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Risk assessment of floating offshore wind turbine based on correlation-FMEA

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ABSTRACT

Floating offshore wind turbine (FOWT) is complexly structured by interdependent subsystems and experiences negative impacts in harsh operating conditions. During the risk and reliability analysis, two issues have to be addressed: system failure mode complexity and mutual correlation. We conducted risk assessment through a modified Failure Modes and Effects Analysis (FMEA) method, named correlation-FMEA,to study the connection between failure modes and its effect on the failure probability of the entire system. A series of failure modes with high priority were determined by conventional FMEA, and the corresponding connections were analyzed to obtain the correlation coefficients using the reliability index vector method. The data used in our research comes from field operation in China. Probability Network Evaluation Technique (PNET) was used to get the weakest failure modes set of the system based on those coefficients. With the results, suggestions for floating wind turbine design were provided regarding aspects of safety and reliability.

1. Introduction

In recent decades, FOWT has rapidly developed due to the surge of renewable energy demand. FOWT, however, is costly and vulnerable. Its frequent demand for maintenance and the difficulty of such procedure call for vast expenditure. Due to the location and high repair time, all capital and operating costs are assumed to escalate. One way to provide effective maintenance is through risk assessment, which are predictions of weak points in the system around the design stage. For a long time this prediction relied on comparison data of similar systems and statistical study. Operation data from worldwide wind farms have been collected to acquire key statistical features, such as failure rate and downtime, revealing wind turbines reliability under various weathers, locations and configurations (Braam and Rademakers, 2004; Ribrant, 2006; Polinder et al., 2007; Spinato et al., 2009; Bussel and Zaaijer, 2011; Zhang et al., 2016).

Failure Modes and Effects Analysis (FMEA) method is widely applied on power-generating system and proves a sound approach. Arabian-Hoseynabadi et al. (2010) introduced FMEA method into wind turbine risk assessment. In order to analyze a failure mode in the FMEA procedure, three character metrics (severity, detection and occurrence) are employed. These metrics are all scaled into several levels and denoted specific values. By multiplying severity, occurrence and detection, Risk Priority Number (RPN) is obtained to measure the risk of failure mode and determine the most hazardous subassemblies.

The direct application of FMEA to FOWT, however, has potential issues. First, FOWT structure and operation condition are more complex compared with inland wind turbine, reflecting the limitation of FMEA on complex systems due to overwhelming workload. Second, similar or equal RPNs appear when the amount of failure modes increases, increases the difficulties or in some cases, impossible to identify the risk sequence. Third, the original assumption considers failure modes as isolated items without correlation, which indeed exists among failure modes (Sun 2015). The assumption yields over-assessment, leading to higher safety redundancy in the design stage.

In this study, we describe a method for FMEA application on FOWT by reducing failure modes and concerning correlation between them after the routine procedure of the algorithm. The FOWT system is divided into subassemblies and components, which defines failure causes and failure modes through various studies (Tavner et al., 2007; Anthony et al., 2015; Madjid and Michailides, 2015), and RPNs are calculated accordingly. In order to reduce the excessive failure modes, failure modes with higher RPNs are selected, named the weak modes. The correlation of two failure modes is defined when both of the modes simultaneously occur on one component or several, and the magnitude of correlation depends on the number of such components.

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Correlations between the weak modes are then calculated. PNET method is used for elimination of weak modes according to the correlation values to yield a devastated failure modes group which could be relied on for optimization in the design stage.

This paper is organized as follows: The correlation-FMEA algorithm is described in Section 2. System grading of FOWT is proposed in Section 3. Results and discussion are in Section 4. Conclusions are drawn at the end.

2. Correlation-FMEA

FMEA could identify, analyze and estimate possible faults in system and the manifestations (Ahire and Relkar, 2012). After analyzing the impact and consequences of each failure mode, vulnerabilities of the system can be confirmed according to the severity and probability of occurrence and detection. Upon this basis, recommendations for maintenance and improvement of relevant components are given, and therefore system reliability can be ameliorated. The FMEA procedure assigns a numerical value to each risk associated with causing a failure, using severity, occurrence and detection as metrics. By multiplying severity by occurrence by detection of the risk, the RPN can be obtained, which reflects criticality rank. Severity refers to the magnitude of the end effect of a system failure. The more severe the consequence, the higher the value of severity will be assigned to the effect. Occurrence refers to the frequency that a failure cause is likely to occur, described in a qualitative way. Detection refers to the likelihood of detecting cause before a failure occurs (Arabian-Hoseynabadi et al., 2010). By targeting high value RPNs, the most risky failure modes can be addressed. The modified severity, occurrence, detection scale and criteria are tabulated in Tables 1–3.

