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RELIABILITY BASED ANALYSIS AND DESIGN OF A TRIPOD OFFSHORE WIND TURBINE STRUCTURE ASSURING SERVICEABILITY PERFORMANCE

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ABSTRACT

Typical tripod foundations are designed using deterministic computational models according to relevant standards and codes. However, for more cost-safety balanced design, uncertainties in significant parameters should be considered in preliminary design to ensure meeting a specific probabilistic safety target in the context of the complex configuration of a tripod structure. In this article, uncertainties associated with design parameters and modelling errors are considered using Monte Carlo simulations, in order to determine the key structural design parameters, and to determine the optimal balance between design parameters and design requirements. A Spearman rank-order correlation based analysis is carried out to understand the effects of design variables on maximum deformation, total weight, and natural frequency, and to have insight about important design parameters for improvement of a preliminary design. It is found that the tower diameter has the most significant effect on the maximum displacement on the hub as validated through engineering case studies. In addition, a statistical framework, which identifies influential design parameters and provides reliability evaluation, is proposed for the structural design of a tripod OWT system. The design cases considered in this study indicate that a simple deterministic design check cannot guarantee the required reliability level of the structure, and the cost-safety balance can be achieved by a reliability analysis with the consideration of the uncertainties in the structure.

Keywords: Offshore wind turbine; tripod foundation; serviceability limit state; statistical correlation analysis; reliability analysis

INTRODUCTION

An offshore wind turbine (OWT) is the main device to generate energy in wind farms. It consists of a long slender column, a heavy mass, and a rotating mass at the top. The foundation is a supporting structure for an OWT, which transfers all loads from the OWT to the ground with allowable deflection. The allowable deflection is considered in the serviceability limit state (SLS) in the design of an OWT, and the tilt at the hub lever should be controlled according to the allowable limit stipulated in engineering codes such as DNVGL-ST0126 [1] and API [2]. If the tilt exceeds the allowable limit, an OWT needs to be shut down.

Foundations for OWTs are generally classified into fixed and floating types, and most of the currently installed and operating turbines are mounted on a fixed foundation [3]. The fixed foundation includes gravity-based, mono-pile, tripod, jacket and suction bucket. Among them, tripod foundations show good potential for OWTs due to their good stability and overall stiffness in water depth ranging from 20 to 40 m. For example, they were successfully installed in Borkum West 2, Global Tech 1, and Alpha Ventus wind farms [4].

To achieve a cost-safety balance for the structural design of the foundations of OWTs, a significant amount of studies in terms of analysis and design of tripods have been carried out in recent years including the following studies: Haskell et al. [5] adopted a pseudo-static analysis method to explore the effects of statistical variation of the model parameters on the predicted pile response by means of sensitivity analyses. Lozano-Minguez et al. [6] used a systematic assessment methodology to select the most preferable configuration among a mono-pile, a tripod, and a jacket considering environmental and economic aspects. In order to minimize the damage to a tripod type OWT-substructure caused by collisions with a boat, the influence of impact on the structure and the performance of a rubber fender for impact prevention were investigated by Lee [7]. Yu et al. [8] conducted a group of earthquake centrifuge tests on a physical model of a wind turbine with tripod foundation. They mentioned that the tripod foundation can provide better resistance in the lateral displacement and structural settlement under earthquake loading. Yeter et al. [9] carried out a spectral fatigue damage prediction and an assessment of tripod offshore wind turbine support structure subjected to combined stochastic waves and winds.

It is unavoidable to consider uncertainties in the design of a support structure, which exist in the strength and stiffness due to natural randomness of materials, in the resistance prediction model, and in the environmental loads. The modeling of uncertainties can be achieved by using fully probabilistic approaches [10] or semi-probabilistic approaches [11]. Consequently, the structural response of the support structure needs to be probabilistically analyzed or, at least, it is desired to investigate the effects of uncertain input parameters, to determine the most significantly affecting parameters [12, 13], and to reduce the number of uncertain variables which leads to improving design efficiency. In this regards, Andersen et al. [14] developed a methodology considering the uncertainties of the soil properties to estimate the natural frequency of a simple OWT model on a mono-pile foundation. Nour El-Din and Kim [15] investigated the sensitivity of the seismic response with respect to the uncertain modeling variables of a jacket platform using Tornado diagram and first-order second-moment techniques. Lee et al. [16] presented a reliability-based optimization method for a mono-pile transition piece in an offshore wind turbine system. Yang et al. [17] proposed a reliability based design optimization methodology for a tripod of OWTs considering dynamic response requirements to decrease weight and cost of a foundation. Vahdatirad et al. [18] considered the uncertainties regarding soil properties and proposed an asymptotic sampling method to estimate the probability distribution of stiffness for the OWT on a mono-pile foundation. However, the uncertainties related to the model and structural properties were not considered in that study.

