. The principle of this method is relatively simple and has been widely used. However, the prediction based on this method is usually low than the actual condition. Quantile is used to compensate for the omission of structure response excluded as a variable. Inverse second-order reliability method (ISORM) approximates the failure surface by a linear function at the design point, leading to the result of contour based on ISORM always conservative, which cannot be ensured by the traditional IFORM method. Monte Carlo method (MCM) avoids the transformation from U space to physical space but calculates the response in the original physical space directly. It a more flexible method, but this method cannot generate concave contours by the limitation of its definition

The constant exceedance probability method (CEPM) applies to all contour estimation condition variables that are large and it quantifies the uncertain contour position. It is also suitable for high-dimension conditions. However, this method determines several regions with the exceedance probability. The highest density region method (HDRM) is developed based on CEPM, it defines the contour in original physical space and can be used in high-dimension conditions but the design region is enclosed by the contour.

The prediction of long-term analysis is a valuable topic for offshore engineering. Although different methods have been proposed, improve calculation time and accuracy are always the problem need to be considered. Different combinations of methods, probability models, and structure could be future work.

3

Research Methodology

In this chapter, an overview of the theory used in this research work is presented. In section 3.1, the principle of the most direct response analysis method-full long term analysis is introduced and a simplified method of full long term analysis is described in section 3.2. The third method -environmental contour method and different approaches, that is, the inverse first-order reliability method (IFORM), inverse second-order reliability method (ISORM), and highest density region method (HDRM), to obtain the environmental contour is introduced in section 3.3. In section 3.4, modified environmental contour method is discussed. This chapter is working as the theoretical support of the following research.

3.1. Full long-term analysis

The evaluation of the wind turbine's long-term extreme response can be considered as a reliability problem, which can be calculated by Equation 3.1.

$$RE = 1 - P_f = \exp \int_{L(R)>0} \ln\left[f_V\,(r)\right] dr \tag{3.1}$$

where RE is the reliability, P_f is the failure probability, *V* is the variables with the joint probability distribution function (PDF) $f_V\,(r)$, *L(R)* is limit state function, which can be calculated by Equation 3.2.

$$L\,(R) = r_e - r \tag{3.2}$$

where r_e is the largest long-term extreme response and *r* is the response of the structure. *V* can be considered as the combinations of the environmental variables and the response, denoted by (r, E), where *E* is all the environmental variables. Usually, environmental variables are considered independent of the response. Giske et al. (Giske et al., 2017) uses the linear approximations of the logarithm and the exponential function yields

$$RE = 1 - P_f = P\,(L\,(R) > 0) = \int_{L(R)>0} f_R\,(r) dr \tag{3.3}$$

$$RE = 1 - P_f = \iint_{r<r_e} f_{R,E}\,(r,e) dr de \tag{3.4}$$

The full long-term analysis is the most direct way, that is, to calculate the response by Equation 3.4 directly. Because of the independence of the environmental variables *e* and the response *r*, the PDF in Equation 3.4 is shown in Equation 3.5.

$$f_{R,E}\,(r,e) = f_{R|E}\,\,(r\,|e\,)\,f_E\,(e) \tag{3.5}$$

Therefore, Equation 3.4 can be rewritten as:

$$1 - P_f = \iint_{r<r_e} f_{R|E}\,\,(r\,|e\,)\,f_E\,(e) dr de = \int F_{R|E}\,\,(r_e\,|e\,)\,f_E\,(e)\,de \tag{3.6}$$

All the environmental variables E need to be integrated in full long-term analysis, causing a large amount of calculations to determine each $F_{R|E}\ (r_e\,|e)$. Although this is the most accurate method, the numerical simulation needs to be made for all environmental conditions in the time domain for this method, which is time-consuming and inefficient. Because of its accuracy, results from this method would be a reference compared with all the other results from a different method.

The long-term extreme value can be obtained by short-term extreme value analysis, shown in Equation 3.7, where $F_R^{LT}\ (r_e)$ and $F_{R|E}^{ST}\ (r_e\,|e)$ stands for the long-term and short-term cumulative distribution function of the extreme response R respectively, E is the environmental conditions that satisfies Equation 3.8.

$$F_R^{LT}\ (r_e) = \int F_{R|E}^{ST}\ (r_e\,|e) f_E\ (e)\, de \tag{3.7}$$

$$\int f_E\ (e)\, de = 1 \tag{3.8}$$

The 1-hour extreme distribution is used in this study, working as a short-term distribution. Assume 10-minute is an independent unit of time, then the 1-hour short-term extreme probability distribution can be extrapolated by a 10-minute maximum response. In this study, three variables are considered, that is wind speed U_w, significant wave height H_s, and spectral peak period T_p. Turbulence intensity is set as a fixed value (15% in this study) (Li et al., 2016). Considering three variables, Equation 3.7 can be rewritten as Equation 3.9.

$$\begin{aligned} F_{R_{1h}}^{LT}\ (r_e) &= \int F_{R_{1h}|E}^{ST}\ (r_e\,|e) \cdot f_E\ (e)\, de \\ &= \iiint F_{R_{1h}|U_w,H_s,T_p}^{ST}\ (r_e\,|u,h,t) \cdot f_{U_w,H_s,T_p}\ (u,h,t)\, dudhdt \\ &= \sum F_{R_{1h}|U_w,H_s,T_p}^{ST}\ (r_e\,|u,h,t) \cdot f_{U_w,H_s,T_p}\ (u,h,t)\, \Delta u \Delta h \Delta t \end{aligned} \tag{3.9}$$

Long-term extreme response r_e can be obtained by Equation 3.10 for 50-year long term extremes.

$$F_{R_{1h}}^{LT}\ (r_e) = 1 - P_f = 1 - \frac{1}{24 \cdot 365.25 \cdot 50} \tag{3.10}$$

3.2. Simplified full long-term analysis

The full long-term analysis integrates a huge number of environmental conditions, it is impractical when applied. Reducing the number of environmental conditions for simulation is the most direct way to improve efficiency. For the research cases with a high exceedance probability (50-year), only the tail part of the extreme cumulative distribution function is concentrated. Most environmental conditions do not contribute to the long-term extreme response analysis. The part of the environmental condition that contributes to the final results is called the required environmental condition, which is focused while others are ignored (Videiro and Moan, 1999). The calculation by reducing unimportant environmental conditions to obtain the same results compared with FLTA is called simplified full long-term analysis (SFLTA). Its principle can be expressed as:

$$1 - P_f = \int_{simplified} F_{R|E}\ (r_e\,|e)\, f_E\ (e) de \tag{3.11}$$

Consider the exceedance probability $G_R^{ST}\ (r_e)$ (Li et al., 2018b), which is calculated by Equation 3.12, then the full long-term analysis can be simplified as Equation 3.13.

$$G_{R_{1h}|U_w,H_s,T_p}^{ST}\ (r_e\,|u,h,t) = 1 - F_{R_{1h}|U_w,H_s,T_p}^{ST}\ (r_e\,|u,h,t) \tag{3.12}$$

$$\begin{aligned} G_{R_{1h}}^{LT}\ (r_e) &= \iiint_{simplified} G_{R_{1h}|U_w,H_s,T_p}^{ST}\ (r_e\,|u,h,t) \cdot f_{U_w,H_s,T_p}\ (u,h,t)\, dudhdt \\ &= \frac{1}{24 \cdot 365.25 \cdot 50} \end{aligned} \tag{3.13}$$

Most of the environmental conditions are not important, because it makes little contribution to the exceedance probability. For these environmental conditions, replace the cumulative distribution function by 1 in long-term extreme analysis, The forecast results of 50-year long-term extreme response will not change significantly. Therefore, it means only the probability distribution of important environmental conditions contributes to the long-term extreme analysis, then Equation 3.9 can be rewritten as (Li et al., 2016):

$$\begin{aligned} F_{R_{1h}}^{LT}(r_e) = &\sum_{(u,h,t)_{im}} F_{R_{1h}|U_w,H_s,T_p}^{ST}(r_e\,|u,h,t) \cdot f_{U_w,H_s,T_p}(u,h,t)\,\Delta u \Delta h \Delta t + \\ &\sum_{(u,h,t)_{ne}} 1 \cdot f_{U_w,H_s,T_p}(u,h,t)\,\Delta u \Delta h \Delta t \end{aligned} \tag{3.14}$$

where $(u,h,t)_{im}$ is the important environmental conditions and $(u,h,t)_{ne}$ is the negligible environmental conditions.

The challenge of SFLTA is the selection of the important environmental conditions that can accurately approximate the full long-term analysis. Usually, the first step is to find the most important wind speed within the operational range, then find the extrapolated most probable extreme to determine the important condition.

3.3. Environmental contour method

The principle of environmental contour method can be expressed in Equation 3.15, where u_{ECM}, h_{ECM} and t_{ECM} is the environmental condition with the largest extreme response on the contour, called 'design point'. In this method, the short-term extreme distribution $F_{R_{1h}|U_w,H_s,T_p}^{ST}(r_e\,|u_{ECM}, h_{ECM}, t_{ECM})$ with environmental condition at design point in a return period (50 years) is used to apply environmental contour method.

$$F_{R_{1h,50y}}(r_e\,|u,h,t) \approx F_{R_{1h}|U_w,H_s,T_p}^{ST}(r_e\,|u_{ECM}, h_{ECM}, t_{ECM}) \tag{3.15}$$

The procedure is illustrated in Figure 3.1

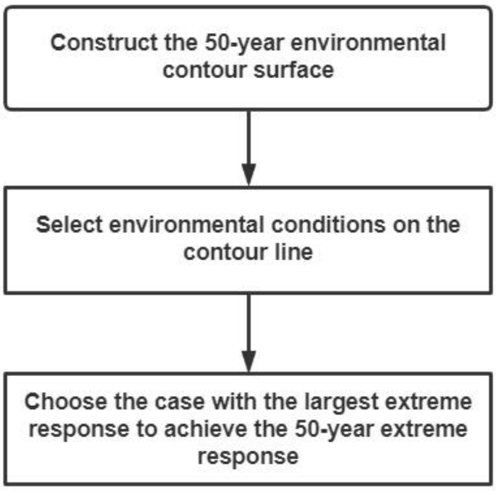


Figure 3.1: Procedure of environmental contour method

3.3.1. Inverse first-order reliability method

The traditional environmental contour method is based on inverse first-order reliability method (Winterstein et al., 1993), this is the first approach to obtain environmental contour in this study. The general equation Equation 3.3 can be simplified in the way that limit state function $L(R) = 0$ in original data space (physical space or R space) is transformed to $L(U) = 0$ in standard normal space (U space).

The limit state surface is the collection of the environmental conditions with the same short extreme response. There is a point u_{design}, called design point on the limit state surface, which is of the maximum probability density in U space. It is also closet to the origin point with a distance of $|u_{design}|$. $r_i = |u_{design}|$ is called reliability index. The first-order approximation is carried out at the design point u_{design}, and the reliability of the approximate linear limit state function is $\Phi(r_i)$, the corresponding failure probability is $\Phi(-r_i)$. Φ represents the cumulative distribution function of the standard normal distribution.

Environmental contour method based on IFORM draws the environmental contour through Rosenblatt transformation (Rosenblatt, 1952). This method excludes the response as a variable, but only consider the environmental variables. The procedure is described as:

- Consider only the environmental variables, calculate the reliability index r_i based on the given failure probability P_f. Find all the points u_{ECM} that satisfy $|u_{ECM}| = r_i$ in U space. r_i is also the radius of the sphere in U space.

$$\sum_{j=1}^{n} u_{j,ECM} = r_i^2 \tag{3.16}$$

  where $r_i = \Phi^{-1}\left(1 - P_f\right)$, n means n-dimension environmental variables.

- Convert points u_{ECM} in U space to R space to determine the environmental contour surface.
- Calculate the response r_p corresponding to a certain quantile *p* (70% - 90%) to obtain a maximum response and its corresponding environmental conditions, that is the forecast results.

$$r_e \approx {F^{ST}_{R_{1h}|U_w,H_s,T_p}}^{-1}(p\,|u_{ECM}, h_{ECM}, t_{ECM}) \tag{3.17}$$

Quantile here is used to compensate for the omission of structure response excluded as a variable. An empirical value of 90% is applied to the largest short-term extreme response in the environmental method. Its relevant recommendations for quantile value are introduced in some studies (Haver and Winterstein, 2009). Multiple factors or increase the number of environmental contours can also be used in some studies (Muliawan et al., 2013).

All the combinations of the environmental variables corresponding to the same return period will be located along a sphere which consists of independent and standard normal variables. Transformation between the physical variables and standard normal variables is performed by the Rosenblatt transformation as follows:

$$\Phi(u_1) = F_{U_w}(u) \tag{3.18}$$

$$\Phi(u_2) = F_{H_s|U_w}(h\,|u) \tag{3.19}$$

$$\Phi(u_3) = F_{T_p|U_w,H_s}(t\,|u,h) \tag{3.20}$$

where Φ represents the cumulative distribution function (CDF) of the standard normal function and *F* represents the CDF of the environmental variables.

$$F_{U_w}(u) = \int f_{U_w}(u)du \tag{3.21}$$

$$F_{H_s|U_w}(h\,|u) = \frac{\int f_{U_w,H_s}(u,h)dh}{f_{U_w}(u)} = \int f_{H_s|U_w}(h\,|u)dh \tag{3.22}$$

$$F_{T_p|U_w,H_s}(t\,|u,h) = \frac{\int f_{U_w,H_s,T_p}(u,h,t)\,dt}{f_{U_w,H_s}(u,h)} = \int f_{T_p|U_w,H_s}(t\,|u,h)dt \tag{3.23}$$

Then the environmental contour can be established by transforming the U space back into the physical space:

$$u = F_u^{-1}\left[\Phi\left(u_1\right)\right] \tag{3.24}$$

$$h = F_h^{-1}\left[\Phi\left(u_2\right)|u\right] \tag{3.25}$$

$$t = F_t^{-1}\left[\Phi\left(u_3\right)|u, h\right] \tag{3.26}$$

3.3.2. Inverse second-order reliability method

Unlike FORM which approximates the failure surface by a linear function at the design point in U space, SORM approximates the failure space by a quadratic function. The approximation of the FORM results in a larger space, causing an overestimated failure probability for a convex failure surface, shown in the left figure of Figure 3.2. On the contrary, the FORM approximates a lower boundary, causing an underestimated failure probability for a concave failure surface in U space, shown in the right figure of Figure 3.2

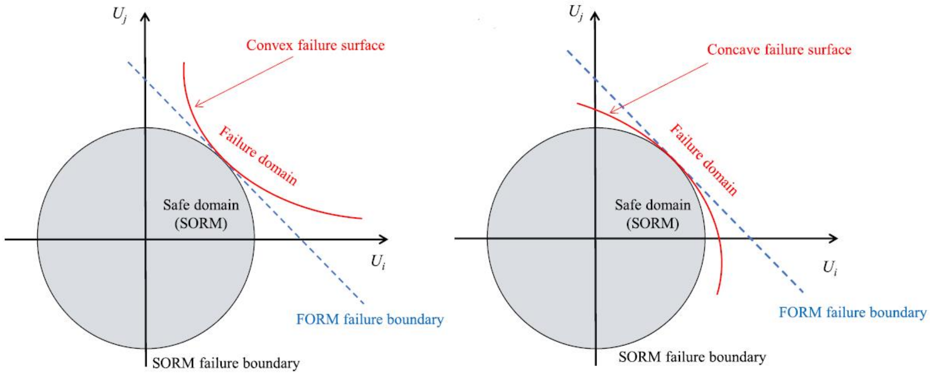


Figure 3.2: Failure probability approximation by the FORM and SORM in U space (Chai and Leira, 2018)

In practical application, the shape of the failure surface is unknown in advance. Therefore, if it is a concave one, the generated environmental contour would be not conservative enough. A more conservative method, inverse second-order reliability method (Chai and Leira, 2018), is proposed to optimize this shortcoming. It is another way to establish environmental contour. It is also an inverse problem of estimating the exceedance probability with a return period like IFORM. First, the exceedance failure P_f is assumed to be known, then find the expression that imposed on the environmental variables. The principle of establishing the environmental contour by ISORM can be expressed by:

$$1 - P_f = \int_{\sum_{j=1}^{n} u_{j,ECM}^2 \leqslant r_i^2} \psi_U\left(u\right) du \tag{3.27}$$

where n means the dimension of environmental variables, a n-dimension sphere with radius r_i. ψ means the standard multivariate normal PDF.

Since for the standard normal variables in U space, *h*as a χ^2 distribution with *n* degrees of freedom, r_i can be determined by Equation 3.28 with a inverse process of χ^2 distribution.

$$\chi^2\left(r_i^2\right) = 1 - P_f \tag{3.28}$$

After obtaining an n-dimension sphere with a radius r_i in U space, the next step is to transform the variable in standard normal space to physical variables in physical space to obtain the environmental contour through Rosenblatt transformation (Rosenblatt, 1952). The process of applying Rosenblatt transformation to obtain environmental contour is similar to that of IFORM.

$$u = F_u^{-1}\left[\Phi\left(u_1\right)\right] \tag{3.29}$$

$$h = F_h^{-1}\left[\Phi\left(u_2\right)|u\right] \tag{3.30}$$

$$t = F_t^{-1}\left[\Phi\left(u_3\right)|u,h\right] \tag{3.31}$$

3.3.3. Highest density region method

The highest density region method (HDRM) is another method to construct the environmental contour. In this method, the environmental contour is defined as the boundary, along which the joint probability density function (PDF) of the environmental variables is a constant. And the total probability enclosed by the boundary is 1-P_f. The principle of this method can be described in Equation 3.32.

$$\int_{f_E(e)\geqslant f_H} f_E\left(e\right)de = 1 - P_f \tag{3.32}$$

The highest density region (R) is defined in Equation 3.33 and the contour (C) is defined in Equation 3.34.

$$R\left(f_H\right) = \{f_E\left(e\right) \geqslant f_H\} \tag{3.33}$$

$$C\left(f_H\right) = \{f_E\left(e\right) = f_H\} \tag{3.34}$$

Two characteristics are met when applying HDRM:

- The probability density of the grid inside the region is at least as large as that outside.
- The region occupies the smallest volume in physical space for a given probability density f_H.