The present work considers correlation between failure modes on the foundation of the FMEA method. Let $G1$, $G2$ be two arbitrary failure modes. According to Hou and Ou (2002) and Sun et al. (2016), the limiting conditions are given in polynomial form

$$G_1 = a_0 + a_1x_1 + a_2x_2 + \cdots + a_nx_n \tag{1}$$

$$G_1 = b_0 + b_1x_1 + b_2x_2 + \cdots + b_nx_n \tag{2}$$

where a_i and b_i, i=0,...,n are coefficients, and x_i are a group of randomly independent variables. Further, we take $\mu(x_i)$ the mean value and $\sigma(x_i)$ the mean square deviation of x_i, thus the correlation coefficient is

$$\rho_{12} = \rho(G_1, G_2) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i b_j Cov(x_i, x_j)}{\sigma_{G_1}\sigma_{G_2}} = \frac{\sum_{i=1}^{n} a_i b_j \sigma_{x_i}^2}{\sigma_{G_1}\sigma_{G_2}} \tag{3}$$

The reliable index vector is given by

$$\boldsymbol{\beta}_1 = (\beta_1 \cos\theta_{11}, \beta_1 \cos\theta_{12}, \ldots, \beta_1 \cos_{1n}) \tag{4}$$

$$\boldsymbol{\beta}_2 = (\beta_2 \cos\theta_{21}, \beta_2 \cos\theta_{22}, \ldots, \beta_2 \cos_{2n}) \tag{5}$$

where θ_{mn} is the angle between the mth index vector and the axis of nth variable, hence

$$\cos\theta_{1i} = \frac{a_i\sigma_{x_i}}{\sigma_{G_1}}, \quad \cos\theta_{2i} = \frac{b_i\sigma_{G_{x_i}}}{\sigma_{G_2}} \tag{6}$$

Table 1
Severity rating scale for FOWT FMEA.

Scale	Description	Criteria
1	Category IV (minor)	Electricity can be generated but urgent repair is required
2	Category III (marginal)	Reduction in ability to generate electricity
3	Category II (critical)	Loss of ability to generate electricity
4	Category I (catastrophic)	Major damage to the turbine as a capital installation

Table 2
Occurrence rating scale for FOWT FMEA.

Scale	Description	Criteria
1–2	Extremely unlikely	Probability of occurrence is less than 0.0001
3–5	Remote	Probability of occurrence is more than 0.0001 but less than 0.001
6–8	Occasional	Probability of occurrence is more than 0.001 but less than 0.01
9–10	Frequent	Probability of occurrence is more than 0.01

Table 3
Detection rating scale for FOWT FMEA.

Scale	Description	Criteria
1–2	Almost certain	Current monitoring methods almost always detect the failure
3–5	High	Good likelihood current monitoring methods will detect the failure
6–8	Low	Low likelihood current monitoring methods will detect the failure
9–10	Almost impossible	No known monitoring methods available to detect the failure

then

$$\rho_{12} = \cos\theta_{G_1G_2} = \cos(\beta_1, \beta_2) = \frac{\boldsymbol{\beta}_1 \cdot \boldsymbol{\beta}_2}{|\boldsymbol{\beta}_1| \cdot |\boldsymbol{\beta}_2|} = \frac{\sum_{i=1}^{n} a_i b_i \sigma_{x_i}^2}{\sigma_{G_1}\sigma_{G_2}} \tag{7}$$

Here we then consider this relationship without losing generalization through the entire system, for the ith and jth failure modes, their correlation coefficient is

$$\rho_{ij} = \cos(\boldsymbol{\beta}_i, \boldsymbol{\beta}_j) \quad (i, j = 1, 2, \cdots n) \tag{8}$$

A main problem in the reliability analysis process for complex system is the excessive failure modes. Finding all failure modes and inserting them into the model is theoretically possible and provides a full assessment but would necessitate excessive calculation work. Analysis shows that only a small proportion of main modes are essential and others could be neglected (Tavner, 2012; Pérez et al., 2013). Generally, for further reduction of failure modes amount the design of simple system is optimized by controlling a weakest failure mode derived from the main modes based upon RPN.

For complex systems, since one weakest mode is inadequate to represent the whole, a weakest failure modes group is employed containing several weakest modes by using PNET method. The selection steps are,

(1) Searching main failure modes and the corresponding structure functions Z_i with the FMEA; Applying reliable index vector algorithm to calculate the reliable index β_i of each failure modes.
(2) Choosing correlation coefficient ρ_O according to practical situation to judge the correlation degree between the failure modes. If ρ_O is too small, excessive reliability will be obtained and it is dangerous for the design; it will be conservative if ρ_O=1. In general, ρ_O should be given according to the amount of failure modes and the importance of the project. Nugent et al. (1991) suggests the correlation coefficient should be set between 0.5 and 0.7, Define a standard correlation coefficient threshold (ρ_0) as the basis to identify related degrees between every two failure modes.ρ_0 is usually defined according to practical circumstances (Sun et al. 2016), in our research ρ_0 is set to be 0.7
(3) Listing m weakest failure modes among main failure modes using the PENT method: suppose the failure mode with the smallest reliable index β_1 as 1st failure mode, calculate its correlation coefficient ρ_{1i} with other failure modes by reliable index vector method. If $\rho_{1i} > \rho_O$ the ith failure mode is highly related to the 1st