By practically extending these previous studies on reliability analysis and deterministic parameter prioritizing analysis to the structural design of an OWT, this study proposes a statistical framework for a structural design of a tripod OWT foundation system, which includes the reliability evaluation of the structure and the statistical correlation analysis for design parameters. The proposed framework highlights a reasonable engineering judgment and understanding for structural design of tripod foundation. This study is a significant extension of a preliminary study in Zhang et al. [19], which combined nonlinear finite element method and Monte Carlo simulations to perform sensitivity analysis of key design parameters on the mechanical behavior of a tripod foundation.

DESCRIPTION OF SUPPORT STRUCTURES

TRIPOD GEOMETRIES

Fig. 1 shows a sketch of a tripod structure for a 3MW OWT. The tripod structure is analyzed at a water depth of 20 m, and it consists of a central column, three pile sleeve legs, three top braces, and six mud braces. Piles are installed at the legs to anchor the tripod to the seabed. The tripod top and bottom are 10 m and –20 m above the mean sea level (MSL). The base of the tripod has the area of 22 m × 22 m. The upper conical tower mounted on the tripod is 79.5 m high, and the hub elevation is 89.5 m above the MSL. The turbine is modeled according to the conventional upwind, variable speed, and collective pitch horizontal axis.

UPPER TOWER STRUCTURE

For convenient transportation and erection, the entire tower is designed as an assembly of four sections, as shown in Fig. 1(c), which shows four pieces of thin-wall cylindrical and conical parts. The pieces have diameters of 4740 mm at the base and 2860 mm at the top. The diameters linearly vary along the height. Each piece has a different thickness as indicated in Fig. 1(c). Circular stiffeners are placed at regular intervals along the height of the tower, and they are welded together along their perimeters.

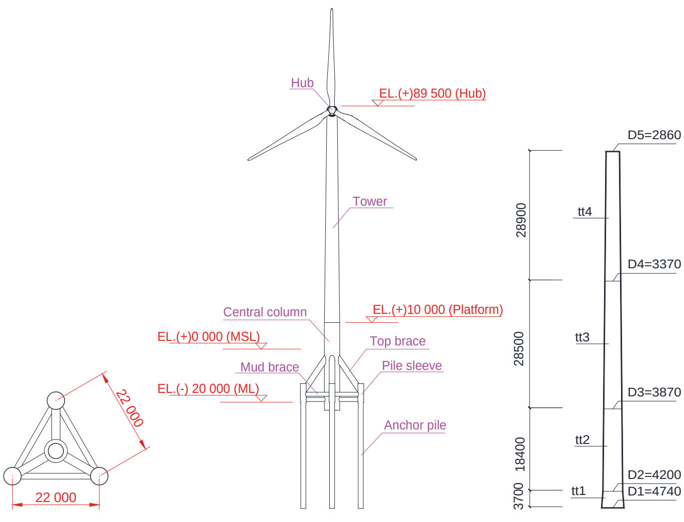


Fig. 1. Sketch map of tripod foundation

FINITE ELEMENT MODELING

A Finite Element (FE) model of the tripod is created in a commercial nonlinear FE code ANSYS, as shown in Fig. 2. *Pipe 59* element is chosen for pile sleeve, mud brace, top brace, and central column. *Beam 188* is chosen for the tower part; and *Mass* element is chosen for nacelle and rotor. Young's modulus, yield strength and Poisson's ratio of steel are 210 GPa, 355 MPa and 0.3 respectively. The pile-soil interaction (PSI) is simulated using *Combine 39* element and soil-pile springs, along the pile penetration length. The model simplifies the interaction between soil and pile by assuming that there is no dependency between the displacements of springs. The lateral soil stiffness is modeled using the *p-y* curve approach, which is described in API [2]. In this curve, the nonlinear relationship between lateral soil reaction (p) and lateral pile displacement (y) can be established and defined in *Combine 39* element by force-deformation (*F-D*) relationship where *F* is the total force applied along the length of the pile. The lateral stiffnesses of soil from –8m to –14 m depth are calculated using *p-y* curves as shown in Fig. 3.

Fig. 2. FE model of the tripod

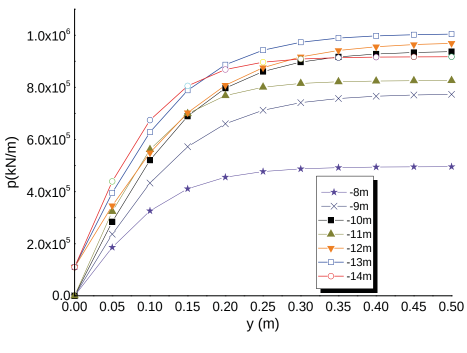


Fig. 3. P-Y curve for soil between –8m and –14m

APPLIED LOADS

OWTs are often exposed to the harsh marine environment, and load combinations required for limit states such as ultimate limit state (ULS) and serviceability limit state (SLS) need to be rigorously considered in the design phase. Essential information regarding the selection of characteristic loads is described in standards and regulations such as DNVGL-ST0126 [1] and IEC [20]. In this study, the primary loads including wind load, wave, current load, and gravity are considered, and load simplifications have been made as provided in the following sub-sections.