The highest density contour can be solved by numerical integration method (Wright, 1986). Three variables are considered in this study, therefore, a derivation of the numerical integration method in three-dimension cases is introduced.

The process starts by discretizing the three-dimension probability density space into $N_1 \times N_2 \times N_3$ elements, of which the size is $\Delta u \times \Delta h \times \Delta t$, shown in Figure 3.3, where the shaded area is the highest density region. Then the average probability density of each element in the first dimension can be calculated by central difference based on the cumulative density function:

$$\overline{f}_{U_w}\left(u\right) = \frac{F_{U_w}\left(u + 0.5\Delta u\right) - F_{U_w}\left(u - 0.5\Delta u\right)}{\Delta u} \tag{3.35}$$

Where $\overline{f}_{U_w}$ is the element-averaged probability density in the first dimension.

For the second dimension, the average probability density of each element is calculated by:

$$\overline{f}_{H_s|U_w}\left(h\,|u\right) = \frac{F_{H_s|U_w}\left(h + 0.5\Delta h\right) - F_{H_s|U_w}\left(h - 0.5\Delta h\right)}{\Delta h} \tag{3.36}$$

Where $\overline{f}_{H_s|U_w}\left(h\,|u\right)$ is the element-averaged probability density in the second dimension.

Similarly, the average probability density of each element in the third dimension is calculated by:

$$\overline{f}_{T_p|U_w,H_s}\left(t\,|u,h\right) = \frac{F_{T_p|U_w,H_s}\left(t + 0.5\Delta t\right) - F_{T_p|U_w,H_s}\left(t - 0.5\Delta t\right)}{\Delta t} \tag{3.37}$$

Where $\overline{f}_{T_p|U_w,H_s}\left(t\,|u,h\right)$ is the element-averaged probability density in the third dimension.

The joint probability density function $\overline{f}$ is calculated by multiplying the three different probability densities:

$$\overline{f}\left(u,h,t\right) = \overline{f}_{U_w}\left(u\right)\cdot\overline{f}_{H_s|U_w}\left(h\,|u\right)\cdot\overline{f}_{T_p|U_w,H_s}\left(t\,|u,h\right) \tag{3.38}$$

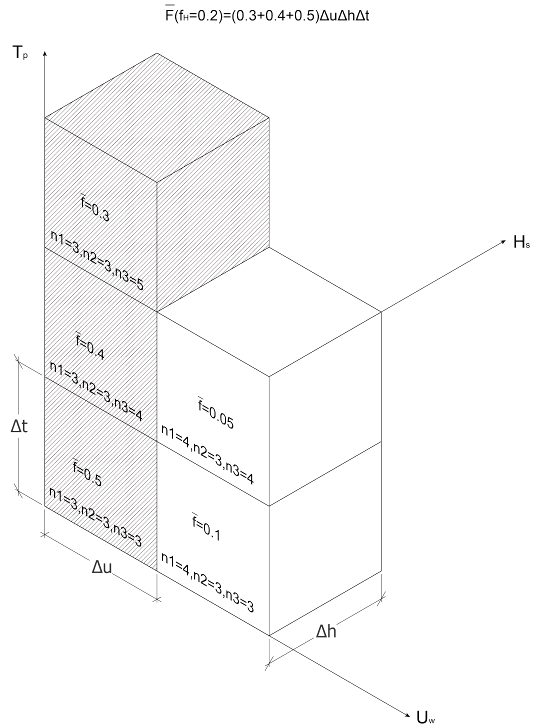


Figure 3.3: Computation of highest density region based on numerical integration method

Then sum up all the probabilities of the elements whose probability is larger than or equal to the minimum probability density f_H (enclosed by the contour of the probability density f_H) to obtain the total probability $\overline{F}\,(f_H)$ in Equation 3.39.

$$\overline{F}\,(f_H) = \sum_{n_1=1}^{N_1}\sum_{n_2=1}^{N_2}\sum_{n_3=1}^{N_3}\begin{cases}\overline{f}\,(u_{n_1},h_{n_2},t_{n_3})\,\Delta u\Delta h\Delta t & f\,(u_{n_1},h_{n_2},t_{n_3}) \geqslant f_H \\ 0 & \overline{f}\,(u_{n_1},h_{n_2},t_{n_3}) < f_H\end{cases} \tag{3.39}$$

For a given exceedance probability P_f, the contour can be found by determining the minimum probability density f_H by solving the Equation 3.40, the highest density region is the elements that fulfill $\overline{f} \geqslant f_H$ of a probability $\overline{F}\,(1-P_f)$, enclosed by highest density contour (Figure 3.4).

$$\overline{F}\,(f_H) = 1 - P_f \tag{3.40}$$

3.4. Modified environmental contour method

Although ECM has been widely applied on marine structures and offshore wind turbines, the effect of this method on offshore wind turbines is not satisfactory (Saranyasoontorn and Manuel, 2005). The critical environmental conditions selected by this method are usually far away from the most dangerous environmental conditions in practice. To obtain the results with small errors and sufficiently reliability compared with the FLTA, a high quantile (above 90%) has to be applied. Even so, for some responses, the selected quantile needs to be as high as 99%, and the select ed quantile value is not consistent with all responses. Therefore, ECM is not suitable for the prediction of the extreme response of offshore wind turbines.

The difference between the offshore wind turbine and the traditional marine structure operation mode is that the response caused by wind load will not increase monotonously with the increase of wind speed.

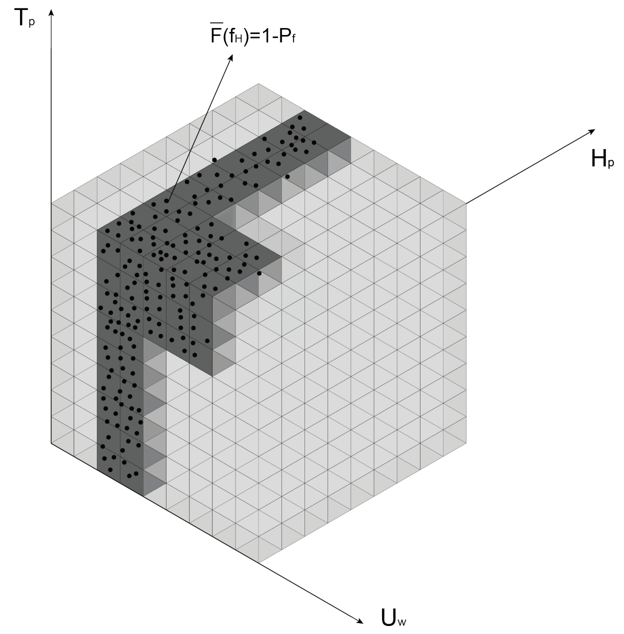


Figure 3.4: Computation of highest density region based on numerical integration method

A greater response of the wind turbine generally occurs in the operating state (between the cut-in wind speed and the cut-out wind speed), instead of extreme environmental conditions. The wind turbine has a variety of different operating modes at different wind speeds, which leads to a discontinuous relationship between extreme response and environmental parameters. However, in each monotonous interval, ECM can be directly applied. The serious problem of ECM is that the calculated response of the selected environmental conditions is far away from the actual situation. If this problem is solved, ECM can be applied again. That is the modified environmental contour method (MECM).

The MECM essentially uses another contour line with a smaller return period to find a combination of environmental conditions, which is expected to find the exact design point. The selection of the ideal location for this new contour requires a full understanding of the characteristics of the system. For a monopile wind turbine, its most important environmental contour is the contour of the corresponding environmental conditions when the system changes its operating mode. such as that corresponding to the cut-out wind speed (when the wind turbine changes to parking state), near the rated wind speed (when it involves the control of the wind turbine, leading to the change in response).

Consider the N-year the extreme responses, it contains $N \cdot 365.25 \cdot 24$ numbers of 1-hour interval. Similarly, each 1-hour time unit is assumed to be independent, then the 1-hour cumulative distribution function of the return period of N year is:

$$F_{R_{1h,Ny}}(r_e) = F_{R_{1h}}^{LT}(r_e)^{N \cdot 365.25 \cdot 24} \tag{3.41}$$

The 50-year 1-hour extreme response cumulative distribution function can be extrapolated from the N-year 1-hour extreme cumulative distribution function:

$$F_{R_{1h,50y}}(r_e) = \left(F_{R_{1h}}^{LT}(r_e)^{N \cdot 365.25 \cdot 24}\right)^{\frac{50}{N}} = \left(F_{R_{1h,Ny}}(r_e)\right)^{\frac{50}{N}} \tag{3.42}$$

$$F_{R_{1h,50y}}(r_e) \approx F_{R_{1h,50y}}(r_e\,|u_N,\ h_N, t_N) = \left[F^{ST}_{R_{1h|U_w,H_s,T_p}}(r_e\,|u_N, h_N, t_N)\right]^{\frac{50}{N}} \tag{3.43}$$

where $F_{R_{1h,50y}}(r_e\,|u_N,\ h_N, t_N)$ is the 50-year 1-hour extreme response cumulative distribution function. The principle of this method is to obtain $F_{R_{1h,50y}}(r_e)$ by extrapolating $F_{R_{1h,Ny}}(r_e)$ and the N-year environmental contour is approximated by $F^{ST}_{R_{1h|U_w,H_s,T_p}}(r_e\,|u_N, h_N, t_N)$.

When wind load is ignored or the wind turbine is parking state, the traditional environmental contour method is suitable for the wind turbine. however, when considering the wind load, the operation mode of the wind turbine is related to the wind speed, the response of the wind turbine is non-monotonic, that is the reason for applying this modified method-to avoid the influence of the non-monotonic behavior and use another contour line to obtain the more precise results without high quantile or correction coefficient. The procedure is illustration in Figure 3.5.

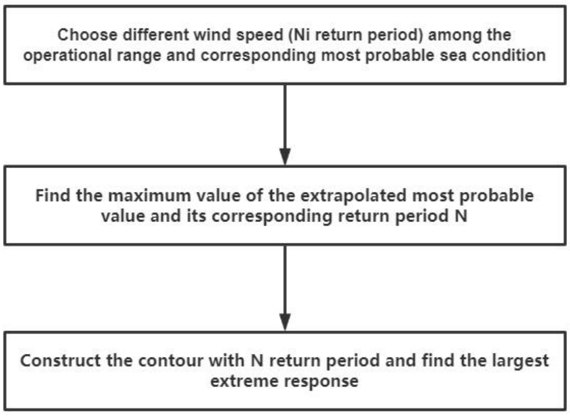


Figure 3.5: Procedure of modified environmental contour method

Besides wind turbine, MECM can be applied on any systems that the operational mode change with the environmental variables or the cases that the extreme responses are non-monotonic with the environmental variables. It is the method without correction coefficient to obtain the more accurate value.

4

Results and Discussion

In this chapter, the results, obtained based on the methodology described in chapter 3 are present. The joint probability density function model used is introduced in section 4.1. In section 4.3, the extreme response analysis based on full long-term analysis can be found. Then, the results of extreme response evaluation based on environmental contour method and modified environmental contour method are presented in section 4.4 and section 4.5, respectively.

4.1. Joint probability density function model

Before drawing the environmental contour surface, the joint probability density function of the three environmental variables U_w, H_s, T_p must be obtained firstly, which is the basis for the environmental contour surface. This paper draws the environmental contour surface based on the ten-year measured data of the center of the North Sea (Li et al., 2013a), and its exceedance probability corresponds to the 50-year return period. The water depth of this site is 20m, and the distance to shore is 300km, shown in (**?**). It should be mentioned that the wind speed in this joint probability density function is the mean wind speed at the height of 10m. For the extreme response analysis, the wind speed at the hub height (90m) is needed. Therefore, a power-law profile with the parameter 0.1 is used in this research (Li et al., 2013a).

$$U_z = U_{10}\left(\frac{z}{10}\right)^{0.1} \tag{4.1}$$

where z is the height above the sea level, and U_{10} represents the reference wind speed at the reference height of 10m.

The joint probability density function can be considered as the combination of a marginal distribution of mean wind speed $U - w$ and a conditional distribution of significant wave height $H - s$ for the given mean wind speed, and a conditional distribution of spectral peak period $T - p$ for given mean wind speed and significant wave height:

$$f_{U_w,H_s,T_p}(u,h,t) = f_{U_w}(u) \cdot f_{H_s|U_w}(h\,|u) \cdot f_{T_p|U_w,H_s}(t\,|u,h) \tag{4.2}$$

One-hour mean wind speed at 10m height U_e is modeled as a 2-parameter Weibull distribution with the parameters α_U (shape parameter) and β_U (scale parameter) then the probability density function is given in Equation 4.3

$$f_{U_w}(u) = \frac{\alpha_U}{\beta_U}\left(\frac{u}{\beta_U}\right)^{\alpha_U-1} \exp\left[-\left(\frac{u}{\beta_U}\right)^{\alpha_U}\right] \tag{4.3}$$

where $\alpha_U = 2.299$ and $\beta_U = 8.920$ (Li et al., 2013a).

The conditional probability density function of significant wave height H_s is also modeled as a 2-parameter Weibull distribution in Equation 4.4.

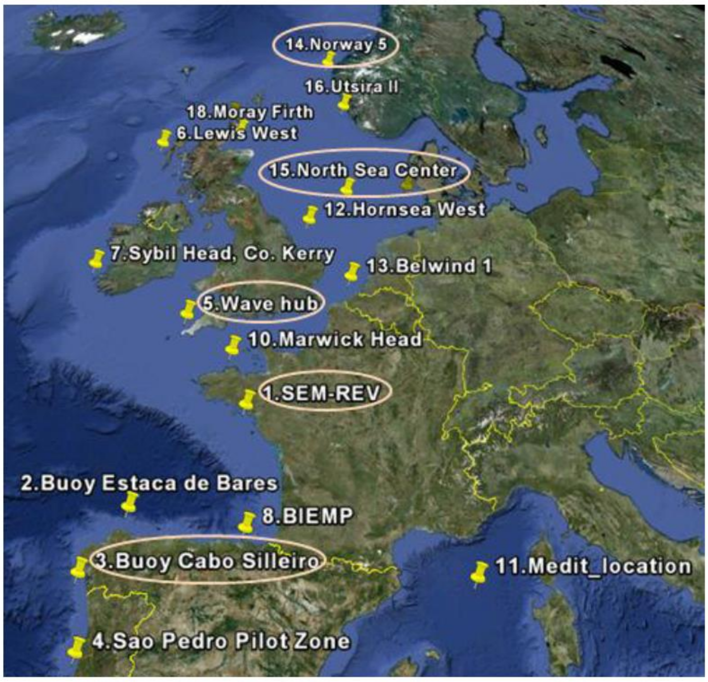


Figure 4.1: Illustration of the location (Site 15) (Li et al., 2013a)

$$f_{H_s|U_w}(h\,|u) = \frac{\alpha_{HC}}{\beta_{HC}}\left(\frac{h}{\beta_{HC}}\right)^{\alpha_{HC}-1}\exp\left[-\left(\frac{h}{\beta_{HC}}\right)^{\alpha_{HC}}\right] \tag{4.4}$$

where α_{HC} is shape parameter and β_{HC} the scale parameter, which are assumed to be conditional on mean wind speed u and modeled as the 3-parameter power functions:

$$\alpha_{HC} = a_1 + a_2 \cdot u^{a_3} \tag{4.5}$$

$$\beta_{HC} = b_1 + b_2 \cdot u^{b_3} \tag{4.6}$$

In this case, the parameters are estimated as $a_1 = 1.755, a_2 = 0.184, a_3 = 1.000, b_1 = 0.534, b_2 = 0.070, b_3 = 1.435$ (Li et al., 2013a).

The conditional probability density function of spectral peak period T_p is modeled as a lognormal distribution from Equation 4.7 to Equation 4.12.

$$f_{T_p|U_w,H_s}(t\,|u,h) = \frac{1}{\sqrt{2\pi}\sigma_{\ln(T_p)}t}\exp\left(-\frac{1}{2}\left(\frac{\ln(t) - \mu_{\ln(T_p)}}{\sigma_{\ln(T_p)}}\right)^2\right) \tag{4.7}$$

$$\mu_{\ln(T_p)} = \ln\left(\frac{\mu_{T_p}}{\sqrt{1 + \nu_{T_p}^2}}\right) \tag{4.8}$$

$$\sigma_{\ln(T_p)}^2 = \ln\left(1 + \nu_{T_p}^2\right) \tag{4.9}$$

$$\nu_{T_p} = \frac{\sigma_{T_p}}{\mu_{T_p}} \tag{4.10}$$

where μ_{T_p} and σ_{T_p} are the mean value and standard deviation of T_p, ν_{T_p} is the coefficient of variance. μ_{T_p} and ν_{T_p} is the function of mean wind speed $U - w$ and significant wave height H_s. μ_{T_p} is given as:

$$\mu_{T_p} = \overline{T_p}(h) \cdot \left[1 + \theta \left(\frac{u - \overline{u}(h)}{\overline{u}(h)}\right)^{\gamma}\right] \tag{4.11}$$

$$\overline{T_p}(h) = e_1 + e_2 \cdot h^{e_3} \tag{4.12}$$

$$\overline{u}(h) = f_1 + f_2 \cdot h^{f_3} \tag{4.13}$$

The coefficient of variation is given as a function of H_s:

$$\nu_{T_p}(h) = k_1 + k_2 \cdot \exp(k_3 h) \tag{4.14}$$

The parameters are estimated as $\theta = -0.477, \gamma = 1.0, e_1 = 5.563, e_2 = 0.798, e_3 = 1.0, f_1 = 3.5, f_2 = 3.592, f_3 = 0.735, k_1 = 0.050, k_2 = 0.388, k_3 = -0.321$ (Li et al., 2013a).

4.2. 5 MW monopile wind turbine model

In this section, the gross properties of the National Renewable Energy Laboratory(NREL) 5 MW monopile wind turbine model is introduced, the more detailed parameters are given in Appendix A, including tower, monopile, drivetrain, hub, nacelle and blade properties. The model is applied to extreme response forecasts.

