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Reliability analysis of offshore wind turbine support structures under extreme ocean environmental loads

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ABSTRACT

Reliability analysis of jacket type offshore wind turbine (OWT) support structure under extreme ocean environmental loads was performed. Limit state function (LSF) of OWT support structure is defined by using structural dynamic response at mud-line. Then, the dynamic response is expressed as the static response multiplied by peak response factor (PRF). Probabilistic distribution of PRF is found from response time history under design significant wave load. Band limited beta distribution is used for internal friction angle of ground soil. Wind load is obtained in the form of thrust force from commercial code called Bladed and then, applied to tower hub as random load. In numerical example, response surface method (RSM) is used to express LSF of jacket type support structure for 5 MW OWT. Reliability index is found using first order reliability method (FORM).

1. Introduction

To assure the safety of offshore wind turbine (OWT) support structures under risky environment, it is required to evaluate probability of failure using reliability analysis [1,2]. If a limit state equation in reliability problem is formulated based on static response, it is quite simple and straight forward to evaluate probability of failure or reliability index. However, reliability analysis of support structure, whose response should be obtained from dynamic analysis, is not that easy in terms of analysis time. Basically the dynamics of support structure is coupled with irregular wave, turbulent wind, and nonlinear ground soil. It takes a lot of time in obtaining a set of dynamic response of OWT with long pile-foundation. In addition, the number of dynamic analysis in a reliability analysis is proportional to the square of the number of random variables.

Therefore, most of previous studies have proposed algorithms to reduce the number of simulation time in reliability analysis. Sometimes, algorithms with small number of random variables have been proposed. Peak-Over-Threshold (POT) is a representative approach to reliability analysis of OWT [3]. Only peak values exceeding a threshold are extracted from response time history. Then extreme value distribution is estimated by using the peak values. Block maxima approach is another widely used one [4]. A long dynamic response history is divided into lots of blocks. Then, maximum values are chosen from each block and used to estimate extreme value distribution. However, randomness of design variables such as ground soil properties and structural parameters were still not considered. If the randomness of such variables is considered, extreme value distribution should be calculated for the every single variable at every step of iteration. Then, total simulation time increases geometrically. Therefore, variations only in wind and wave are considered in those studies.

In this study, a new approach to reliability analysis of OWT support structure under dynamic load is proposed. Dynamic peak response is estimated by using static response and a factor accounting dynamic amplification. Since the static response is used during reliability analysis, much less computational cost is required than using dynamic response. Jacket type support structure for 5 MW OWT is used for numerical example of the approach.

2. Reliability analysis of support structures

2.1. Reliability analysis using peak response factor

Dynamic response of a support structure is dependent on such design variables as mechanical properties of support structures, ground materials, and even design loads. They all should be treated as random variables in reliability analysis of support structures. Then, a limit state equation for support structure can be defined as

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$$g = R_{\mathrm{all}} - R_{\mathrm{p}}(X) \tag{1}$$

where R_{all} is the allowable response of the structure; R_{P} is the maximum peak response due to design wave and wind load; X is the design random variable. PDF of R_{p} is dependent upon design variables (X) such as ground soil stiffness, wind speed, etc. Therefore, different PDFs for each X can be drawn as in Fig. 1.

The joint PDF for R_{p} and X can be found by multiplying them as

$$f_{R_{\mathrm{p}},X}(r_{\mathrm{p}},x) = f_{R_{\mathrm{p}}|X}(r_{\mathrm{p}}|x)f_X(x) \tag{2}$$

Fig. 2 shows the contour for $f_{R_{\mathrm{p}},X}(r_{\mathrm{p}},x)$. The hatched area is the region where the limit state function becomes negative, which means failure in the reliability analysis. Using the failure region, probability of failure can be calculated as

$$P_{\mathrm{f}} = \int_{g<0} f_{R_{\mathrm{p}},X}(r_{\mathrm{p}},x)\mathrm{d}r_{\mathrm{p}}\mathrm{d}x = \int_{-\infty}^{\infty}\int_{R_{\mathrm{all}}}^{\infty} f_{R_{\mathrm{P}}|X}(r_{\mathrm{p}}|x)f_X(x)\mathrm{d}r_{\mathrm{p}}\mathrm{d}x \tag{3}$$

As can be seen in Fig. 2, calculation of P_{f} is quite difficult since the failure region is skewed to the PDF. To get P_{f} easier, a new random variable called peak response factor (PRF) is introduced as follows.

$$R_{\mathrm{n}} = R_{\mathrm{p}}/R_{\mathrm{st}} \tag{4}$$

where R_{st} is the static response under design condition. Of course, R_{st} is the variable dependent on such parameters as ground properties and wind, wave load. Eq. (4) is introduced in this study to utilize the idea that dynamic peak response might be proportional to static response if the dynamic properties of support structure doesn't change that much. Using eq. (4), the limit state equation can be rewritten as

$$g(X) = R_{\mathrm{all}} - R_{\mathrm{n}}R_{\mathrm{st}}(X) \tag{5}$$

R_{n} is a function forcing frequencies and the natural frequencies. But for small change of natural frequencies, it can be assumed to be constant with acceptable error. Then, R_{n} can be treated as independent of X, and level II type of reliability analysis such as FORM can be easily applied. Fig. 3 shows the flowchart of the approach combining a special purpose code such as Bladed to find thrust force distribution and a general structural analysis code for reliability analysis.