Wind loads

Wind loads include loads on the rotor and the tower. The wind loads on an impeller can be obtained from the blade element theory and dynamic stall, dynamic wake model. Aerodynamic properties of blades were obtained from reference [21].

The wind loads distribution along the altitude of the tower is expressed as follows:

$$f(z) = \frac{1}{2} C_d \rho D V^2(z) \tag{1}$$

where ρ is the density of air, which is 1.225 kg/m^3, C_d is drag coefficient, D is the diameter of the tower, and $V(z)$ is wind speed (in meters per second) at height z (in meters) and can be calculated using the following formula:

$$V(z) = (\frac{z}{z_{ref}})^m V(z_{ref}) \tag{2}$$

where $V(z_{ref})$ is the known wind speed at the reference height z; the exponent m is an empirically derived coefficient that varies depending on the stability of the atmosphere. In this study, m is taken to be 0.143.

Wave loads

For a slender structure such as a pile in a tripod, a diffraction effect is negligible for waves, and the Morison formula can be applied to the wave force. The horizontal force applied to the element of the cylinder at level z is expressed as:

$$dF = dF_m + dF_d = C_m \ \rho\pi \frac{D^2}{4} \ \dot{u}_w \, dz + \ C_d \ \rho \frac{D}{2} |u_w| u_w dz \tag{3}$$

where the first term (dF_m) is an inertia force, and the second term (dF_d) is the drag force. C_m and C_d are the inertia and quadratic drag coefficients, respectively. ρ is the water density, and D is the diameter of a structural member. $\dot{u}_w$ and u_w are the horizontal acceleration and velocity of water, respectively. The positive force direction is the wave propagation direction. The resulting force can be derived by integrating the force over the length of the structure from the seabed to the MSL. In this study, C_m = 1.0 and C_d = 2.0.

Current loads

The current loads are affected by the angle between the wave and current directions, and the wave and current loads reach the maximum values when the wave and current are in same directions [21]. In this study, the maximum current is considered.

Gravity

The weight of each of nacelle, rotor, and turbines is simplified to a mass point, and the point is located 2.5 m away from the center line of the tower, as shown in Fig. 4. The mass of the tower and foundation is considered to have a gravity acceleration of 9.8 m/s^{2}.

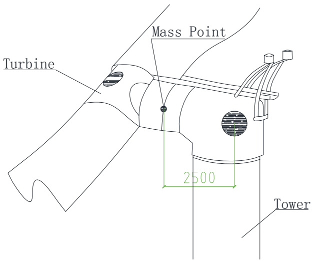


Fig. 4. Schematic diagram of mass point

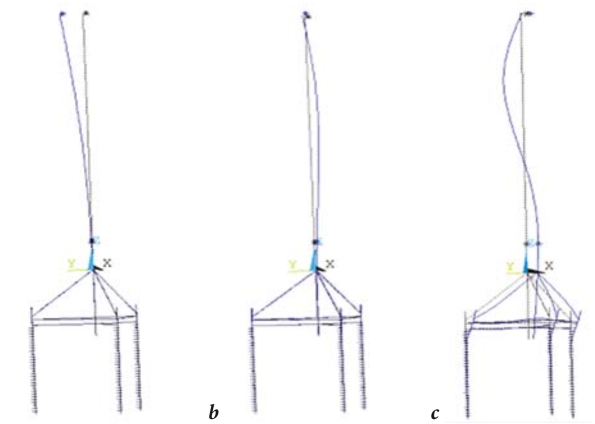
DETERMINISTIC ANALYSIS AND RESONANCE CHECK

In the phase of preliminary design, the dimensions of the tripod and the tower are determined based on the requirements in codes of practice such as DNV and API and experts' experience. The details of the dimensions are listed in table 1.

Tab. 1. Schematic diagram of mass point

Components	Size (diameter × thickness)	Unit
Pile	ø 2000 × 40	mm
Pile sleeve	ø 2200 × 30	mm
Mud brace	ø 1500 × 30	mm
Top brace	ø 2200 × 40	mm
Central column	ø 4500 × 40	mm
Tower	ø 2860 × 20 to ø 4740 × 50	mm
Nacelle and rotor	163.3	ton

First, to check the occurrence of resonance, a modal analysis is performed to get the natural frequencies of the structure. Fig. 5 shows the three modes shapes for the support structure system. The deformation and natural frequency are computed using ANSYS.