Offshore wind turbines have many advantages that onshore wind turbines do not have, such as large space available on the sea, abundant offshore wind energy reserves, and low noise and visual pollution. Therefore, offshore wind turbines can choose larger blades to increase the single-machine power. At present, wind turbines with a single-machine power of 5 MW have been extensively studied and are generally installed and operated. Engineers and scientists are working on 10 MW units. Jonkman et al. (Jonkman et al., 2009) of the National New Energy Laboratory in the United States developed a 5MW benchmark wind turbine for offshore wind research based on some public information on wind turbine such as the Dutch offshore wind power conversion project, known as the NREL 5 MW wind turbine. Besides, different support structures are provided for this wind turbine, used for the response analysis or model test.

The research site in this study is the center of the North Sea, which is the shallow water area. Therefore, the support structure selected for the NREL 5 MW wind turbine is the monopile. FAST, developed by the National New Energy Laboratory is used to calculate the dynamic response of the structure subjected to different wind and wave loads. The modules of structural dynamics, aerodynamic loads, inflow wind, control and electrical-drive dynamics, hydrodynamic loads and sub-structural dynamics are considered. The control volumes for the monopile system are shown in Figure 4.2. The forces and moments at the base of wind turbine tower and monopile are analyzed encountered in 50 years.
The monopile wind turbine system is composed of a monopile, tower, hub and nacelle, and blade. The overall structure is shown in Figure 4.3. Some gross properties are shown in Table 4.1. More detailed properties are given in Appendix A.

4.3. Extreme response evaluation based on full long-term analysis

The range of environmental variables selected in this study is shown in Table 4.2. The selected wind speed at the hub height (90 m) is 2 m/s-40 m/s with a spacing of 2 m/s. The significant wave height starts at 1 m with the increment of 2 m to the upper limit-15 m, and the range of spectral peak period is 2 s to 24 s with the spacing of 2 s. There is a total $(20 \cdot 10 \cdot 12)$ numerical simulation examples of environmental conditions required.

The response of interest is the fore-aft shear force on the base of the monopile F_2, the pitch moment on the base of the monopile M_2, the fore-aft shear force on the base of the tower F_1 and the pitch moment on the base of the tower M_1. The illustration of response and wind turbine is shown in Figure 4.4 and Table 4.3.

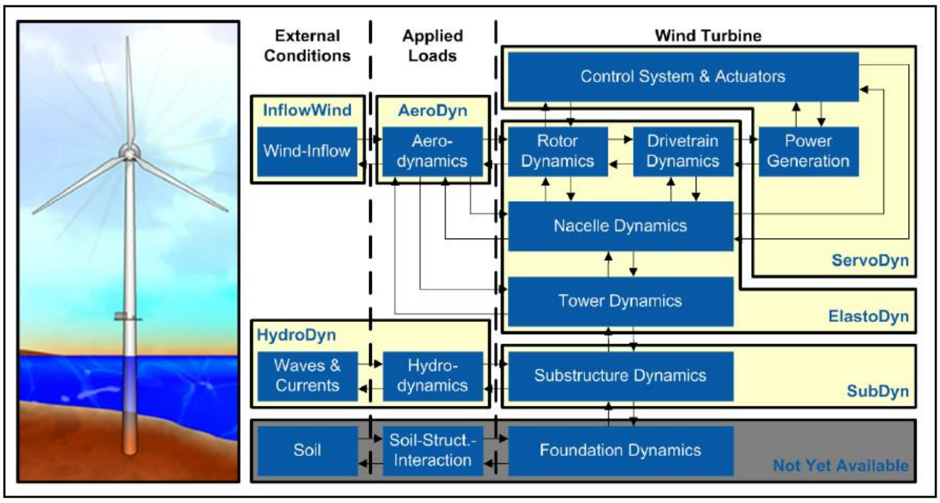


Figure 4.2: The illustration of the control volumes for monopile system (Jonkman and Jonkman, 2016)

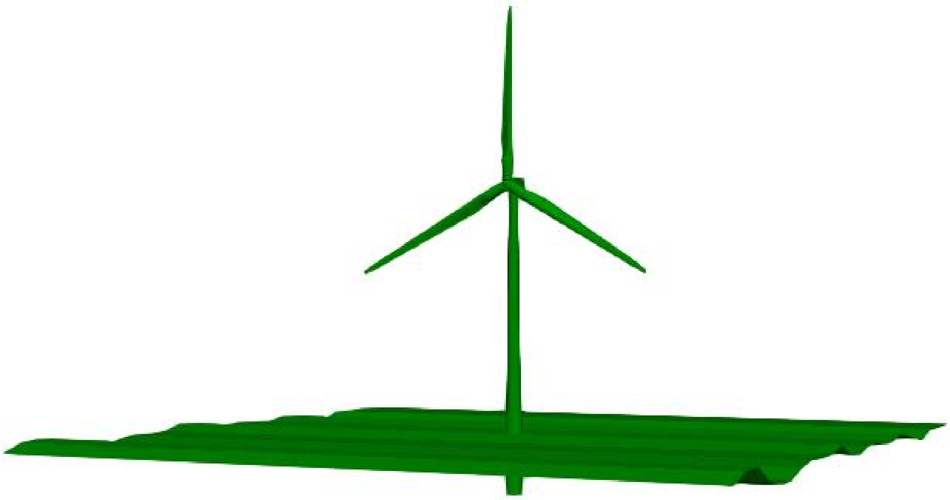


Figure 4.3: Model of 5 MW monopile offshore wind turbine

Table 4.1: Gross properties of monopile wind turbine

Parameter	
Rated Power	5 MW
Blade Model	Upwind, 3 Blades
Control System	Variable Speed, Collective Pitch
Hub Height	90 m
Rotor, Hub Diameter	126 m, 3 m
Drivetrain	High Speed, Multiple-Stage Gearbox
Cut-in, Rated, Cut-out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Rated Tip Speed	80 m/s
Overhang, Shaft Tilt, Precone	5 m, 5º, 2.5º
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg

Table 4.2: The range of environmental variables in FLTA

Variable	Minimum	Maximum	Increment
$U_{hub}(m/s)$	2	40	2
$H_s(m)$	1	10	1
$T_p(s)$	2	24	2

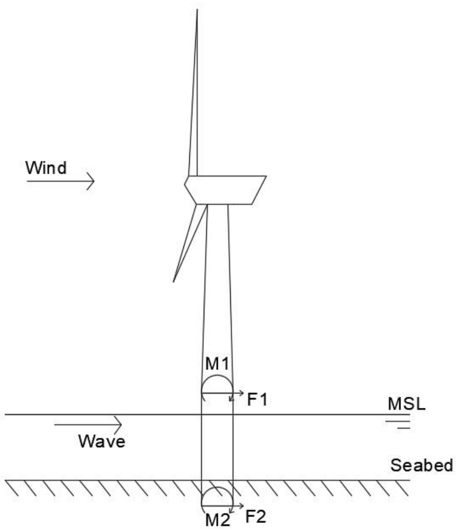


Figure 4.4: Illustration of responses of wind turbine

Table 4.3: Responses considered in this section

Response	Description
F_1	fore-aft shear force on the base of the tower
M_1	pitch moment on the base of the tower
F_2	fore-aft shear force on the base of the monopile
M_2	pitch moment on the base of the monopile

In order to the short-term 1-hour extreme response cumulative function $F^{ST}_{R_{1h}|U_w,H_s,T_p}(r_e\,|u,h,t)$, for each environmental condition, 20 seeds are given for numerical simulation. Gumbel method, Weibull tail method and Up-crossing rate method can be used for short-term response analysis. In this study, all the extreme results will be fitted according to Gumbel distribution, which gives the 10-minute extreme value distribution $F^{ST}_{R_{10min}}(x)$ for each environmental condition. The cumulative distribution function of Gumbel distribution is expressed as:

$$F(x) = e^{-e^{-\frac{x-\mu_G}{\beta_G}}} \tag{4.15}$$

where μ_G and β_G are location parameter and scale parameter, respectively.

An example of Gumbel fitting of 20 random seeds for the fore-aft shear force on the base of the tower F_1 with the environmental condition of $U_w = 23m/s, H_s = 6.83m, T_p = 8.21s$ is shown in Figure 4.5. The horizontal axis and the vertical axis represent the structural response F_1 and variables $-\ln(-\ln(F(x)))$, respectively. Through the Equation 4.16, find the slope and intercept of the fitted curve (95 % confidence interval), and then determine μ_G and β_G (Brodtkorb et al., 2000) The detailed data and fitting curves of other responses is shown in Appendix B.

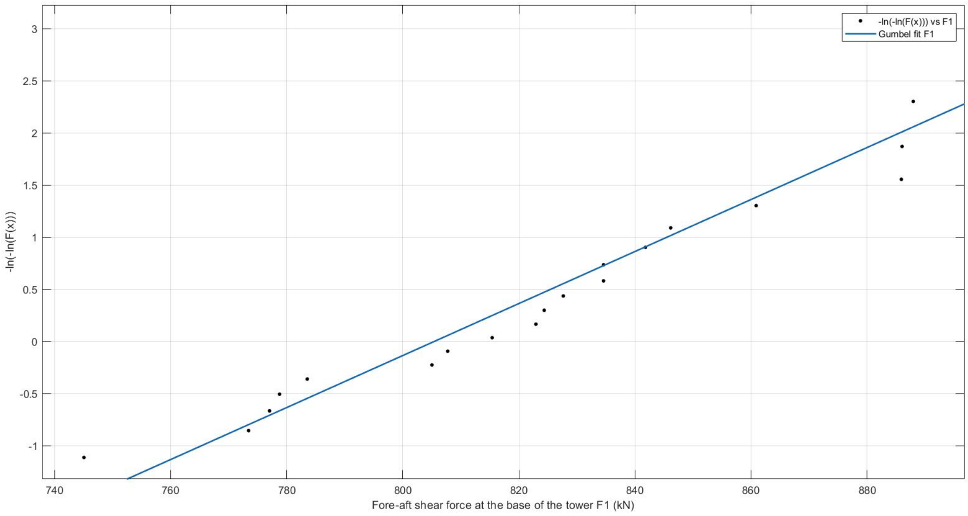


Figure 4.5: Gumbel fitting of 20 random seeds for F_1 at a certain environmental condition

$$-\ln(-\ln(F(x))) = \frac{1}{\beta_G}\cdot x - \frac{\mu_G}{\beta_G} \tag{4.16}$$

It has been proved that dividing one hour into six independent ten minutes is reliable (Li et al., 2013b). By considering the extreme response conditions in every ten minutes are independent, the 1-hour extremums cumulative distribution function is shown in Equation 4.17.

$$F^{ST}_{R_{1h}|U_w,H_s,T_p}(r_e\,|u,h,t) = F^{ST}_{R_{10\,\mathrm{min}}|U_w,H_s,T_p}(r_e\,|u,h,t)^6 \tag{4.17}$$

In this case, μ_G and β_G are estimated as 805.455 and 40.11, respectively. In this study, simplified full long-term analysis is applied, and the important environmental conditions are of the wind speed of 8-25 m/s at the height of the hub. The results of response analysis based on FLTA are shown in Table 4.4, which work as a benchmark of the following method.

Table 4.4: Extreme responses based on full long-term analysis

Method	$F_1(kN)$	$M_1(kN \cdot m)$	$F_2(N)$	$M_2(N \cdot m)$
FLTA	1.56E+03	1.20E+05	5.35E+06	1.57E+08

4.4. Extreme response evaluation based on environmental contour method

4.4.1. Environmental contour method based by IFORM

The principle of environmental contour method based by IFORM has been described in chapter 3, the steps are as follows:

- Build 50-year 3D environmental contour surface.
- Choose environmental condition on the contour line.
- Select the environmental condition causing the maximum extreme response and using a high fractile or correction factor to obtain the extreme response.

Consider one hour as a separate unit of time, and the total number of one hour in fifty years is $24 \cdot 365.25 \cdot 50$, therefore the exceedance probability is:

$$P_f = \frac{1}{24 \cdot 365.25 \cdot 50} = 2.28154 \times 10^{-6} \tag{4.18}$$

For the contour surface considering three variables (turbulence intensity is set to be a constant as 15% in the following simulation), the exceedance probability corresponds to the limit state sphere with radius r_i. which is calculated to be $r_i = 4.58$ by Equation 4.19. Limit state surface in U space is shown in Figure 4.6.

$$\Phi(r_i) = 1 - P_f \tag{4.19}$$

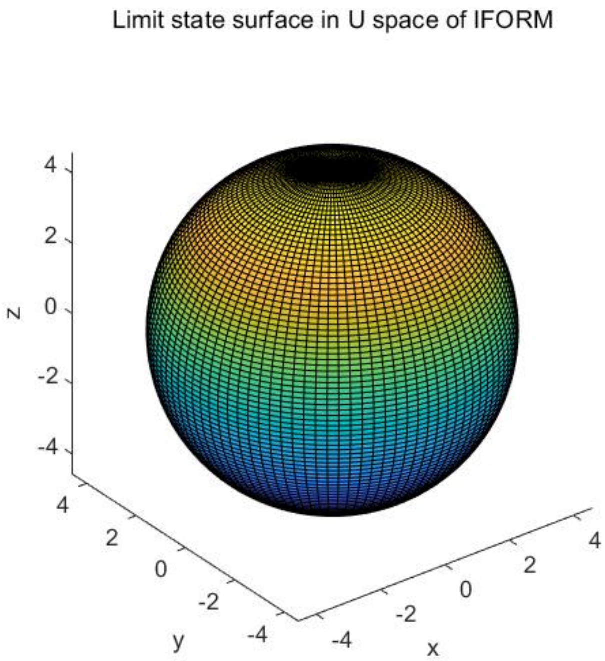
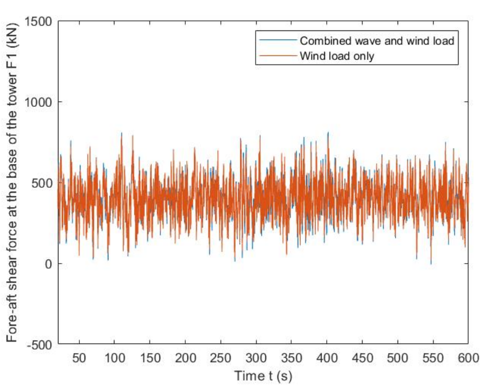


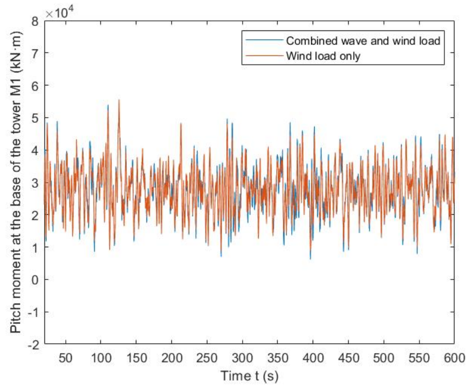
Figure 4.6: Limit state surface in U space of IFORM

Limit state surface in U space shown can be converted to physical space (Figure 4.8), which contains different variables.

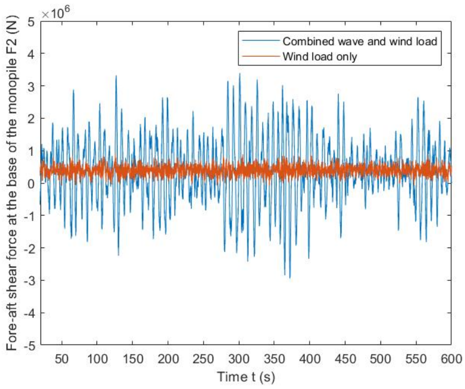
The illustration of the wind turbine model and response is the same as shown in Figure 4.4 and Table 4.3. For the four different responses, first, judge their characteristics to improve efficiency. The time history comparison of the structure responses under the combined wind and waves loads and the wind load only are shown in Figure 4.7. The selected environmental condition of the combined wind and waves loads is $U_w = 23m/s, H_s = 3m, T_p = 18s$ while that of the wind load only is $U_w = 23m/s$.



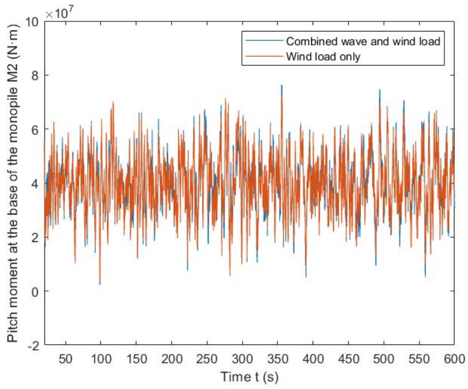
(a) Time history comparison of F_1



(b) *Time history comparison of* M_1



(c) *Time history comparison of* F_2



(d) *Time history comparison of* M_2

Figure 4.7: Time history comparison of responses

Because the monopile is ten meters above sea level, the fore-aft shear force on the base of the tower F_1 and the pitch moment on the base of the tower M_1 can be considered to be affected by wind load only. For the fore-aft shear force on the base of the monopile F_2, it is the wave-dominated force, shown in Figure 4.7(c) and the pitch moment on the base of the monopile M_2 is wind dominated, shown in Figure 4.7(d). Based on these principles, a two-dimensional environmental line under different wind speeds can be drawn for extreme response prediction.

The limit state surface in physical space is shown in Figure 4.8, where the three coordinate axes correspond to three physical variables, that is, mean wind speed U_w, significant wave height H_s, and spectral peak period T_p.

By depicting the two-dimensional contours under different wind speeds, the combination of environmental variables is determined, then calculate the extreme response and obtain the corresponding environmental condition.