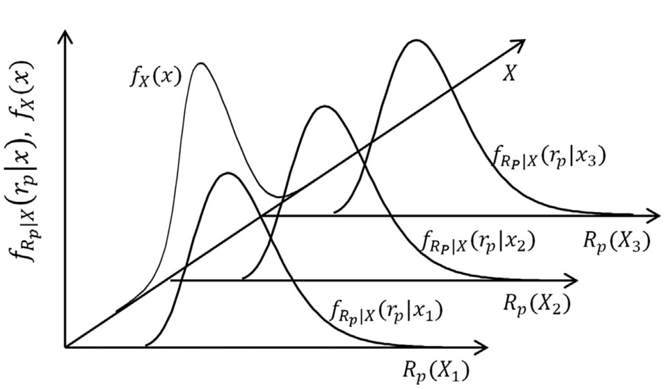

Fig. 1. PDFs of R_{p} for different X's.

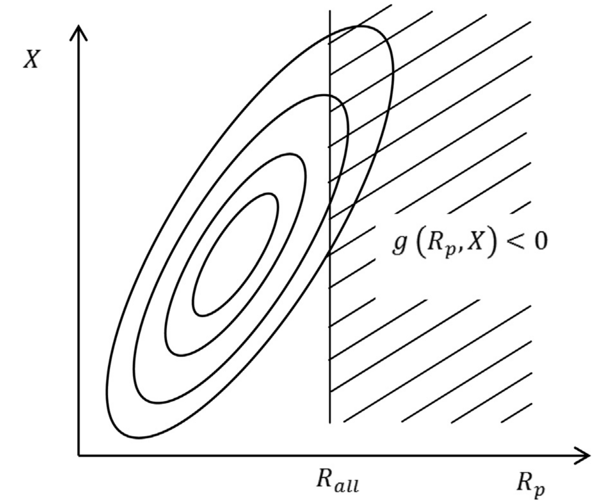

Fig. 2. Contour plot for $f_{R_{\mathrm{p}},X}(r_{\mathrm{p}},x)$.

2.2. Distribution of peak response

This section describes how to find distribution function for peak response of support structure. There are numerous peak responses during wave and wind loading. Among them, it is important to take significant ones from a structural point of view to form distribution function. There are several approaches to obtain distribution for the peak response. Widely used on is block maxima method. In this method, long time history response is divided into several block and those peak responses exceeding a threshold value are gathered to estimate PDF. The other method is the so-called Peak-Over-Threshold (POT) method. In POT method, all peak responses exceeding a pre-defined threshold value are taken to find distribution. Fig. 4 shows extreme value sampling example by the two methods. In block maxima, some significant peak responses might be lost during sampling from each block. This can be made up for by decreasing the unit block size. Distribution function from POT method is dependent on the threshold value. But there exists some useful criteria to pre-set relevant value for the threshold [5].

2.3. Design wave load

Using Morison equation, the dynamic fluid force on moving cylinder can be formulated as

$$f_{\mathrm{W}} = \frac{1}{2}\rho_{\mathrm{W}}C_{\mathrm{D}}D|U-\dot{r}|(U-\dot{r}) + C_{\mathrm{M}}\rho_{\mathrm{W}}A\frac{\partial U}{\partial t} \tag{6}$$

where C_{D} and C_{M} denote the drag coefficient and inertia coefficient, respectively; ρ_{W} denotes water density; A projected area normal to the cylinder axis per unit length; D the effective diameter of circular cylindrical member including marine growth, U the component of the velocity vector of the water normal to the axis of the member.

To obtain the static response of support structure used in eq. (4), virtual static force should be defined. In static analysis, the structural motion like $\dot{r}$ in eq. (6) cannot be used. Therefore, the structural velocity term in eq. (6) is neglected. In addition, the maximum water particle motion can be obtained by applying Airy's theory with sine and cosine is set to below [6]

$$\sin\Theta_0 = \pm\frac{\pi DC_{\mathrm{M}}}{HC_{\mathrm{D}}}\frac{2\sin h^2(ks)}{2kd + \sin h(2kd)} \tag{7}$$