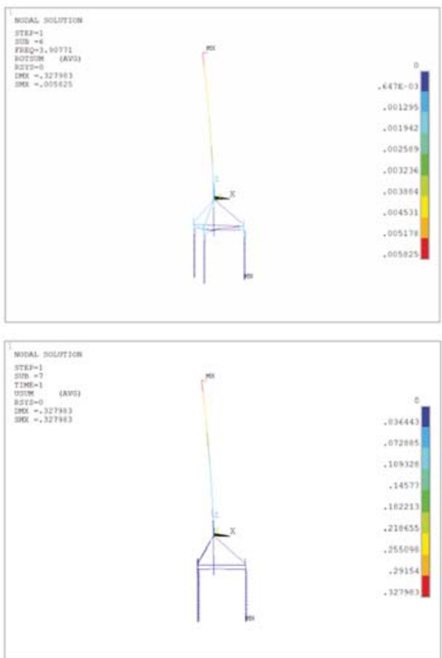
a **b** **c**

Fig. 5. First three mode shapes of tripod structure
*(**a**) 1st frequency=0.342Hz; (**b**) 2nd frequency=2.065Hz; (**c**) 3rd frequency=3.891Hz*

A constant speed for the turbine is assumed in the analysis. The constant rotational speed is the first excitation frequency, and the second excitation frequency is the blade passing frequency *NP*, in which *N* is the number of rotor blades. In this study, a three-blade V90-3 MW (Vestas) wind turbine has an operational interval between 8.6 rpm and 18.4 rpm. The rotor frequency (termed *1P*) lies in the range of 0.143 Hz to 0.306 Hz, and the corresponding *3P* frequency lies in the range of 0.429 Hz to 0.920 Hz. The DNVGL-ST-0126 code [1] suggests that the first natural frequency should not be within the 10% of the *1P* range and the 10% of the *3P* range. It is confirmed from Fig. 5 that the first natural frequency in the designed tripod is not within 10% of *1P* and *3P* ranges, and the structure does not resonate. In the support structure, the bending is predominant in vibration.

One of the main aims of the support structure is to transfer all the loads from the wind turbine to the ground bearing allowable deformation to assure a safe operation of turbines. The DNVGL-ST-0126 code [1] specifies a 0.25 degree limit on tilt at the hub level in SLS criteria. Fig. 6 shows the total rotation vector of the support structure. It is seen that the maximum rotation on the hub level is 5.825 × 10^{-3}rad, that is, the tilt of 0.33 degree, which is greater than the allowable title of 0.25 degree specified in DNV.

In summary, the natural frequency of the support structure preliminary design lies outside of the excitation frequencies, which avoids resonance. However, the deformation at the hub level exceeds the required threshold value. Therefore, it is required to refine the design by increasing the stiffness of the support structure to meet the deformation requirement. It requires the selection of key parameters that mostly affect the performance of the structure. The statistical correlation analysis and the reliability based design procedure introduced in the next sections are necessary for this process.



a

b

Fig. 6. Deformation of support structure
*(**a**: the total rotation vector; **b**: total displacement vector)*

STATISTICAL CORRELATION ANALYSIS FOR KEY DESIGN PARAMETER SELECTION

STATISTICAL PARAMETER SELECTION USING THE CONCEPT OF A CORRELATION COEFFICIENT

This section proposes to use a statistical correlation analysis that helps to identify the statistical relation between the design parameters and the structural performance. In this study, the randomness of the design parameters is considered, and its effect on the structural performance is measured using the statistical correlation coefficient.

The structural response of the target tripod can be expressed as follows:

$$Y = g(x_1, x_2, x_3 ... x_n) \tag{4}$$

where Y is the structural response such as deformation, stress, and natural frequency; $x_1, x_2, x_3 ... x_n$ are input variable; and g is the function, which represents the analysis carried out by the finite element model in this study. In this study, the Spearman rank-order correlation coefficient (SROC) is chosen to represent the statistical correlation between the structural response and the design input variables. The SROC is calculated to be

$$SROC = \frac{COV(Y, x_i)}{\sigma_{xi}\sigma_Y} \tag{5}$$

where $COV(X, x_i)$ is the covariance of Y and x_i, and σ_{xi} and σ_Y are the standard deviations of x_i and Y, respectively. *SROC* represents the degree of a linear statistical relationship between two variables. The values of *SROC* range between −1 and +1, and the absolute value of *SROC* represents the strength of the relationship. As the absolute value of *SROC* approaches 1, the relation between two variables becomes a linear deterministic relation. As the value of *SROC* approaches 0, the relation between two variables becomes purely random. The sign of *SROC* indicates the direction of the linear relationship, and the positive sign indicates that an increase in one variable is associated with an increase in the other variable, while the negative sign indicates that an increase in one variable is associated with a decrease in the other variable.