For the larger response caused by wind load and wave load, that is, the wind speed near the rated

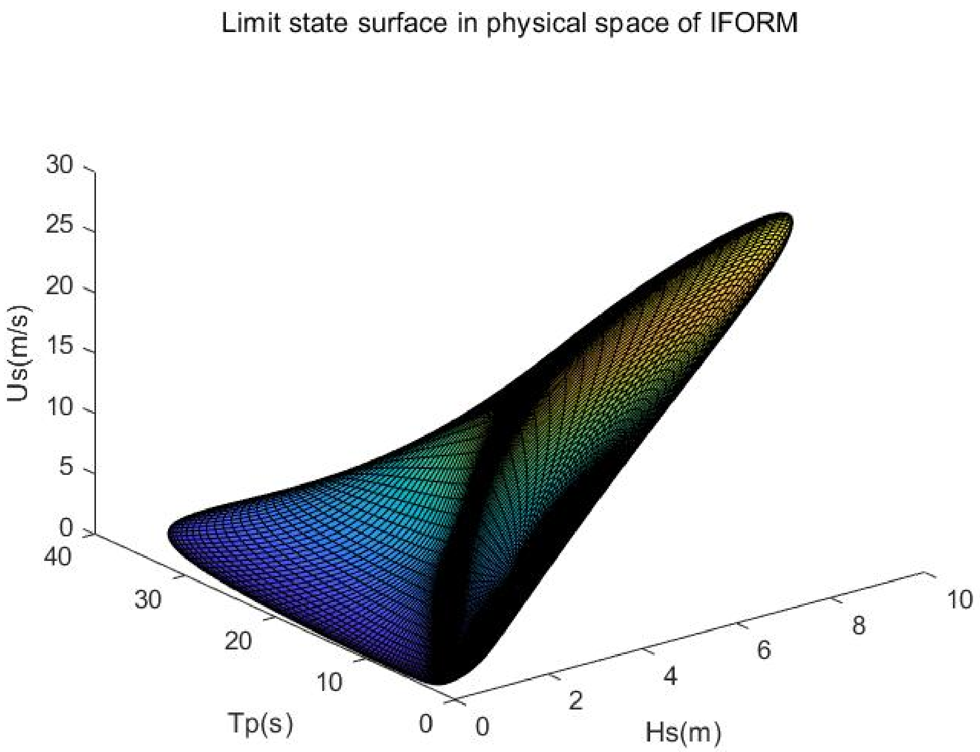


Figure 4.8: Limit state surface in physical space of IFORM

speed and the cut-out wind speed, several contour lines are drawn for the selection of environmental conditions. For F_1 and M_1, because it is only affected by wind loads, its environmental contour line is just a point containing only one variable of wind speed, which corresponds to the point of the maximum wind speed on the three-dimensional contour surface, shown in Table 4.5.

Table 4.5: Selection of critical environmental condition for F_1 and M_1 based on IFORM

Variable	Unit	Description	Value
$U_{w,max,IFORM}$	m/s	Maximum wind speed on the 3D environmental contour (10 m)	27.20
$U_{hub,max,IFORM}$	m/s	Maximum wind speed on the height of hub (90 m)	33.88

For the fore-aft shear force on the base of the monopile F_2, it is dominated by wave loads, usually, high wind speed corresponds to large significant wave height, leading to large wave loads. Therefore, the extreme response of F_2 appears near the cut-out wind speed. As shown in Figure 4.9, where environmental contour line is given about H_s and T_p on different wind speed at the height of hub. It ranges from 23 m/s to 25 m/s with the spacing of 1 m/s.

For the pitch moment on the base of the monopile M_2, it is dominated by wind load. Therefore, the extreme response of M_2 appears near the rated wind speed, slightly higher than rated wind speed. As shown in Figure 4.10, where environmental contour line is given about H_s and T_p on different wind speed at the height of hub. It ranges from 12 m/s to 15 m/s with increment of 1 m/s. For each wind speed, different environmental combinations should be selected along the contour lines to find the environmental condition that causes the maximum extreme response.

Similar to the data processing method in section 4.3, 20 seeds are given for each environmental condition to perform a ten-minute numerical simulation. All the extremum in the simulation are fitted according to the Gumbel distribution, which gives the 10-minute extreme value distribution $F^{ST}_{R_{10min}}(x)$ for

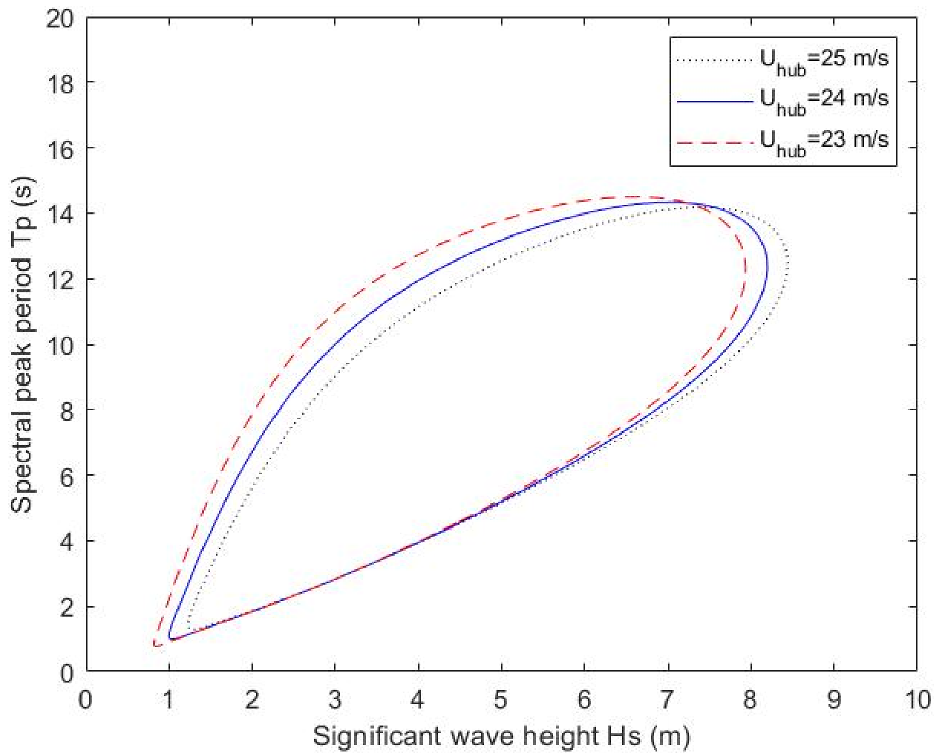


Figure 4.9: Contour lines under different wind speed for F2 based on IFORM

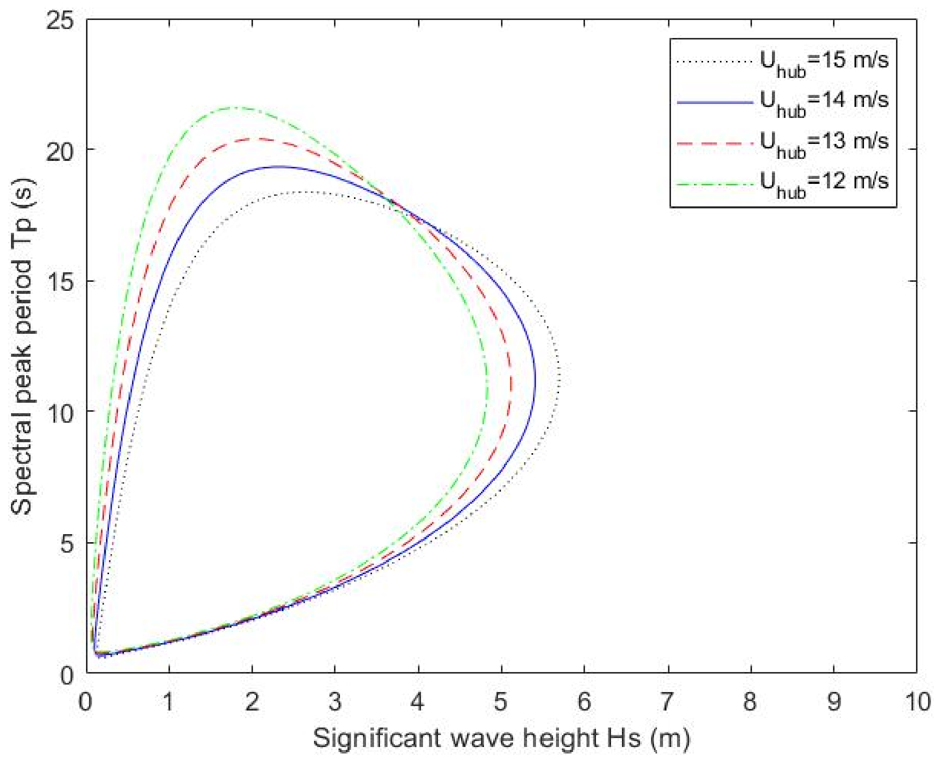


Figure 4.10: Contour lines under different wind speed for M2 based on IFORM

each environmental condition. Assume that one hour contains six independent ten minutes, through Equation 4.17, 1-hour extreme distribution $F^{ST}_{R_{1h}|U_w,H_s,T_p}\ (r_e\ |u,h,t)$ can be obtained. μ_G in the expression is the mode of the Gumbel distribution, which is also the most probable value. The expression for the most probable value extrapolated to one hour is:

$$\mu_{G_{1h,50year}} = \mu_G + \beta_G \cdot \ln 6 \tag{4.20}$$

where μ_G and β_G is the estimated value from the fitting curve. The results with different environmental conditions in the table are all extrapolated values.

According to the combination of environmental variables shown in the 2D environmental contour lines in Figure 4.9 and Figure 4.10, choose the point on the contour line to calculate the response. The selected environmental conditions are listed in Table 4.6, Table 4.7 and Table 4.8.

Table 4.6: Selection of critical environmental condition for F_1 and M_1 based on IFORM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$F_1(kN)$	$M_1(kN \cdot m)$
33.88	-	-	8.86E+02	5.11E+04

Table 4.7: Selection of critical environmental conditions for F_2 based on IFORM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$F_2(N)$
25	7.09	8.21	4.10E+06
24	6.94	8.46	4.04E+06
23	6.83	8.21	4.01E+06

Table 4.8: Selection of critical environmental conditions for M_2 based on IFORM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$M_2(N \cdot m)$
15	3.90	4.60	1.15E+08
14	3.97	4.94	1.17E+08
13	3.99	5.29	1.16E+08
12	4.09	6.01	1.16E+08

The critical environmental conditions at different wind speeds are listed in the table. It can be seen from the table that the extreme response of the fore-aft shear force on the base of the monopile appears near cut-out wind speed. In this case, a high significant wave height is generated with a high wind speed. The extreme response of pitch moment on the base of the monopile appears slightly higher than the rated wind speed, which is with a high wind load. When considering fore-aft shear force and pitching moment on the base of the tower by the environmental contour method based on IFORM, because it is only affected by wind load, the unique variable is wind speed. The critical environmental condition for the extreme response is the maximum wind speed once in 50 years. The summary of extreme response and critical environmental conditions of ECM based on the IFORM is shown in Table 4.9.

All the extreme responses in Table 4.9 are the most probable value (MPV), the next step is error analysis and considers different quantile to obtain useful results with small errors compared with the results from FLTA. The comparison and the error are shown in Table 4.10. It can be seen from Table 4.10 that the results from ECM based on IFORM are generally lower than that from FLTA (MPV is nearly 25% lower than the results from FLTA). Even considering a high quantile, this method does not perform well. This is because there is no accurate and unique quantile value to ensure that all results are reliable at the same time. For $F_2(N)$, 95% is used, however, 95% is not suitable for $M_2(N \cdot m)$, but 99.9% compared with the results from FLTA. In practice, there are no results from FLTA as a benchmark, therefore, the selection of quantile value is lacking a reference, but choose subjectively. Quantile is different for a

Table 4.9: Selected environmental conditions and extreme responses of ECM based on the IFORM

	$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	Extreme response
$F_1(kN)$	33.88	-	-	8.86E+02
$M_1(kN \cdot m)$	33.88	-	-	5.11E+04
$F_2(N)$	25	7.09	8.21	4.10E+06
$M_2(N \cdot m)$	14	3.97	4.94	1.17E+08

different response and influenced by the environment, and the results change greatly with the change of fractile in the tail region of the probability distribution. In some studies, quantile is replaced by a correction factor, 1.25 is used on MPV to predict extreme responses (Muliawan et al., 2013).

Table 4.10: Results of different quantile of ECM based on IFORM and differences compared with FLTA

Quantile	$F_2(N)$			$M_2(N \cdot m)$		
	IFORM	FLTA	Error	IFORM	FLTA	Error
MPV	4.10E+06	5.35E+06	-23.29%	1.17E+08	1.57E+08	-25.62%
50%	4.23E+06	5.35E+06	-20.97%	1.19E+08	1.57E+08	-24.41%
60%	4.33E+06	5.35E+06	-19.03%	1.20E+08	1.57E+08	-23.40%
70%	4.45E+06	5.35E+06	-16.75%	1.22E+08	1.57E+08	-22.21%
80%	4.61E+06	5.35E+06	-13.77%	1.25E+08	1.57E+08	-20.66%
90%	4.87E+06	5.35E+06	-9.00%	1.28E+08	1.57E+08	-18.18%
95%	5.26E+06	5.35E+06	-1.77%	1.32E+08	1.57E+08	-15.80%
99%	5.67E+06	5.35E+06	5.91%	1.41E+08	1.57E+08	-10.41%
99.9%	6.45E+06	5.35E+06	20.56%	1.53E+08	1.57E+08	-2.78%

4.4.2. Environmental contour method based by ISORM

The analysis of ECM based on ISORM starts from the standard normal space like that of IFORM, but the difference is that the radius $r_{i,ISORM}$ of the limit state sphere in U space. $r_{i,ISORM}$ is determined to be $r_{i,ISORM} = 5.38$ by Equation 4.21.

$$\chi^2 \left(r_{i,SORM}^2\right) = 1 - P_f \tag{4.21}$$

where P_f is calculated by Equation 4.18. The limit state surface in U space based on ISORM is shown in Figure 4.11. Then, transfer the limit state surface in U space to physical space, shown in Figure 4.12 to obtain the combination of environmental variables.

The process of data analysis is similar to that in the previous section. Through the three-dimensional environmental surface in physical space, the contour lines of the significant wave height H_s and spectral peak period T_p under different wind speeds are drawn, and the select environmental conditions along the contour line to calculate the extreme response.

For F_1 and M_1, the selected contour line converges to a point corresponding to the maximum wind speed on the environmental contour surface, shown in Table 4.11.

Table 4.11: Selection of critical environmental condition for F_1 and M_1 based on ISORM

Variable	Unit	Description	Value
$U_{w,max,ISORM}$	m/s	Maximum wind speed on the 3D environmental contour (10 m)	30.66
$U_{hub,max,ISORM}$	m/s	Maximum wind speed on the height of hub (90 m)	38.20

The critical environmental condition to calculate F_1 and M_1 is shown in Table 4.12. F_1 and M_1 in Table 4.12 are extrapolated value.

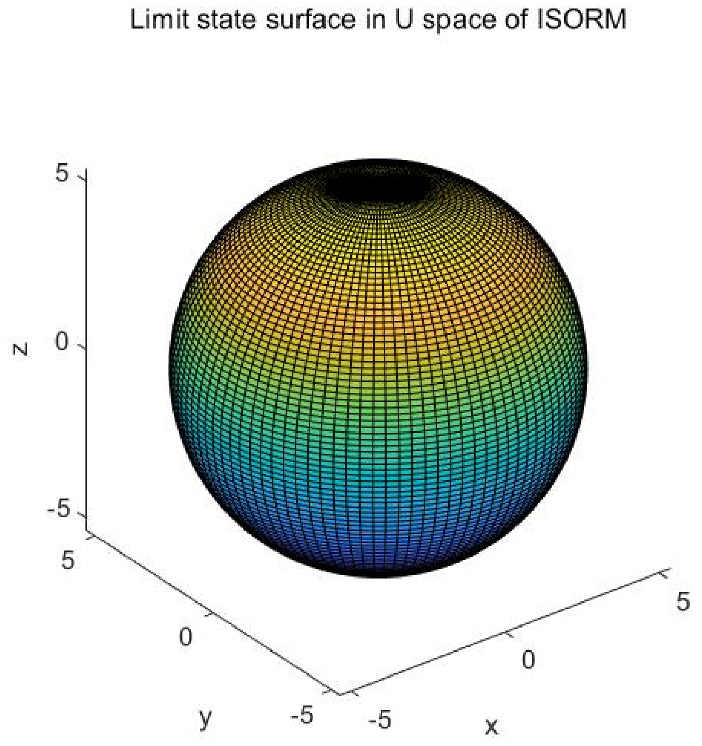


Figure 4.11: Limit state surface in U space of ISORM

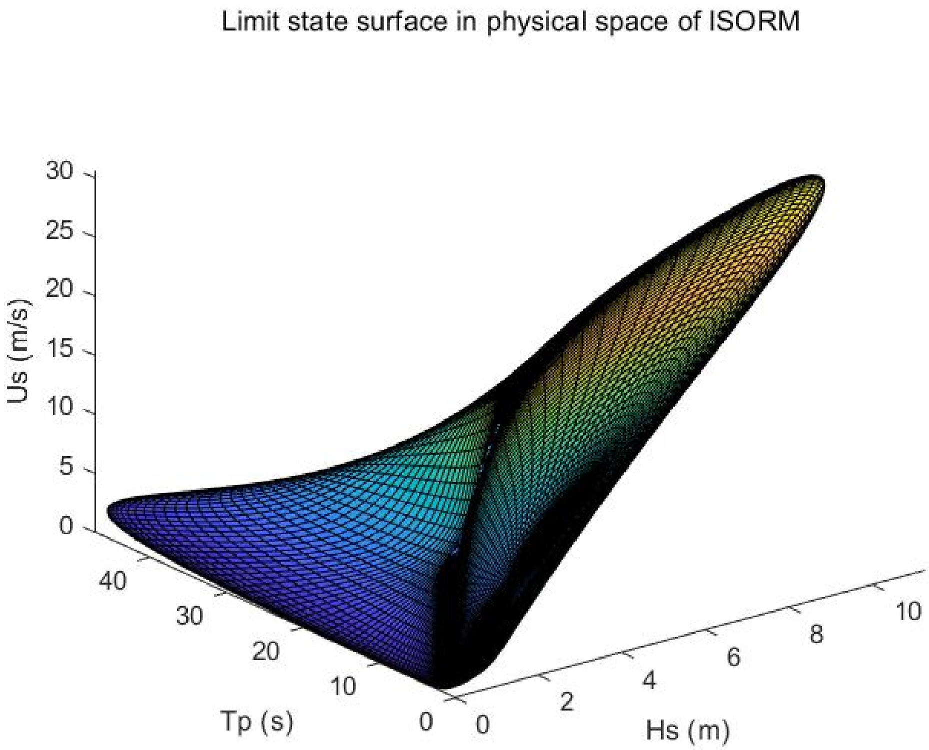


Figure 4.12: Limit state surface in physical space of ISORM

Table 4.12: Extreme responses of F_1 and M_1 based on ISORM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$F_1(kN)$	$M_1(kN \cdot m)$
38.20	-	-	8.01E+02	4.99E+04

For F_2, the contours around the cut-out wind speed are drawn, ranging from 23 m/s to 25 m/s with the increment of 1 m/s, to predict the extreme response of shear force on the bottom of monopile, as shown in Figure 4.13. Find the point along the contour line for each wind speed to find the extreme response and the corresponding environmental conditions.