Among various methods for estimating *SROC*, the Monte Carlo simulation (MCS) is chosen in this study due to its straight-forwardness in implementation and its accuracy upon the convergence of the result. Latin Hypercube Sampling [22] is a representative advanced MCS method to reduce the number of iterations required for the crude MCS.

In this study, applied loads including wind, wave and current are considered for extreme cases. Considering that loads are already based on a conservative assumption, the uncertainties of the resistance of the structure are of interests. In MCS analysis, geometric parameters including the thickness and diameters of structural components and material property parameters are considered as design variables. These variables are considered as random variables, and their statistical distributions are provided in Table 2 with references. The maximum displacement at the hub level D_{max} and the frequencies are taken as output variables. From a convergence test, the sample size of 5000 was selected in this study.

Tab. 2. Random input variable specifications

Random input variables	Symbol	Mean	C.o.v	Distribution type	Ref.
Elastic modulus (GPa)	TM	210	7.6%	Normal	[23]
Yield strength (MPa)	YS	355	6.8%	Lognormal	
Outer diameter of central column (mm)	D1	5200	10%	Normal	[24] [25]
Thickness of central column (mm)	T1	60	10%	Normal	
Outer diameter of top brace (mm)	D2	2200	10%	Normal	
Thickness of top brace (mm)	T2	40	10%	Normal	
Outer diameter of pile sleeve (mm)	D3	2000	10%	Normal	
Thickness of pile sleeve (mm)	T3	30	10%	Normal	
Outer diameter of mud brace (mm)	D4	1500	10%	Normal	
Thickness of mud brace (mm)	T4	30	10%	Normal	
Outer diameter of anchorage pile (mm)	D5	1800	10%	Normal	
Thickness of anchorage pile (mm)	T5	38	10%	Normal	
Outer diameter of tower bottom (mm)	TD1	4700	10%	Normal	
Thickness of tower segment 1 (mm)	TT1	60	10%	Normal	
Thickness of tower segment 2 (mm)	TT2	38	10%	Normal	
Thickness of tower segment 3 (mm)	TT3	30	10%	Normal	
Thickness of tower segment 4 (mm)	TT4	24	10%	Normal	

ANALYSIS RESULTS AND DISCUSSIONS

The statistical correlation analysis results using *SROC* are shown in Fig. 7(a), where the *SROC* between the maximum lateral deflection and the parameters for structural geometry and material property are provided. It is seen that the diameter of the tower bottom (TD1) has the most significant effect to the lateral deflection of the hub showing the *SROC* of −0.88. The negative value means that the increase in the diameter of the tower bottom results in the decrease in displacement. The other parameters having a significant effect include the elastic modulus (EM), the diameter of the central column of the tripod (D1), and the thickness of tower segment 2 (TT2). The other parameters such as D2, T1, D5, TT3, T2 and D4 have a little influence to the maximum deflection.

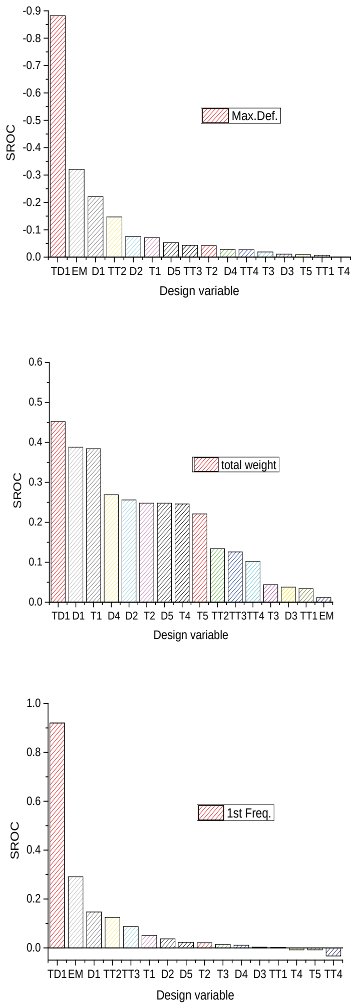


Fig. 7. SROCs of design variables to maximum deflection (a) total weight (b) and the first natural frequency (c)

To consider the effect of each design parameter to the total cost, the *SROC* between each parameter and the total weight is estimated. The weight is chosen as a cost measure as it is related to the amount, transportation, and installation of construction material. Fig. 7(b) shows the *SROC* between each of the parameters and the total weight. It shows that the design variable with the greatest effect on the total weight is TD1, and the variable with the second greatest effect is the diameter of the central column of the tripod, D1. Variables TT2, TT3, TT4, T3, D3 and TT1 have a negligible contribution to total weight.

Compared to traditional offshore structures, OWT foundations impose a stricter requirement for the natural frequency to avoid resonance, and therefore, it is important for designers to know the correlation of natural frequency and design parameters. Fig. 7(c) presents the *SROC* of the first-order natural frequency of the tripod foundation to diameter, thickness and elastic module of the structure. The natural frequency of tripod is highly dependent on the thickness of tower bottom (TD1) and elastic module (EM). In other words, an adjustment of the thickness of the tower bottom is recommended if natural frequency of foundation structure does not meet the design requirements. On the other hand, TT1, T2, D3, T3, D4, T4, D5 and T5 show no significant effect on the first-order natural frequency, and they do not significantly affect the design.

A statistical correlation analysis helps to identify important parameters, and it is also useful in reducing the size of problems with a large number of random variables because only a few variables generally have a significant effect on the structural response. For instance, there are 17 random variables in the probabilistic structural analysis, and only 8 variables have effects on the deflection (Fig. 7(a)) from which 3 variables (TD1, D1 and D2) whose SROCs are greater than 0.2, other variables have insignificant effects on maximum deflection and they can be neglected in preliminary design.

VALIDATIONS OF STATISTICAL CORRELATION ANALYSIS RESULTS

The results of the statistical correlation analysis are summarized in Table 3 for ranks 1–4 and 13–16. In addition, the variation rates of the maximum deflection, the total weight and the 1st natural frequency are provided according to the 10% increase of TD1, D1, TT1, which show good agreement with the results of *SROC*. It is seen from Fig. 8 that the maximum deflection, the total weight, and the 1st natural frequency change by 17.5%, 12.1% and 3.0%, respectively, when increasing the 10% of TD1, while they change by 2.9%, 2.6% and 0.2% when increasing the 10% of TT1. It means that, when the deflection or natural frequency does not meet the code requirements, it is effective to modify parameters that are highly dependent on the structural response and to neglect insignificant parameters.

Tab. 3. Ranks of sensitive design parameters

Rank	Maximum deflection	Total weight	1st natural frequency
1	TD1	TD1	TD1
2	EM	D1	EM
3	D1	T1	D1
4	TT2	D4	TT2
13	D3	T3	TT1
14	T5	D3	T4
15	TT1	TT1	T5
16	T4	EM	TT4

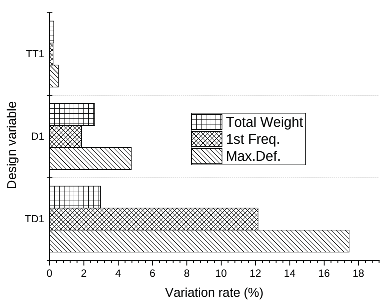


Fig. 8. Variations rate of structural responses due to changing a design variable

RELIABILITY ANALYSIS

RELIABILITY ANALYSIS USING MCS

After identifying significant parameters for the improvement of structural design, it is necessary to perform a reliability analysis and check if the proposed design provides the best cost-safety balance meeting the target reliability level.

In this study, for reliability analysis, the MCS method is used because it does not involve the calculation error due to approximation, and the computational cost of MCS is affordable especially for serviceability reliability analysis as the target reliability level for the serviceability limit state is not too high. The reliability is often represented by the reliability index β that is related to the probability of failure P_f in the following relation:

$$\beta = -\Phi^{-1}(P_f) \quad (6)$$

where $-\Phi^{-1}(\cdot)$ is the inverse standard normal cumulative distribution function [25]. Although P_f can be estimated using either approximations or statistical simulations, approximations such as the first-order reliability method have limitations in handling highly nonlinear limit state functions. According to MCS, the probability of failure is estimated as follows:

$$P_f = \frac{N_f}{N} \quad (7)$$

where N_f is the number of simulations in the failure domain, and N is the total number of random simulations. The accuracy of the simulation depends on convergence that is represented by the coefficient of variation (C.o.v) of the estimated probability of failure as follows [26]:

$$C.o.v_{P_f} = \delta_{P_f} \approx \sqrt{\frac{1-P_f}{NP_f}} \quad (8)$$

In this study, Latin hypercube sampling (LHS) has been used to get improved convergence using a stratified sampling technique [26].

RELIABILITY ANALYSIS FOR THE TARGET STRUCTURE

This study mainly considers a serviceability limit state because it directly affects the operation of OWTs and has more frequency than the ultimate limit state. The serviceability criteria are defined based on the tolerance requirements for the operation of the wind turbine. Typically these tolerances are specified in some codes of practice (e.g. DNV) or a design specification supplied by turbine manufactures. Examples of the specific requirements are as follows: the limiting value for lateral deflections for a cantilever beam is given as $H/100$ in the DNV GL-ST-0126 code [1], which is related to the straight line joining the support. Here, H is the projecting length. The limiting lateral deflection is also advised to be controlled within 1/200 ~ 1/125 of tower height H based on their operating experience [27].