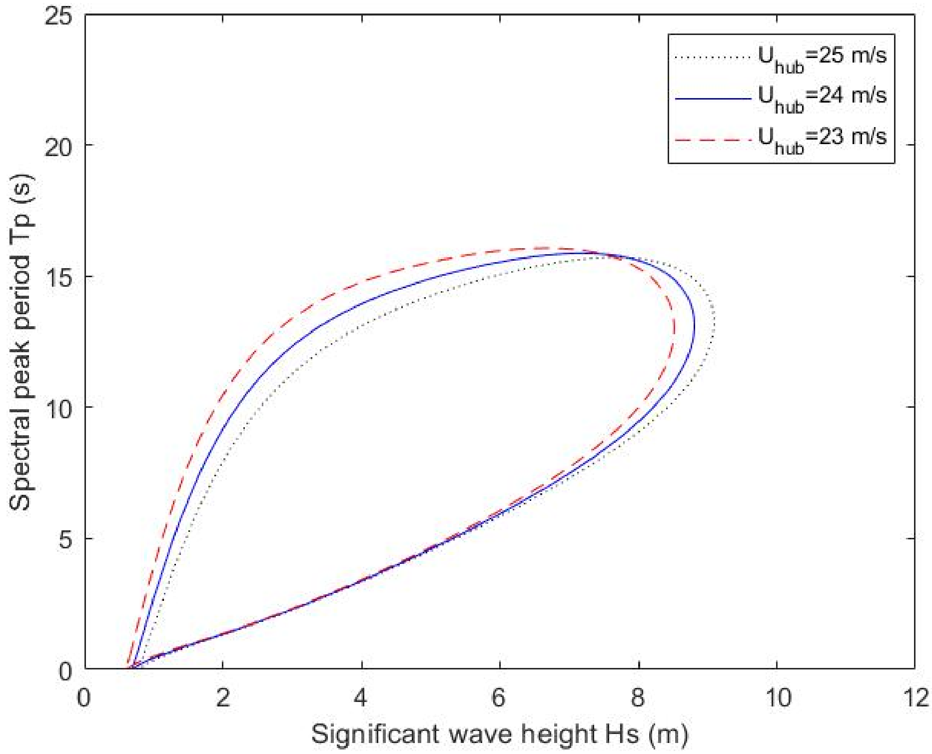


Figure 4.13: Contour lines under different wind speed for F2 based on ISORM

For M_2, create the contours around the rated wind speed, ranging from 12 m/s to 15 m/s with the spacing of 1 m/s, choose the point along the contour to predict the extreme response of pitch moment on the bottom of monopile, as shown in Figure 4.14.
The selections of the critical environmental condition for each wind speed are shown in Table 4.13 and Table 4.14. The results in the following tables are all the extrapolated most probable values.

Table 4.13: Selection of critical environmental conditions for F_2 based on ISORM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$F_2(N)$
25	7.33	7.84	4.74E+06
24	7.16	7.75	4.27E+06
23	6.97	7.65	4.01E+06

The summary of extreme response and critical environmental conditions of ECM based on the ISORM is shown in Table 4.15. It can be seen from the table that the extreme response of the fore-aft shear force on the base of the monopile appears near cut-out wind speed, which is dominated by wave load. The extreme response of pitch moment on the base of the monopile appears slightly higher than the

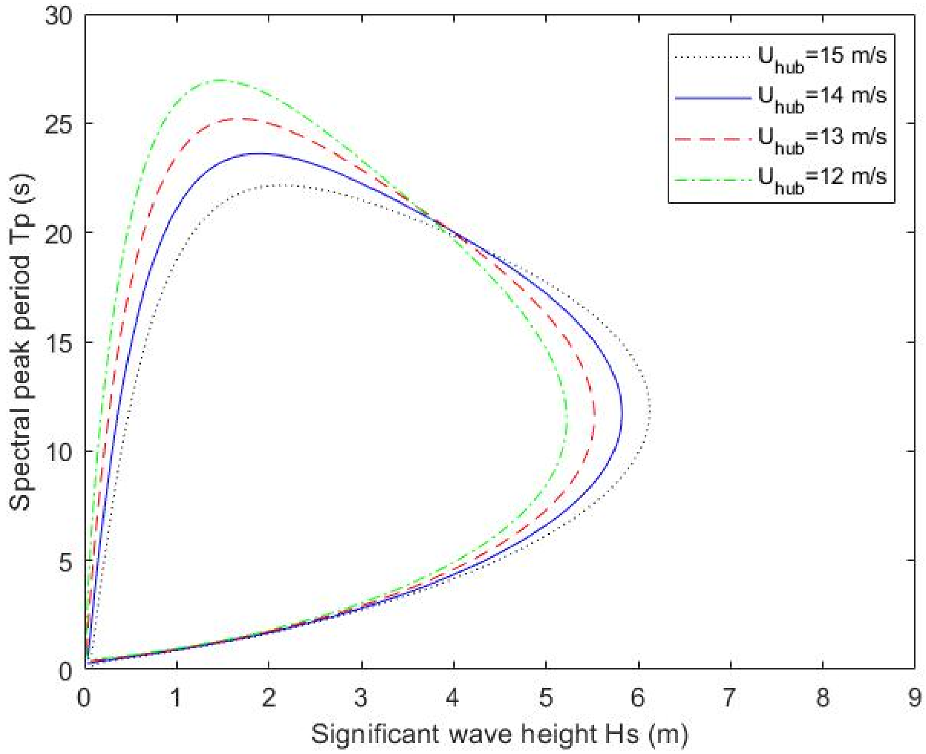


Figure 4.14: Contour lines under different wind speed for M2 based on ISORM

Table 4.14: Selection of critical environmental conditions for M_2 based on ISORM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$M_2(N \cdot m)$
15	3.95	4.07	1.15E+08
14	4.01	4.36	1.21E+08
13	4.06	4.71	1.18E+08
12	4.10	5.15	1.20E+08

rated wind speed, which is dominated by wind load. When considering fore-aft shear force and pitching moment on the base of the tower, it is only affected by wind load. The critical environmental condition for the extreme response is the maximum wind speed once in 50 years.

Table 4.15: Selected environmental conditions and extreme responses of ECM based on the ISORM

	$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	Extreme response
$F_1(kN)$	38.20	-	-	8.01E+02
$M_1(kN\cdot m)$	38.20	-	-	4.99E+04
$F_2(N)$	25	7.33	7.84	4.74E+06
$M_2(N\cdot m)$	14	4.01	4.36	1.21E+08

It is obvious that the most probable extreme response predicted by ECM based on ISORM is always more conservative than that of IFORM, the overall prediction value is closer to that from FLTA than the result obtained based on IFORM. However, as shown in Table 4.16, if MPV is used to represent the extreme response, the reliability of all responses cannot be guaranteed. 70% quantile of F1 is more close to that of FLTA, but M2 is not. Similarly, the quantile needs to be considered, but the challenge is the same as in IFORM. There is no accurate quantile value that can be applied to all responses, but the advantage is that the MPV obtained by ISORM is more conservative than that obtained by IFORM. For the response on the base of the tower, it is only influenced by wind load, the results obtained by IFORM and ISORM are similar. This is the limitation of the ECM method and will be explained in detail later.

Table 4.16: Results of different quantile of ECM based on ISORM and differences compared with FLTA

Quantile	$F_2(N)$			$M_2(N\cdot m)$		
	ISORM	FLTA	Error	ISORM	FLTA	Error
MPV	4.74E+06	5.35E+06	-11.48%	1.21E+08	1.57E+08	-23.21%
50%	4.92E+06	5.35E+06	-8.07%	1.23E+08	1.57E+08	-21.77%
60%	5.07E+06	5.35E+06	-5.23%	1.25E+08	1.57E+08	-20.57%
70%	5.25E+06	5.35E+06	-1.89%	1.27E+08	1.57E+08	-19.15%
80%	5.48E+06	5.35E+06	2.47%	1.30E+08	1.57E+08	-17.30%
90%	5.86E+06	5.35E+06	9.45%	1.34E+08	1.57E+08	-14.34%
99%	7.03E+06	5.35E+06	31.31%	1.49E+08	1.57E+08	-5.08%
99.5%	7.37E+06	5.35E+06	37.79%	1.53E+08	1.57E+08	-2.34%

4.4.3. Environmental contour method based by HDRM

The process of ECM based on HDRM calculates the response in the space of the original variables. The limit space surface of the combination of environmental variables is shown in Figure 4.15.

The contour lines of the significant wave height H_s and spectral peak period T_p under different wind speeds are plotted through this three-dimensional environmental contour surface, and then select environmental conditions along the contour line to determine the extreme response of 50-year return period.

Similarly, for F_1 and M_1, the point corresponding to the maximum wind speed of return period of 50 years is selected, shown in Table 4.17.

Table 4.17: Selection of critical environmental condition for F_1 and M_1 based on HDRM

Variable	Unit	Description	Value
$U_{w,max,HDRM}$	m/s	Maximum wind speed on the 3D environmental contour (10 m)	30.69
$U_{hub,max,HDRM}$	m/s	Maximum wind speed on the height of hub (90 m)	38.24

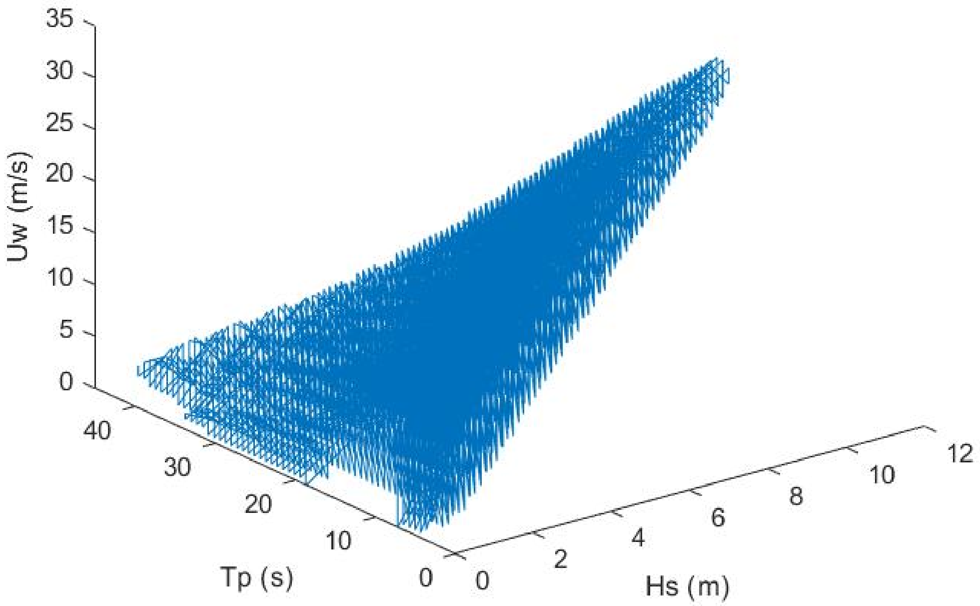


Figure 4.15: Limit state surface in physical space of HDRM

The critical environmental condition to calculate F_1 and M_1 is shown in Table 4.18. F_1 and M_1 in Table 4.18 are the extrapolated most probable value.

Table 4.18: Extreme responses of F_1 and M_1 based on HDRM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$F_1(kN)$	$M_1(kN \cdot m)$
38.24	-	-	7.89E+02	4.75E+04

For F_2, it is the wave-dominated response, draw the contour line near the cut-out wind speed, and for the wind-dominated response M_2, the contours around the rated wind speed are selected, which ranges from 23 m/s to 25 m/s and 12 m/s to 15 m/s with the increment of 1 m/s used to predict the extreme response of shear force and pitch moment on the bottom of monopile, as shown in Figure 4.16 and Figure 4.17. Points are selected along the contour lines to obtain the combination of environmental variables under different wind speed to find the extreme response.
The selections of the critical environmental condition for each wind speed and the extrapolated most probable results are shown in Table 4.19 and Table 4.20.

Table 4.19: Selection of critical environmental conditions for F_2 based on HDRM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$F_2(N)$
25	7.31	7.81	4.59E+06
24	7.15	7.76	4.19E+06
23	6.91	7.58	4.15E+06

The summary of extreme response and critical environmental conditions of ECM based on the HDRM is shown in Table 4.21. It can be seen from the table that the extreme response of the fore-aft shear force on the base of the monopile appears near cut-out wind speed, which is dominated by wave load.

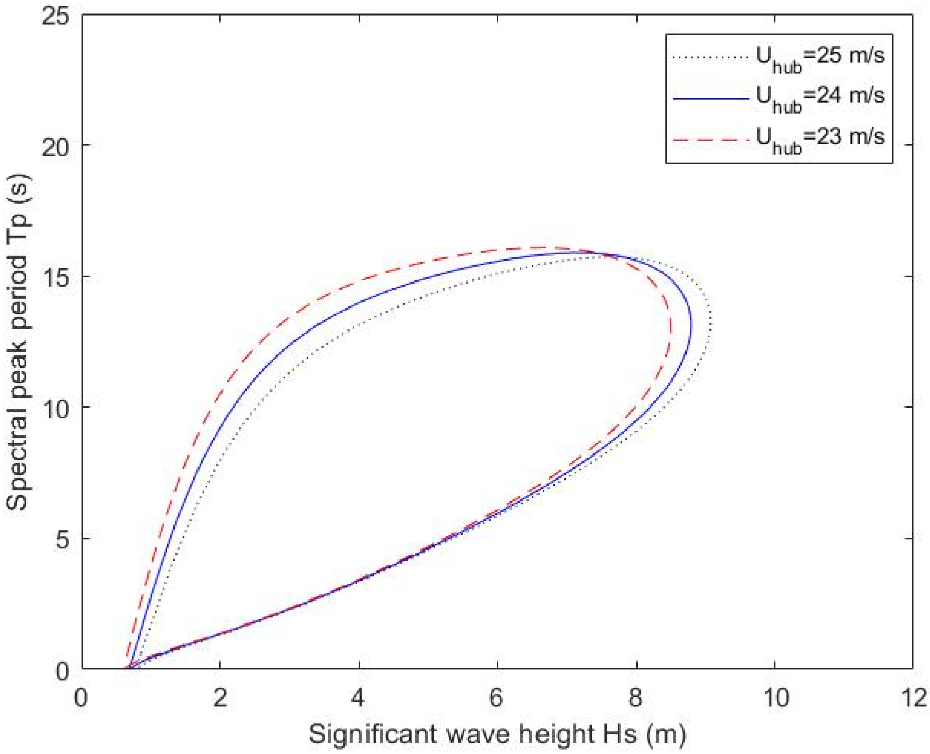


Figure 4.16: Contour lines under different wind speed for F2 based on HDRM

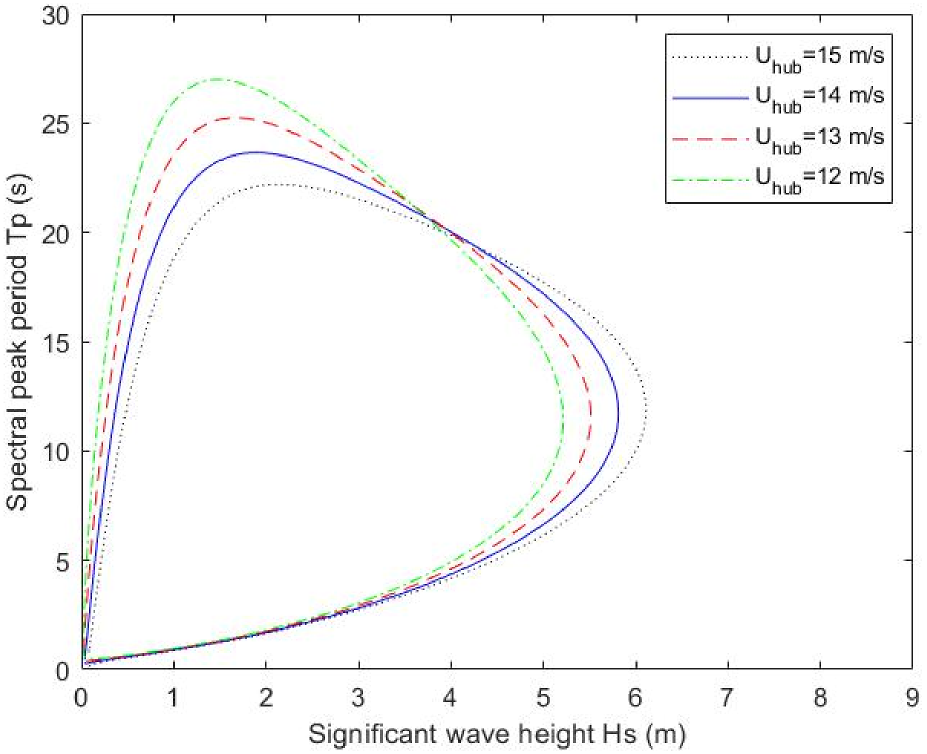


Figure 4.17: Contour lines under different wind speed for M2 based on HDRM

Table 4.20: Selection of critical environmental conditions for M_2 based on HDRM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$M_2(N \cdot m)$
15	3.74	3.75	1.16E+08
14	3.90	4.18	1.21E+08
13	3.98	4.57	1.19E+08
12	4.04	5.02	1.21E+08

The extreme response of pitch moment on the base of the monopile appears slightly higher than the rated wind speed, which is dominated by wind load. When considering fore-aft shear force and pitching moment on the base of the tower, it is only affected by wind load. The critical environmental condition for the extreme response is the maximum wind speed once in 50 years.

Table 4.21: Selected environmental conditions and extreme responses of ECM based on the HDRM

	$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	Extreme response
$F_1(kN)$	38.24	-	-	7.89E+02
$M_1(kN \cdot m)$	38.24	-	-	4.75E+04
$F_2(N)$	25	7.31	7.81	4.59E+06
$M_2(N \cdot m)$	14	3.90	4.18	1.21E+08

The results from ECM based on HDRM are more conservative than that of IFORM as well, shown in Table 4.22. However, MPV is still not representative. Similarly, the quantile needs to be considered like the previous two methods. The comparison of three different approaches to obtain environmental contour is shown in Table 4.23.

Table 4.22: Results of different quantile of ECM based on HDRM and differences compared with FLTA

Quantile	$F_2(N)$			$M_2(N \cdot m)$		
	HDRM	FLTA	Error	HDRM	FLTA	Error
MPV	4.59E+06	5.35E+06	-19.39%	1.21E+08	1.57E+08	-22.84%
50%	4.73E+06	5.35E+06	-11.62%	1.23E+08	1.57E+08	-21.42%
60%	4.85E+06	5.35E+06	-9.40%	1.25E+08	1.57E+08	-20.23%
70%	4.99E+06	5.35E+06	-6.78%	1.27E+08	1.57E+08	-18.84%
80%	5.17E+06	5.35E+06	-3.36%	1.30E+08	1.57E+08	-17.01%
90%	5.46E+06	5.35E+06	2.11%	1.35E+08	1.57E+08	-14.09%
99%	6.38E+06	5.35E+06	19.23%	1.49E+08	1.57E+08	-4.96%

The results of traditional ECM based on IFORM underestimate the extreme response, compared with the results of FLTA. If the extreme response predicted by ECM is used as a design reference, no matter which method is used to obtain the contour, the predicted value is dangerous, which will bring potential security risks. ISORM and HDRM optimize the results of IFORM to a certain extent. Environmental contour obtained by the ISORM is a similar concept to the HDRM and the predicted extreme response is also similar. However, the problem caused by ECM itself has not been resolved, that is the non-monotonic of the response especially caused by wind load. The wind turbine has different operating modes with different wind speeds, rather than the response caused by wind load increases monotonically with the increase of wind speed. This is distinct in the force and moment on the base of the tower. ECM is widely used on traditional marine structures, whose response is monotonic. For systems with non-monotonic responses caused by wind loads such as wind turbines, MECM was developed to evaluate extreme responses. The results of MECM are described in section 4.5.

Table 4.23: Comparison of different approaches to obtain contour based on ECM

Method	$F_1(kN)$	$M_1(kN \cdot m)$	$F_2(N)$	$M_2(N \cdot m)$
IFORM	8.86E+02	5.11E+04	4.10E+06	1.17E+08
ISORM	8.01E+02	4.99E+04	4.74E+06	1.21E+08
HDRM	7.89E+02	4.75E+04	4.59E+06	1.21E+08
FLTA	1.56E+03	1.20E+05	5.35E+06	1.57E+08

4.5. Extreme response evaluation based on modified environmental contour method

4.5.1. Number of simulation

According to Equation 3.43, the number of simulations is different depending on the selected return period. Enough random seeds need to be selected to ensure the accuracy of the results (20 seeds are selected for the return period of 50-year in ECM). Firstly, choose a series of wind speeds at the increment of $1m/s$ within the wind speed range of $9-25m/s$. Select the most likely sea conditions under the wind speed, ten minutes of simulation are performed for each environmental condition and extrapolate the extreme response of the N-year return period to 50-year return period, which is similar to the extrapolation method of the ECM in the previous chapter. Assuming that each 1-hour is an independent time unit, the extreme value distribution is fitted according to the Gumbel distribution, μ_G and β_G are location parameter and scale parameter, respectively. Then the new most probable extrapolated value can be expressed as:

$$\mu_{G_{1h,50year}} = \mu_G + \beta_G \cdot \ln\left(6 \cdot \frac{50}{N}\right) \tag{4.22}$$

$$\widehat{\mu}_{G_{1h,50y}}(n) = \widehat{\mu}_G(n) + \widehat{\beta}_G(n) \cdot \ln\left(6 \cdot \frac{50}{N}\right) \tag{4.23}$$

where N is the return period, $\widehat{\mu}_G(n)$ and $\widehat{\beta}_G(n)$ are the estimates with n times. For different return period N, the number of simulations (n) required is different. It is found that N is much smaller than 50, β_G has a greater impact on the result than μ_G. Therefore, enough simulation times are needed to ensure the accuracy of the results. Equation 4.15 can be rewritten as:

$$x = -\ln\left[-\ln F(x)\right] \cdot \beta_G + \mu_G \tag{4.24}$$

This is a linear equation, simple linear regression was used for parameter fitting. In this study, check the 95% confidence interval is used to test the accuracy of parameter fitting. If assuming the error satisfies the normal distribution, the confidence interval is calculated by Equation 4.25.

$$\mu^{CI\pm}_{G_{1h,50y}} = \widehat{\mu}_{G_{1h,50y}} \pm t_{0.975,n-2} \cdot \sqrt{\frac{var\left(\mu_{G_{1h,50y}}(n)\right)}{n-2}} \tag{4.25}$$

where $t_{0.975,n-2}$ is 97.5% quantile of Student's t-distribution with n-2 degree of freedom and var the variance, which can be calculated by Equation 4.26 by variance and co-variance of μ_G and β_G.

$$\begin{aligned} var\left[\mu_{G_{1h,50y}}(n)\right] &= var\left[\mu_G(n)\right] + \left[\ln\left(6 \cdot \frac{50}{N}\right)\right]^2 \cdot var\left[\beta_G(n)\right] \\ &+ 2\ln\left(6 \cdot \frac{50}{N}\right) \cdot cov\left[\mu_G(n), \beta_G(n)\right] \end{aligned} \tag{4.26}$$

The result is evaluated by Equation 4.27 to determine the number is enough and the extrapolated value is accurate.

$$CI\%(n) = \frac{\mu^{CI+}_{G_{1h,50y}}(n) - \mu^{CI-}_{G_{1h,50y}}(n)}{\widehat{\mu}_{G_{1h,50y}}(n)} \leqslant 3\% \tag{4.27}$$

The most probable wave condition of different wind speeds based on the probability density function and the most probable extrapolated value of extreme responses corresponding to the wind speed are listed in Table 4.24.

Table 4.24: The most probable environmental conditions and corresponding return period

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$N(year)$	$F_2(N)$	$M_1(N\cdot m)$	$F_1(kN)$	$M_1(kN\cdot m)$
4	0.81	6.61	1.26E-04	1.13E+06	3.68E+07	2.89E+02	2.19E+04
5	0.81	6.22	1.34E-04	1.33E+06	5.19E+07	4.92E+02	3.52E+04
6	1.01	6.22	1.45E-04	1.53E+06	7.07E+07	6.76E+02	5.06E+04
7	1.21	6.22	1.61E-04	1.87E+06	9.80E+07	9.59E+02	6.88E+04
8	1.41	6.61	1.82E-04	2.29E+06	1.31E+08	1.18E+03	8.94E+04
9	1.62	6.61	2.11E-04	2.55E+06	1.46E+08	1.31E+03	1.02E+05
10	1.62	6.22	2.50E-04	3.07E+06	1.39E+08	1.12E+03	8.50E+04
11	1.82	6.22	3.03E-04	2.96E+06	1.24E+08	1.22E+03	8.62E+04
12	2.22	6.99	3.76E-04	3.77E+06	1.44E+08	1.21E+03	8.91E+04
13	2.42	6.99	4.79E-04	3.95E+06	1.38E+08	1.39E+03	8.76E+04
14	2.63	6.99	6.25E-04	4.76E+06	1.45E+08	1.16E+03	9.34E+04
15	2.83	6.99	8.37E-04	5.49E+06	1.71E+08	1.60E+03	1.18E+05
16	3.03	6.99	1.15E-03	5.59E+06	1.79E+08	1.80E+03	1.33E+05
17	3.23	7.37	1.63E-03	5.57E+06	2.03E+08	1.83E+03	1.34E+05
18	3.64	7.76	2.36E-03	5.04E+06	1.90E+08	1.68E+03	1.28E+05
19	3.84	7.76	3.53E-03	5.19E+06	1.64E+08	1.37E+03	1.09E+05
20	4.04	7.76	5.42E-03	5.26E+06	1.28E+08	1.38E+03	9.75E+04
21	4.44	8.14	8.58E-03	5.70E+06	1.53E+08	1.48E+03	9.33E+04
22	4.65	8.14	1.40E-02	5.86E+06	1.54E+08	1.34E+03	9.10E+04
23	4.85	8.14	2.34E-02	5.74E+06	1.22E+08	1.22E+03	8.63E+04
24	5.25	8.53	4.05E-02	5.47E+06	1.36E+08	8.86E+02	6.55E+04
25	5.45	8.53	7.22E-02	6.17E+06	1.19E+08	1.19E+03	7.94E+04
26	5.86	8.91	1.33E-01	1.68E+06	9.34E+07	8.17E+02	5.52E+04

The maximum extreme response of F_2 occurs at cut-out wind speed, $25m/s$, while that of F_1, M_1 and M_2 occurs at $17m/s$, higher than rated wind speed. It is more obvious in the Figure 4.18.
The return period N of the two critical wind speed is calculated by Equation 4.28.

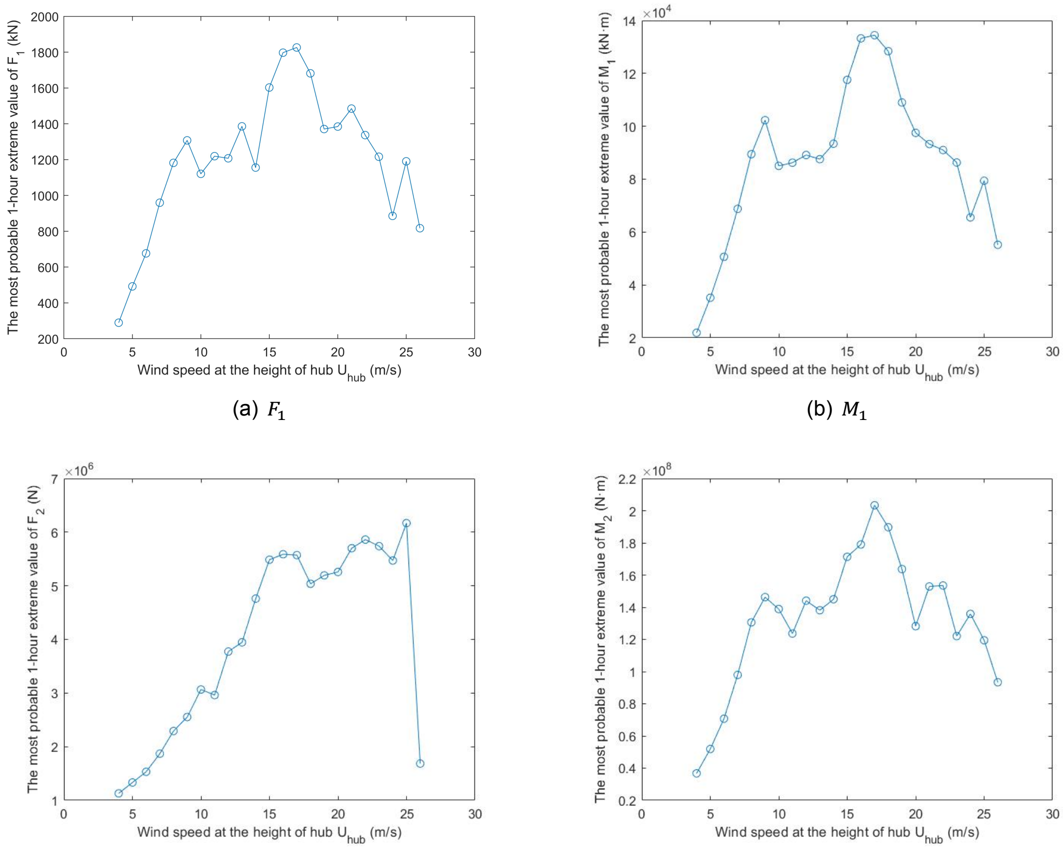
$$N = \frac{1}{(1 - F_{U_w}) \cdot 365.25 \cdot 24} \tag{4.28}$$

where $1 - F_{U_w}$ is the exceedance probability. The MECM is based on the environmental contour corresponding to the critical wind speed (F_2 corresponds to 7.22E-02 year return period, F_1, M_1 and M_2 corresponds to 1.63E-03 year return period) to predict the extreme response of wind turbine for the return period of 50-year. To ensure the reliability of the results, according to the principle of the confidence interval, 60 random seeds and 80 random seeds are provided for environmental conditions corresponding to the return period of 7.22E-02 years and 1.63E-03 years, respectively.

4.5.2. Modified environmental contour method based on IFORM

For the extreme response of F_2, construct the environmental contour surface of the return period of 7.22E-02 year. The two-dimension contour line of significant wave height and spectral peak period under different wind speed is shown in Figure 4.19. The wind speed at the height of hub ranges from 23 m/s to 25 m/s with an increment of 0.5 m/s. Select combination of environmental variables along the contour line to find the largest extreme response. Similarly, Figure 4.20 shows the two-dimensional contours of H_s and T_p in the range of 15 m/s to 17 m/s of U_{hub} for the return period of 1.63E-03 year, which is used to evaluate the response of M_2.

For F_1 and M_1, since only the effect of wind load is considered, the contour line becomes a point. Instead of selecting the maximum wind speed once in N years directly, but choosing different wind speeds and



(a) F_1

(b) M_1

(c) F_2

(d) M_2

Figure 4.18: Extrapolated most probable 1-hour extreme response

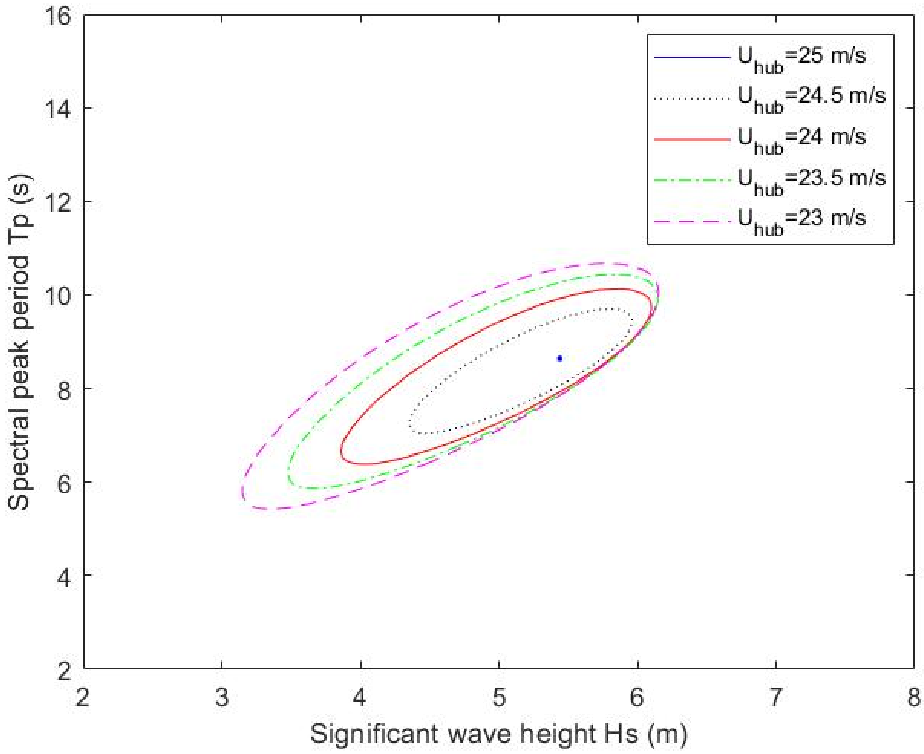


Figure 4.19: Contour lines under different wind speed for F2 of MECM based on IFORM

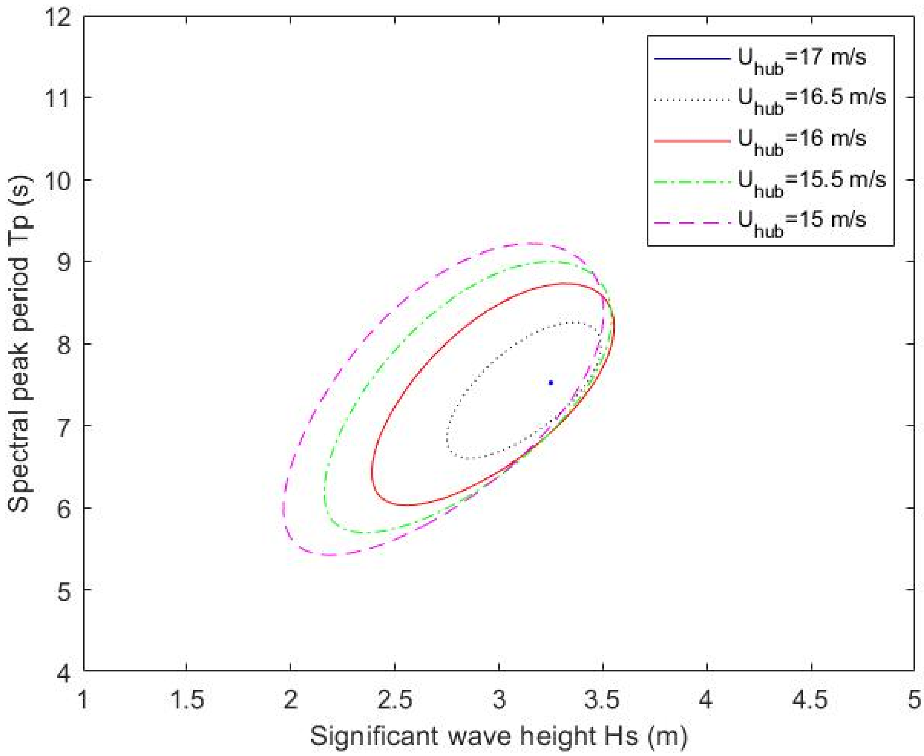


Figure 4.20: Contour lines under different wind speed for M2 of MECM based on IFORM

evaluate its extreme response, then extrapolate the maximum response to obtain the extreme response once in 50 years, and the corresponding combination of environmental variables.

According to Figure 4.19 and Figure 4.20, for the contour line of H_s and T_p under different U_{hub}, select different environmental condition along the contour line to find the maximum extreme response. The selection of environmental condition of different responses are listed in Table 4.25, Table 4.26 and Table 4.27.