In this study, five thresholds values for lateral deflection including H/200, H/175, H/150, H/125 and H/100 are considered in the reliability analysis to investigate the effect of a range of threshold values, which are determined based on a combination of the provisions of design standard and practical engineering experience. Simultaneously, to investigate the effect of modeling error, parameter ε is introduced and multiplied to the variation of *Ex* to amplify the variation of the overall result. Thereby, the 10% increase in the value of ε results in roughly 10% decrease in the variation of the deflection.

Table 4 lists the probability results for the five different threshold values for deflection. The analysis results are computed by the combination of Finite Element Method (FEM) and the LHS method.

Effects of thresholds

From the results provided in table 4, it is apparent that failure probability decreases for greater thresholds. It is also observed that the selection of SLS criteria impacts the foundation design and costs. The threshold value should be carefully chosen considering the balance in the operation cost and safety.

Effects of Ex

To see the effect of additional uncertainties such as the modeling uncertainties, additional variations are put to the important parameter *Ex* manually. The additional variation has been multiplied to the C.o.v of *Ex*. From the data in table 4, it is apparent that failure probability increases with increasing the Elastic Module *Ex variation.* As an example, for the threshold H/200, the failure probability changes from 2.0906×10^{-1} to 2.6987×10^{-1} when *Ex* factor changes from 1 to 1.1.

Tab. 4. Probabilistic results of different thresholds in 5 cases (5,000 MCS)

Case	Factors of $Ex(\varepsilon)$	Threshold	Failure probability P_f	Reliability index β
1	1	H/200	2.0906×10^{-1}	0.8097
		H/175	1.1095×10^{-1}	1.2215
		H/150	4.6992×10^{-2}	1.6747
		H/125	1.5439×10^{-2}	2.1586
		H/100	3.9230×10^{-3}	2.6586
2	1.05	H/200	2.5910×10^{-1}	0.6461
		H/175	1.3862×10^{-1}	1.0865
		H/150	5.7291×10^{-2}	1.5779
		H/125	1.8729×10^{-2}	2.0807
		H/100	4.7086×10^{-3}	2.5965
3	1.1	H/200	2.6987×10^{-1}	0.6132
		H/175	1.4112×10^{-1}	1.0753
		H/150	5.8688×10^{-2}	1.5659
		H/125	1.9463×10^{-2}	2.0650
			4.7145×10^{-3}	2.5961

In addition, it is also noted that some of the serviceability criteria do not meet the reliability level specified in current international codes. The target reliability index for the serviceability limit state provided in international codes including EN 1990 [28] and ISO 2394 [29] are 1.5. That corresponds to the failure probability of 6.6807×10^{-2}. For example, for Case 1, the calculated failure probability of H/200 is 2.0906×10^{-1}, which is greater than the target failure probability 6.6807×10^{-2}. However, in the deterministic analysis in section 2.5, it is shown that the maximum lateral deformation of the structure is 327 mm (H/243) in Fig. 6, which satisfies the deflection limit H/100 in DNVGL-ST-0126 [1]. This example shows that the optimal cost-safety balance can be achieved by a careful reliability analysis rather than a simple deterministic check.

PROPOSED RELIABILITY BASED DESIGN FRAMEWORK

This study proposes to use a reliability based framework to design an OWT structure by combining the statistical correlation analysis procedure and the reliability analysis procedure presented in the previous sections. A flowchart for this framework is presented in Fig. 9, which includes the following four stages: structural configuration, deterministic analysis, statistical correlation analysis, and reliability analysis. In the preliminary design of the tripod, first, the structural configuration including tower and foundation geometries is determined based on the estimations of design conditions and the engineers' experience. Generally, the tower height is decided by the wind turbine diameter and the speed at the tower height in the wind farm and the foundation height is related to the water depth. The base layout (the distance of the anchored pile) should consider the structural stability to avoid overturning subject to horizontal loads including wind, wave, and current loads. Since the diameters and thicknesses of the components in a tower and a foundation are massive and are difficult to be determined directly from engineering estimations, they need to be determined through some iteration processes. For their initial approximate values determined based on engineering experience, the structural responses such as stress and deformation need to be estimated using an FE analysis to check SLS stipulated in code and practice. If the results are satisfied, a further step of the reliability analysis needs to be carried out, where the target probability in MCS is taken as criteria for judging the response whether the reliability requirements are met. In the reliability analysis, the uncertainties of geometry and material properties need to be considered. If the results do not meet the reliability requirement, the important design parameters identified from the statistical correlation analysis need to be altered to improve the structural design to meet the design requirement. The iterations updating the tripod model are repeated until the final robust design is obtained.

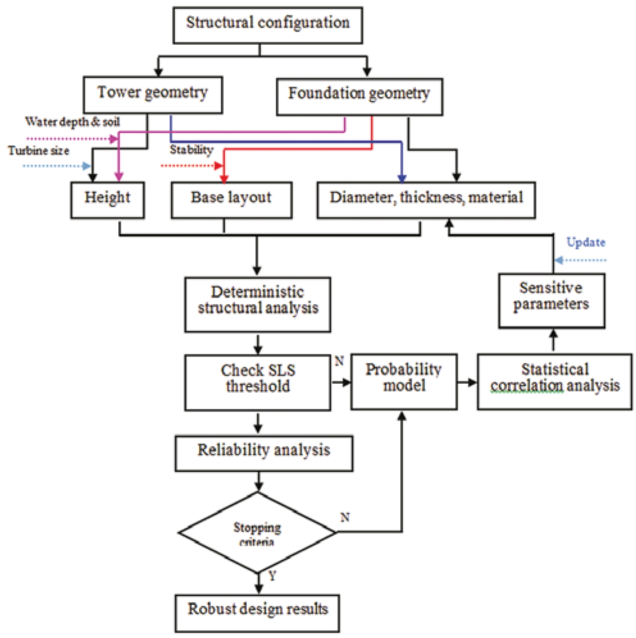


Fig. 9. SA flow chart of reliability based preliminary design of tripod in SLS

Case study

As can be seen from the deterministic analysis results in case 1, the failure probability for threshold H/200 is greater than the target value of 6.6807×10^{-2}, while that for H/100 is smaller than the target value. These two cases indicate that the structure is conservative or unsafe. In either case, to achieve the target probability, the deformation should be controlled by adjusting important parameters identified from the statistical correlation analysis until meeting the target reliability level. It should be also mentioned that the natural frequency and total weight of new design will also change according to the change of design parameters.

To demonstrate the proposed framework, we take threshold H/200 in Case 1, and the failure probability for the current design proposal is 2.0906×10^{-1}. This means that the support structure stiffness is not sufficient, and the design parameters need to be adjusted to increase the stiffness of the structure. According to the steps in the flow chart, to reach target failure probability $P_f = 6.6807 \times 10^{-2}$, the preferred options for adjusting design parameters based on the statistical correlation analysis results in Section 3 are to increase TD1, to increase D1, or to increase TT2. For these three options, the variation rates of total weight and the 1st natural frequency due to updating TD1 are summarized in Table 5.

Table 5 describes the changes of the values of the three parameters TD1, D1 and TT2. In the three options, TD1 has the most significant effect on the deflection of the support structure. To satisfy the deflection criterion in terms of the reliability level, the diameter of TD1 is increased by 10%. It should be noted that to obtain a similar level of reliability, D1 and TT2 need to be increased by 150% and 195%, respectively. The order of the effectiveness of the change of these parameters exactly agrees with the order obtained in the statistical correlation analysis results.

In addition, while making the change in the values of these three parameters, the total weight and natural frequency will change due to the changes in diameter and thickness. Among them, option 1 gives the smallest weight and the natural frequency that is still outside of the 10% of *1P* and *3P* ranges. Therefore, changing the most significant parameters TD1 is the most effective and economical option for the design of the target structure.

Tab. 5. Variation rate of geometry, total weight and 1st natural frequency to meet probability level

Option	Variation	Total weight	1st natural frequency	Failure probability P_f	Reliability index β
TD1		+2.9 %	0.384	0.0566	1.5840
D1	+150%	+10.4%	0.372	0.0903	1.3389
TT2	+195%	+13.0%	0.362	0.0782	1.4173

CONCLUSIONS

A reliability based structural design framework for a 3 MW OWT tripod foundation was proposed in this study. The proposed framework combined the statistical correlation analysis and the reliability analysis, which were carried out based on a finite element model. First, the statistical correlation analysis was based on the Spearman rank-order correlation analysis to give insight into important design parameters in a preliminary design phase. It was found that the diameter of the tower bottom, the material properties, and the outer diameter of the central column showed a strong effect on the maximum displacement of the tower in the order of significance. These parameters showed a considerable impact on the improvement of structural design compared to the other not-important parameters. Second, in the reliability analysis, the MCS with Latin Hypercube sampling technique was used to consider the uncertainties in structural geometries and modeling errors. The effects of thresholds and uncertainties were discussed through multiple reliability analyses. The reliability analysis results showed that a simple deterministic analysis result does not guarantee the achievement of the required reliability level of the structure, and it is necessary to perform reliability analysis to achieve the best cost-safety balance in a structural design.

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