Table 4.25: Selection of critical environmental conditions for F_1 and M_1 of MECM based on IFORM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$F_1(kN)$	$M_1(kN \cdot m)$
17	-	-	1.71E+03	1.35E+05

Table 4.26: Selection of critical environmental conditions for F_2 of MECM based on IFORM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$F_2(N)$
25	5.44	8.64	6.15E+06
24.5	5.96	9.45	6.21E+06
24	6.10	9.74	6.39E+06
23.5	6.15	9.91	6.15E+06
23	6.15	10.04	5.99E+06

Table 4.27: Selection of critical environmental conditions for M_2 of MECM based on IFORM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$M_2(N \cdot m)$
17	3.25	7.52	1.83E+08
16.5	3.51	8.02	1.74E+08
16	3.55	8.21	1.74E+08
15.5	3.54	8.31	1.69E+08
15	3.50	8.38	1.65E+08

The summary of extreme response and critical environmental conditions of MECM based on the IFORM is shown in Table 4.28.

It can be seen from Table 4.28 that the prediction results are different from those predicted by the environmental contour method when the modified environmental contour method is used to predict the extreme response of a monopile wind turbine for the return period of 50 years when wind turbulence is assuming to be a constant as 15%. In the wind speed range of 23 m/s to 25 m/s, the extreme response of the fore-aft force on the base of monopile occurs at the wind speed of 24 m/s. For the fore-aft force and pitch moment on the base of the tower and the pitch moment on the base of monopile, the extreme response occurs at the wind speed of 17 m/s.

4.5.3. Modified environmental contour method based on ISORM

In the same way, The return period of 7.22E-02 year and 1.63E-03 year are chosen to build the environmental contour surface for the extreme response of F_2 and M_2, respectively. The two-dimension contour line of H_s and T_p is shown in Figure 4.21 and Figure 4.22. The wind speed at the height of hub rangeing from 23 m/s to 25 m/s, 15 m/s to 17 m/s are drawn with an increment of 0.5 m/s, respectively. Select points along the contour line to find the largest extreme response.

According to Figure 4.19 and Figure 4.20, for the contour line of H_s and T_p under different U_{hub}, select different environmental condition along the contour line to find the maximum extreme response. The selection of environmental condition of different responses are listed in Table 4.29, Table 4.30 and Table 4.31.

Table 4.28: Summary of the extreme responses of MECM based on the IFORM

	$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	Extreme response
$F_1(kN)$	17	-	-	1.71E+03
$M_1(kN \cdot m)$	17	-	-	1.35E+05
$F_2(N)$	24	6.10	9.74	6.39E+06
$M_2(N \cdot m)$	17	3.25	7.52	1.83E+08

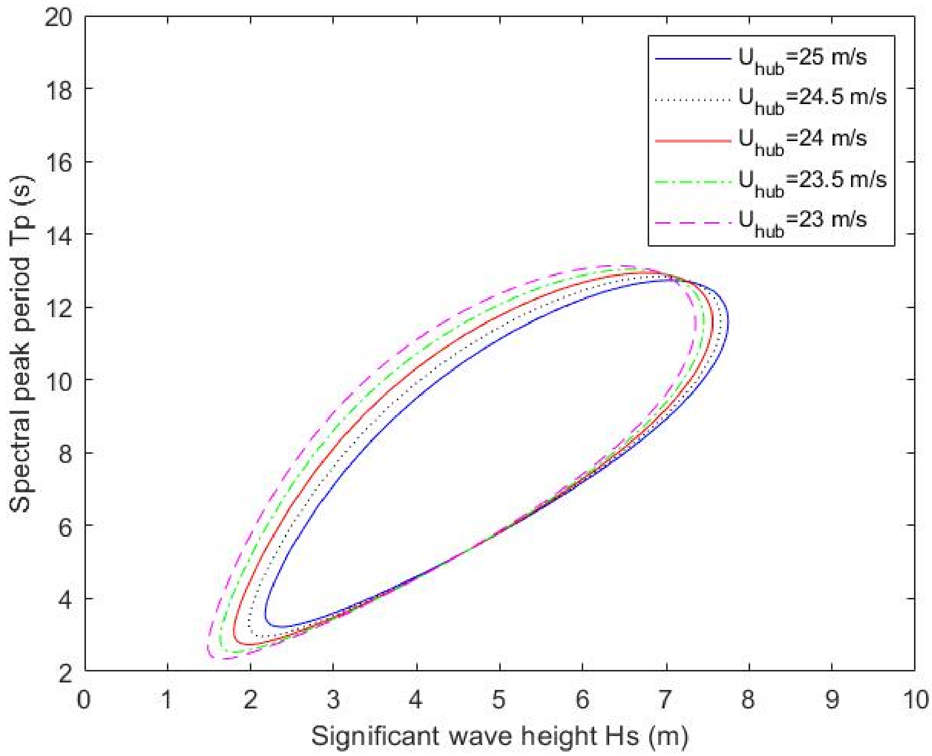


Figure 4.21: Contour lines under different wind speed for F2 of MECM based on ISORM

Table 4.29: Selection of critical environmental conditions for F_1 and M_1 of MECM based on ISORM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$F_1(kN)$	$M_1(kN \cdot m)$
17	-	-	1.71E+03	1.35E+05
23.34	-	-	1.09E+03	7.92E+04

Table 4.30: Selection of critical environmental conditions for F_2 of MECM based on ISORM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$F_2(N)$
25	7.74	11.59	6.71E+06
24.5	7.66	11.60	7.04E+06
24	7.56	11.58	7.11E+06
23.5	7.46	11.56	7.02E+06
23	7.35	11.56	6.63E+06

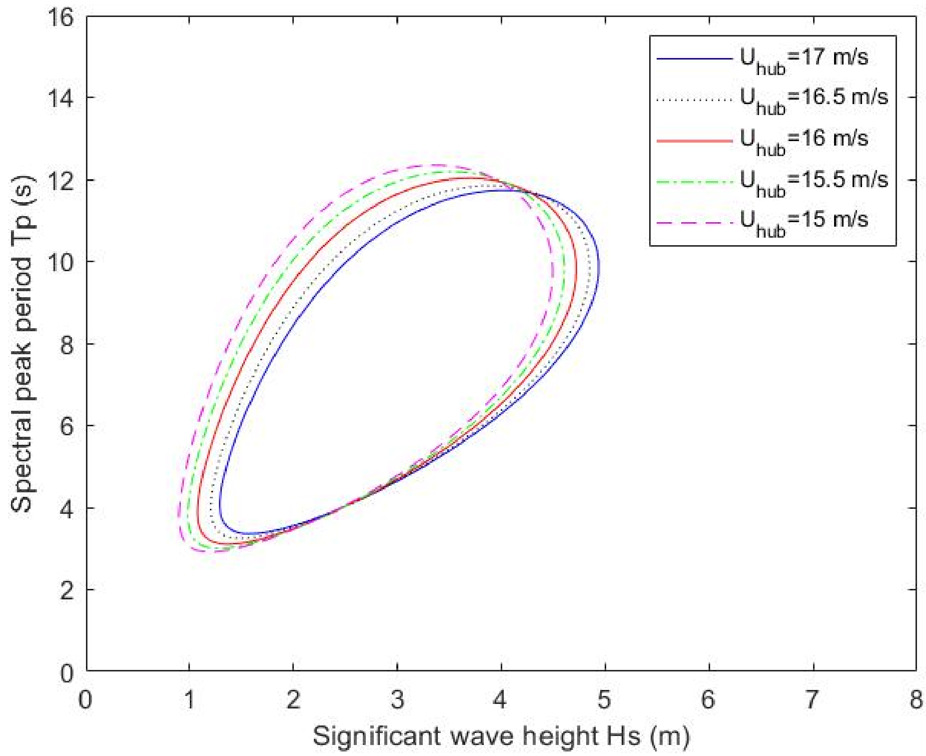


Figure 4.22: Contour lines under different wind speed for M2 of MECM based on ISORM

Table 4.31: Selection of critical environmental conditions for M_2 of MECM based on ISORM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$M_2(N \cdot m)$
17	4.94	9.85	1.88E+08
16.5	4.83	9.84	1.79E+08
16	4.72	9.80	1.81E+08
15.5	4.61	9.78	1.71E+08
15	4.49	9.75	1.69E+08

The summary of extreme response and critical environmental conditions of MECM based on the ISORM is shown in Table 4.32.

Table 4.32: Summary of the extreme responses of MECM based on the ISORM

	$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	Extreme response
$F_1(kN)$	17	-	-	1.71E+03
$M_1(kN \cdot m)$	17	-	-	1.35E+05
$F_2(N)$	24	7.56	11.58	7.11E+06
$M_2(N \cdot m)$	17	4.94	9.85	1.88E+08

As shown in Table 4.32 that the prediction results are different from those predicted by the environmental contour method when the modified environmental contour method is used to predict the extreme response of a monopile wind turbine for the return period of 50 years when wind turbulence is assuming to be a constant as 15%. In the wind speed range of 23 m/s to 25 m/s, the extreme response of the fore-aft force on the base of monopile occurs at the wind speed of 24 m/s. For the fore-aft force and pitch moment on the base of the tower and the pitch moment on the base of monopile, the extreme response occurs at the wind speed of 17 m/s. The prediction of the fore-aft force and pitch moment on the base of the tower is the same as that from IFORM because only wind load is considered for this response. Consider the operation mode of the wind turbine, select different wind speed to find the extreme response. Therefore, the results are the same and occur at a wind speed of 17 m/s. For the fore-aft force and pitch moment on the base of monopile, things are different. Because of the different contour line, different environmental condition is selected on the contour line, leading to different results. The results from ISORM are much conservative than that of IFORM, which can better meet the safety requirements in the design stage.

4.5.4. Modified environmental contour method based on HDRM

For the extreme response of F_2, construct the environmental contour surface of the return period of 7.22E-02 year. The two-dimension contour line of significant wave height and spectral peak period under different wind speed is shown in Figure 4.23. The wind speed at the height of hub ranges from 23 m/s to 25 m/s with an increment of 0.5 m/s. Select combination of environmental variables along the contour line to find the largest extreme response. Similarly, Figure 4.24 shows the two-dimensional contours of H_s and T_p in the range of 15 m/s to 17 m/s of U_{hub} for the return period of 1.63E-03 year, which is used to evaluate the response of M_2.

According to Figure 4.23 and Figure 4.23, for the contour line of H_s and T_p under different U_{hub}, select different environmental condition along the contour line to find the maximum extreme response. The selection of environmental condition of different responses are listed in Table 4.33, Table 4.34 and Table 4.35.

Table 4.33: Selection of critical environmental conditions for F_1 and M_1 of MECM based on HDRM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$F_1(kN)$	$M_1(kN \cdot m)$
17	-	-	1.71E+03	1.35E+05
23.36	-	-	1.11E+03	7.95E+04

The summary of extreme response and critical environmental conditions of MECM based on the HDRM is shown in Table 4.36. The prediction results are different from those predicted by the environmental contour method when the modified environmental contour method is used to predict the extreme response of a monopile wind turbine for the return period of 50 years when wind turbulence is assuming to be a constant as 15%. Similarly, the prediction results of MECM based on HDRM is similar to those from ISORM. Because a similar contour surface is obtained compared with ISORM, the critical environmental contour and the predicted extreme response are similar. In the wind speed range of 23 m/s to 25 m/s, the extreme response of the fore-aft force on the base of monopile occurs at the wind speed

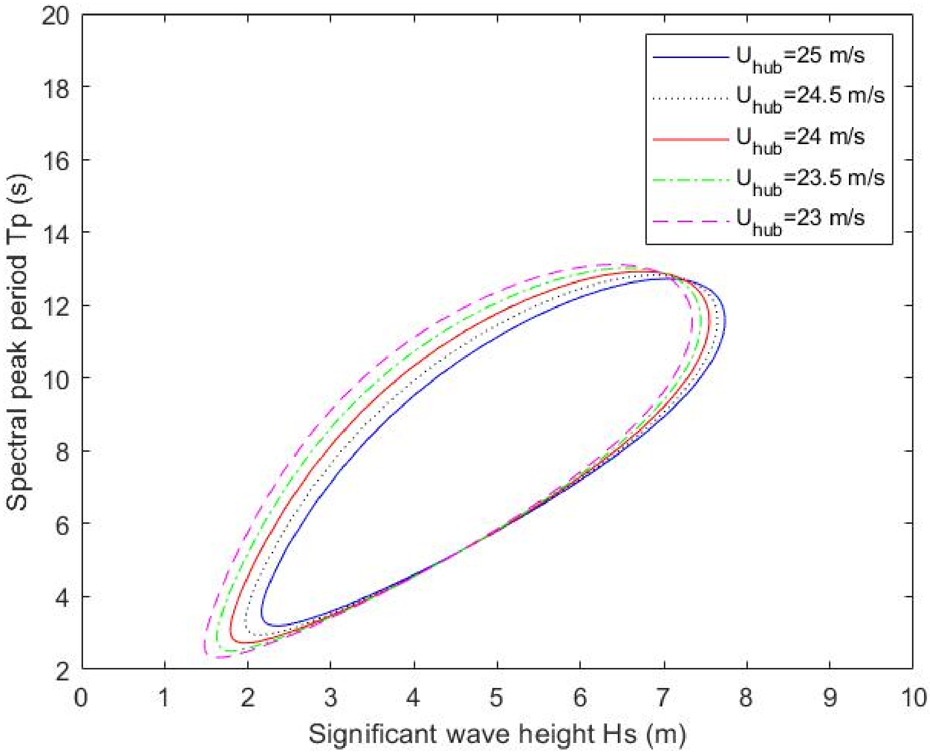


Figure 4.23: Contour lines under different wind speed for F2 of MECM based on HDRM

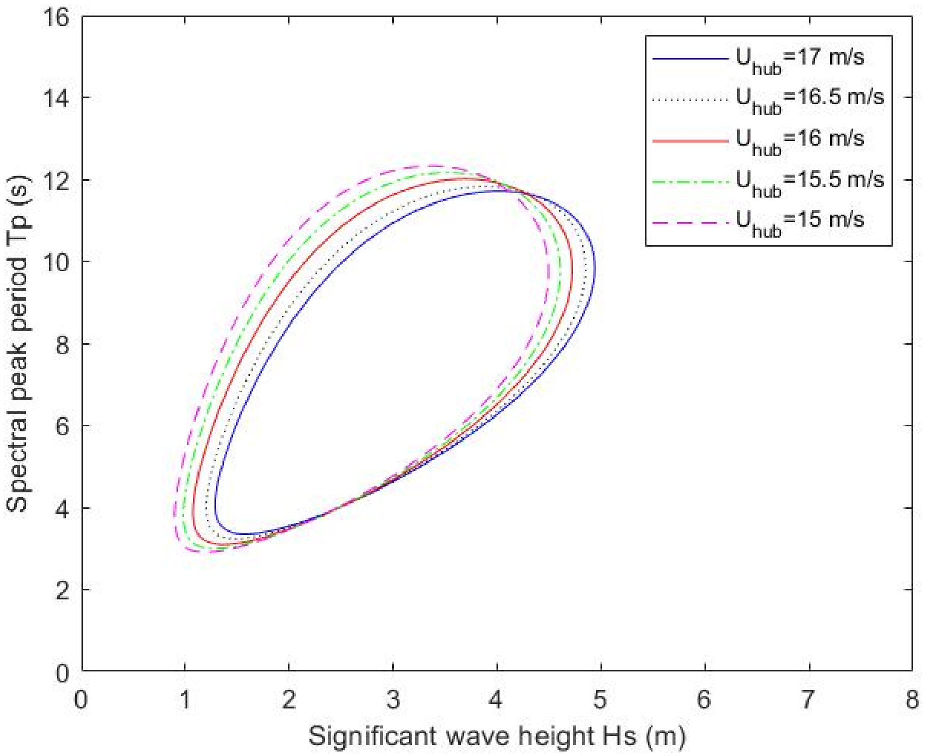


Figure 4.24: Contour lines under different wind speed for M2 of MECM based on HDRM

Table 4.34: Selection of critical environmental conditions for F_2 of MECM based on HDRM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$F_2(N)$
25	7.73	11.58	6.70E+06
24.5	7.64	11.64	6.99E+06
24	7.54	11.64	7.07E+06
23.5	7.44	11.62	6.98E+06
23	7.33	11.60	6.69E+06

Table 4.35: Selection of critical environmental conditions for M_2 of MECM based on HDRM

$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	$M_2(N \cdot m)$
17	4.93	9.90	1.87E+08
16.5	4.84	9.87	1.77E+08
16	4.72	9.85	1.75E+08
15.5	4.61	9.80	1.70E+08
15	4.49	9.76	1.69E+08

of 24 m/s. For the fore-aft force and pitch moment on the base of the tower and the pitch moment on the base of monopile, the extreme response occurs at the wind speed of 17 m/s. The prediction of the fore-aft force and pitch moment on the base of the tower is the same as that from IFORM and ISORM because only wind load is considered for this response. Consider the operation mode of the wind turbine, select different wind speed to find the extreme response. Therefore, the results are the same and occur at a wind speed of 17 m/s. For the fore-aft force and pitch moment on the base of monopile, things are different. Because of the different contour line, different environmental condition is selected on the contour line, leading to different results. The results from HDRM are much conservative than that of IFORM like ISORM.

Table 4.36: Summary of the extreme responses of MECM based on the HDRM

	$U_{hub}(m/s)$	$H_s(m)$	$T_p(s)$	Extreme response
$F_1(kN)$	17	-	-	1.71E+03
$M_1(kN \cdot m)$	17	-	-	1.35E+05
$F_2(N)$	24	7.54	11.64	7.07E+06
$M_2(N \cdot m)$	17	4.93	9.90	1.87E+08

The comparison with the result of full long-term analysis, environmental contour method, and modified environmental contour method based on different approaches to obtain environmental contour is shown in Table 4.37.

The prediction results from the modified environmental contour method are much better than those from the environmental contour method. The results of the environmental contour method are too low to meet the safety requirements. The accuracy of the modified environmental contour forecast results is more conservative, and it can effectively meet the safety requirements in the design stage compared with the full long-term analysis. For the environmental contour method considering three environmental variables (mean wind speed U_w, significant wave height H_s and spectral peak period T_p) based on IFORM, the correction factor 1.76, 2.35, 1.30, 1.34 are applied to the fore-aft force at the bottom of the tower, the pitch moment at the bottom of the tower, the fore-aft force at the bottom of the monopile, and the pitch moment at the bottom of the monopile. Correspondingly, 1.95, 2.40, 1.13 and 1.29 for ISORM and 1.97, 2.53, 1.16 and 1.29 for HDRM. Since 1.1 to 1.3 are commonly applied for marine structures as the correction factor when applying the environmental contour method. The environmental contour method can more accurately predict the force and pitch moment on the base of the monopile, while the forecast of the force and moment on the base of the tower dominated by wind

Table 4.37: Results obtained based on FLTA, ECM and MECM

Method	$F_1(kN)$	$M_1(kN \cdot m)$	$F_2(N)$	$M_2(N \cdot m)$
FLTA	1.56E+03	1.20E+05	5.35E+06	1.57E+08
ECM_IFORM	8.86E+02	5.11E+04	4.10E+06	1.17E+08
ECM_ISORM	8.01E+02	4.99E+04	4.74E+06	1.21E+08
ECM_HDRM	7.89E+02	4.75E+04	4.59E+06	1.21E+08
MECM_IFORM	1.71E+03	1.35E+05	6.39E+06	1.83E+08
MECM_ISORM	1.71E+03	1.35E+05	7.11E+06	1.88E+08
MECM_HDRM	1.71E+03	1.35E+05	7.07E+06	1.87E+08

loads is inaccurate, and its extreme response predictions will be greatly underestimated. The result is not conservative. The main reason is that the response caused by the wind load is non-monotonic to the wind turbine. When the wind speed is higher than the rated wind speed, the control system of the wind turbine will affect the magnitude of its response, and when the wind speed is beyond the cut-out wind speed, the wind turbine will park, when the wind load will drop rapidly.

Table 4.38: Results obtained based on FLTA, ECM and MECM

Method	$F_1(kN)$	$M_1(kN \cdot m)$	$F_2(N)$	$M_2(N \cdot m)$
ECM_IFORM	-43.21%	-57.42%	-23.36%	-25.48%
ECM_ISORM	-48.65%	-58.42%	-11.40%	-22.93%
ECM_HDRM	-49.42%	-60.42%	-14.21%	-22.93%
MECM_IFORM	9.62%	12.50%	19.44%	16.56%
MECM_ISORM	9.62%	12.50%	32.90%	19.75%
MECM_HDRM	9.62%	12.50%	32.15%	19.11%

When considering different approaches to obtain the environmental contour, the IFORM is the most traditional one and its results underestimate the extreme response but can be used on the prediction of the response on the base of the monopile by considering the correction factor. The ISORM and HDRM are two more conservative methods to obtain the contour, the predicted values of these two methods are conservative too, where are closer to the results obtain by FLTA. The percentage difference of ECM, MECM, and FLTA based on different approaches to obtain is shown in Table 4.38. In summary, MECM is much better than the results from ECM according to safety requirements in the design stage. When applying the environmental contour method, the inverse second-order reliability method to obtain contour is more recommended. Because its contour is more conservative than the traditional inverse first-order reliability method but the calculation code more stable than the highest density region method in three dimensions. When applying the modified environmental contour method, the traditional inverse first-order reliability is more recommended because no matter which method is applied to obtain the environmental contour, the predicted extreme response all satisfies the requirement of security. The IFORM is the simplest in principle and fastest in the calculation.

5
Conclusions and Recommendations

5.1. Conclusions

In this paper, the NREL 5 MW wind turbine supported in a monopile structure in the North Sea is used as the model to explore the influence of the different approaches to obtain environmental contours on the extreme response. Different approaches consisting of inverse first-order reliability method, inverse second-order reliability method, and highest density region method, are used to obtain environmental contours subjected to combined wave and wind load which is assumed to be in the same direction. Three environmental variables of mean wind speed, significant wave height, and spectral peak period are considered. For contour lines obtained by different approaches, the environmental contour method and the modified environmental contour method are applied to predict the extreme response of the wind turbine for the return period of 50 years. The response in this study is the fore-aft force on the base of the tower and monopile and the pitch moment on the base of the tower and monopile. Comparing the extreme response obtained by different methods with that from the full long-term analysis, the following conclusions are drawn.

Compared with the full long-term analysis, the prediction results of the modified environmental contour method are closer than that of the environmental contour method. But the overall prediction results show a trend of overestimation for the modified environmental contour method. Of course, the overestimation can effectively guarantee safety in the design stage of the wind turbine. In this sense, the modified environmental contour method has better prediction accuracy for extreme responses than the environmental contour method.

The results of the environmental contour method based on the IFORM underestimate the extreme response, while the ISORM and HDRM optimize the results of IFORM with the difference of 10% to 40%, the predicted value is dangerous, which will bring potential security risks. The results of the modified environmental contour is more conservative, which overestimate the extreme response with the difference of 10% to 20%. The conservative results ensure the safety of the design.

When applying the environmental contour method, the inverse second-order reliability method to obtain contour is more recommended. Because its contour is more conservative than the traditional inverse first-order reliability method but the calculation code more stable than the highest density region method in three dimensions. For the response on the base of monopile, a correction factor of 1.2 can be used when applying ECM, however, for the response subjected to wind load dominated or wind load only, ECM is not suitable for an offshore wind turbine because of the non-monotonic behavior of the structure.

When applying the modified environmental contour method, the traditional inverse first-order reliability is more recommended because no matter which method is applied to obtain the environmental contour, the predicted extreme response all satisfies the requirement of security. IFORM is the simplest in principle and fastest in the calculation.

5.2. Recommendations

This part is about the shortcomings and prospects. The recommendations for future work stem from ideas that were left out of the scope of the current research.

When applying the full long-term analysis, the accuracy of the method can be improved by reducing the increment of environmental variables, however, it is worth noting that the required calculation examples will also respond exponentially. When selecting the combination of environmental conditions on the two-dimensional environmental contour, the points can also be selected more intensively, which can improve the accuracy of the environmental contour method.

The reason for this overestimation may be that in the study, the turbulence intensity was set to a constant value of 15%, which may be far from the critical environmental conditions in the actual situation. Assume the turbulence intensity as another environmental variable, and establish the model of four environmental variables to evaluate the extreme response. This can be future work.

Another method to obtain environmental contour is the direct Monte Carlo method. The Monte Carlo method which has been applied in structural reliability analysis is proposed as a more precise approach to interpreting the environmental contour. The direct Monte Carlo method allows the definition of environmental contour in original space directly. That avoids the difference due to the transformation. Research the extreme response based on the direct Monte Carlo method can be the future work.

Further research work can be carried out on floating wind turbines or other devices combined wind and wave load. The environmental contour method and the modified environmental contour method considering the environmental variable of turbulence intensity are applied to the extreme response analysis of floating wind turbines or other devices combined wind and wave load, where the displacement of the platform and the tension of the mooring line may be more sensitive to wind conditions, so the intensity of turbulence may play a more important role.

A

Property of 5 MW wind turbine model

In this chapter, the detailed information of the NREL 5 MW monopile wind turbine model is introduced, including tower property, monopile property, drivetrain property, hub and nacelle property, and blade property. The model is applied to extreme response forecast.

The tower is connected with the monopile at the height of 10 m above the mean sea level (MSL). The diameter of the tower tube changes uniformly and the thickness of the tower also changes uniformly with the height. Table A.1 summarizes the basic parameters of the tower.

Table A.1: Tower properties of monopile wind turbine

Tower Parameter	
Elevation of Tower Base	10 m
Elevation of Tower Top	87.6 m
Diameter of Tower Base	6.5 m
Diameter of Tower Top	3.87 m
Tower Mass	347460 kg
Structural-Damping Ratio	0.01

The main properties of the monopile are shown in Table A.2, which extends downward from 10 m above sea level to the baseline of the muddy-water boundary. Water depth is 20 m. The outer diameter of the monopile is 6 m, and the wall thickness is 6 cm.

Table A.2: Monopile properties of monopile wind turbine

Monopile Parameter	
Diameter	6 m
Thickness	6 cm
Elevation above MSL	10 m
Length in Water	20 m

Table A.3, Table A.4 and Table A.5 shows the basic properties of drivetrain, hub and nacelle and blade respectively.

More information about the property of the 5 MW wind turbine model, such as blade aerodynamic properties, blade structural properties, and baseline control system properties, can be obtained in references for details(Jonkman et al., 2009).

Table A.3: Drivetrain properties of monopile wind turbine

Drivetrain Parameter	
Rated Rotor Speed	12.1 rpm
Gearbox Ratio	97:1
Rated Generator Speed	1173.7 rpm
Electrical Generator Efficiency	94.4%
High-Speed Shaft Brake Time Constant	0.6 s
Generator Inertia about High-Speed Shaft	534.116 $kg \bullet m^2$
Fully-Deployed High-Speed Shaft Brake Torque	28116.2 $N \bullet m$
Equivalent Drive-Shaft Torsional-Spring Constant	867637000 $N \bullet m/rad$
Equivalent Drive-Shaft Torsional-Damping Constant	6215000 $N \bullet m/(rad/s)$

Table A.4: Hub and nacelle properties of monopile wind turbine

Hub and Nacelle Parameter	
Elevation of Yaw Bearing above Ground	87.6 m
Hub Mass	56780 kg
Nacelle Mass	240000 kg
Hub Inertia about Low-Speed Shaft	115926 $kg \bullet m^2$
Nacelle Inertia about Yaw Axis	2607890 $kg \bullet m^2$
Nacelle CM Location Downwind of Yaw Axis	1.9 m
Nacelle CM Location above Yaw Bearing	1.75 m
Equivalent Nacelle-Yaw-Actuator Linear-Damping Constant	9028320000 $N \bullet m/rad$
Equivalent Nacelle-Yaw-Actuator Linear-Spring Constant	19160000 $N \bullet m/(rad/s)$

Table A.5: Blade properties of monopile wind turbine

Blade Parameter	
Blade Length	61.5 m
Blade Mass	17740 kg
First Mass Moment of Inertia	363231 $kg \bullet m$
Second Mass Moment of Inertia	11776047 $kg \bullet m2$
Center of Mass Location	20.475 m

B
Extreme responses and curve fitting

In this chapter, one can find the detailed data about the extreme responses with 20 random seeds of the environmental condition of $U_w = 23.00m/s, H_s = 10.00m, T_p = 18.00s$ and the curve fitting based on Gumbel distribution.

B.1. Extreme responses

In this section, the detailed information of extreme responses with 20 random seeds of the environmental condition of $U_w = 23.00m/s, H_s = 10.00m, T_p = 18.00s$ is given in Table B.1.

Table B.1: Extreme responses with 20 random seeds of $U_w = 23.00m/s, H_s = 10.00m, T_p = 18.00s$

$F_1(kN)$	$M_1(kN \cdot m)$	$F_2(N)$	$M_2(kN \cdot m)$	-ln(-ln(F(x)))
7.45E+02	4.93E+04	3.74E+06	9.01E+07	-1.11
7.73E+02	5.07E+04	3.76E+06	9.28E+07	-0.86
7.77E+02	5.11E+04	3.88E+06	9.35E+07	-0.67
7.79E+02	5.11E+04	4.39E+06	9.39E+07	-0.51
7.84E+02	5.12E+04	4.60E+06	9.39E+07	-0.36
8.05E+02	5.21E+04	4.64E+06	9.44E+07	-0.23
8.08E+02	5.30E+04	4.99E+06	9.61E+07	-0.09
8.15E+02	5.30E+04	5.01E+06	9.86E+07	0.04
8.23E+02	5.30E+04	5.01E+06	9.92E+07	0.17
8.24E+02	5.34E+04	5.09E+06	9.95E+07	0.30
8.28E+02	5.41E+04	5.17E+06	1.03E+08	0.44
8.35E+02	5.53E+04	5.38E+06	1.04E+08	0.58
8.35E+02	5.57E+04	5.85E+06	1.07E+08	0.73
8.42E+02	5.65E+04	5.88E+06	1.09E+08	0.90
8.46E+02	5.65E+04	6.04E+06	1.11E+08	1.09
8.61E+02	5.69E+04	6.12E+06	1.12E+08	1.30
8.86E+02	5.87E+04	6.12E+06	1.20E+08	1.55
8.86E+02	5.87E+04	6.72E+06	1.26E+08	1.87
8.88E+02	5.93E+04	7.68E+06	1.46E+08	2.30
8.90E+02	5.98E+04	9.29E+06	1.56E+08	3.02

B.2. Curving fitting

All the data (of the environmental condition $U_w = 23.00m/s, H_s = 10.00m, T_p = 18.00s$) shown in Table B.1 are fitted by Gumbel distribution described in Equation 4.15 and Equation 4.16. The fitting curve of extreme responses (M_1, F_2 and M_2) of 20 random seeds is shown in Figure B.1, Figure B.2 and Figure B.3.

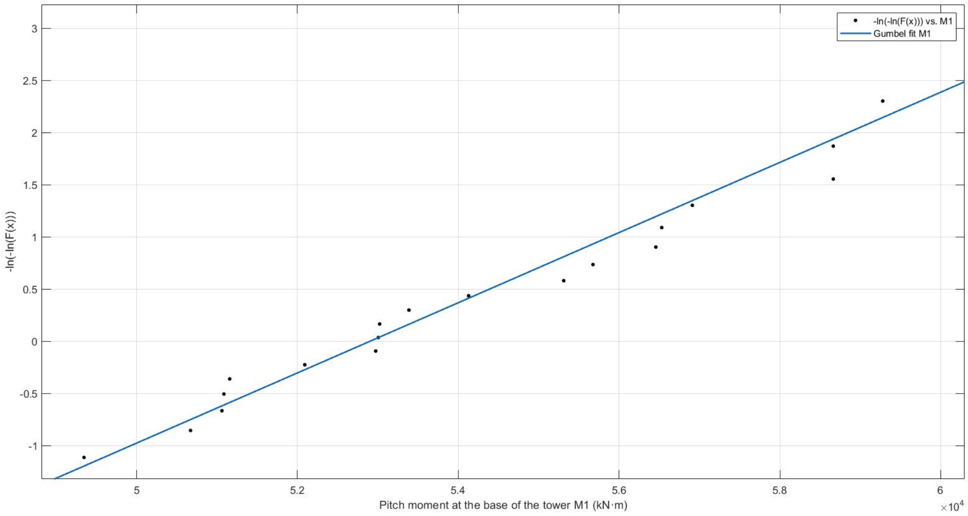


Figure B.1: Gumbel fitting of 20 random seeds for M_1

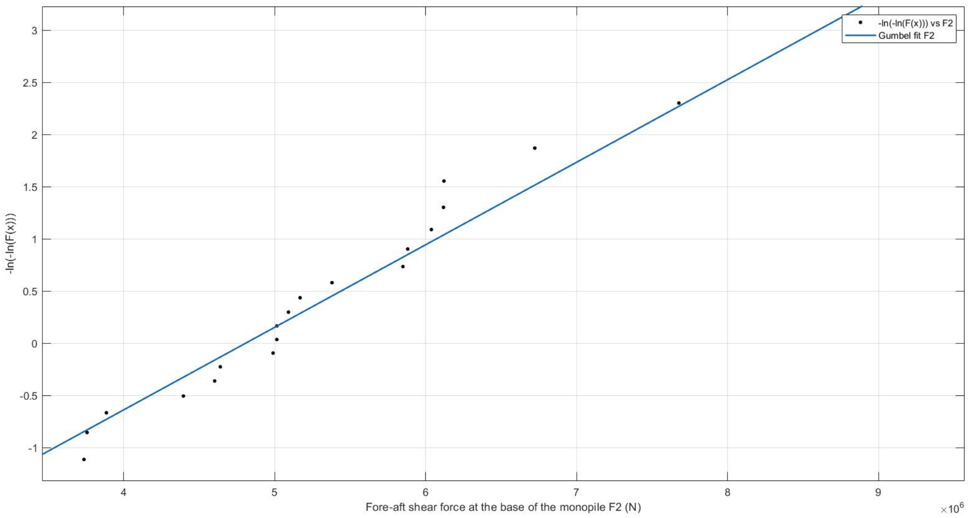


Figure B.2: Gumbel fitting of 20 random seeds for F_2

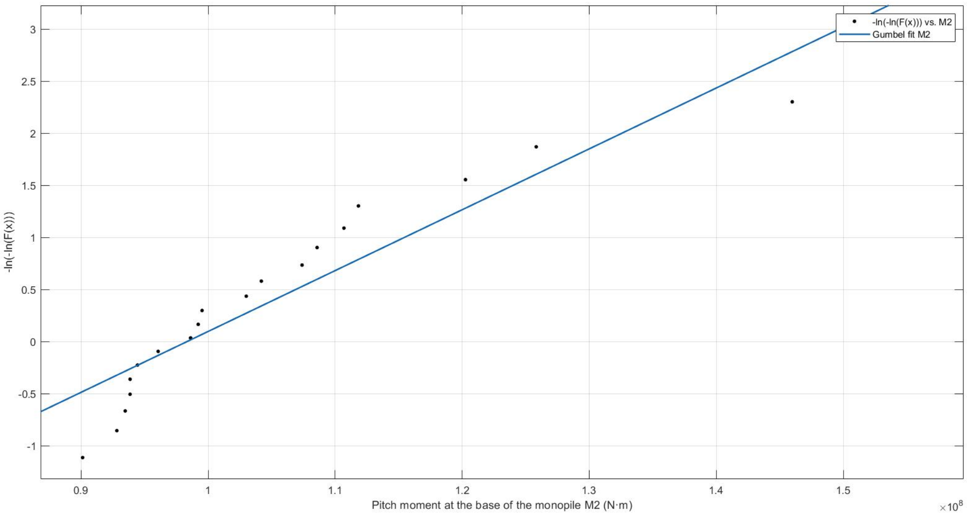


Figure B.3: Gumbel fitting of 20 random seeds for M_2

For the curves of different extreme responses, the estimation of parameters μ_G and β_G is shown in Table B.2.

Table B.2: Estimation of parameters μ_G and β_G of different response

Parameter	Variable		
	M_1	F_2	M_2
μ_G	5.29E+04	4.81E+06	9.83E+07
β_G	2.97E+03	1.26E+06	1.71E+07

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