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Reliability of floating foundation concepts for vertical axis wind turbines

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Abstract

Offshore wind turbines are developing at a rapid pace. By far the most common turbine configuration is the HAWT (Horizontal Axis Wind Turbine) and development of these machines is largely centered about drive train and blade issues with some work concerning foundations/supporting structures. Several teams around the world are developing floating supporting structures for HAWT, mainly for deep water deployment. This paper describes the development of a floating support structure for Vertical Axis Wind Turbines (VAWT) with particular focus on structural/survival risk and reliability. Unlike Oil & Gas floating support structures, wind turbine floaters need to resist significant dynamic wind and machine loading in addition to wave excitation. Coupling of dynamic response modes can be difficult and consideration of these within a reliability framework presents several challenges. The paper describes a simplified procedure for risk assessment so that potential areas of concern can be quickly identified and uses a VAWT to illustrate the methods and reasoning employed.

Keywords

Offshore Wind Turbines, Reliability Assessment, Coupling of Dynamics, Vertical Axis Wind Turbines

Nomenclature

A	Wave Amplitude
C_{55}	System Restoring in Pitch
f_x	Joint Probability Density Function
F_x, F_y	Mooring Excitation Forces
F_5	Steady State Moment
F_{thrust}	Thrust Force
FORM	First Order Reliability Method
g	Acceleration of Gravity
HAWT	Horizontal Axis Wind Turbine
M_{WP}	Waterplane area Moment
M_B	Boyant Mass
M_G	Gravitational Mass
N	Mooring Axial Force
N_{all}	Allowable Axial Force (mooring line)
P_f	Probability of Failure
r	Inner Diameter
R	Outer Radius
RAOs	Response Amplitude Operators
s	Length of Mooring Line
SORM	Second Order Reliability Method
U	Wind Speed
Vs	Wind Speed
VAWT	Vertical Axis Wind Turbine
X_i	Random Variables
Z	Limit State Function
Z_{CG}	Centre of Gravity
Z_{CB}	Centre of Buoyancy
Z_{hub}	Hub Elevation
Φ	Cumulative Distribution Function
β	Reliability Index
ξ	System Steady State Pitch
ρ	Density
φ	Azimuth Angle, Angle of Rotation of the VAWT
ω	Wave Frequency

Introduction

Evolution of offshore structures, following the development of oil and gas platforms and their deployment in deeper waters, reaching depths that exceed 500 m, has created an interesting potential for transferring technologies to the offshore wind industry. Scalability of structures in locations distant from shore has increased the interest in novel designs of floating concepts of support structures that facilitate installation and maintenance over their service life. Engineering of such structures imposes special requirements due to their scale and the severe environmental conditions have to be considered. For the case of novel structures, where service experience is not available, design within a reliability context seems to be a pragmatic way to achieve minimum levels of accepted performance, avoiding over sizing of the resulting structure (Kolios and Brennan, 2009).

The scope of this paper is to present the consideration of the global reliability of a floating support structure for the reference case of a vertical axis wind turbine, after a brief review of the different available concepts of support structures and a reference to the basic concepts of structural reliability. In addition, the issue of coupling the dynamic phenomena due to the wind, wave and rotational excitation of the wind turbine, and their input to the estimation of reliability is discussed.

Vertical Axis Wind Turbines

Deployment of several wind farms during the last decade has highlighted some aspects that indicate the potential for higher structural efficiency for alternative configurations as compared with the 'conventional' turbines. Horizontal Axis Wind Turbines (HAWTs) place their rotors and drive-train at the top of very tall towers, impeding installation and limiting their size; maintenance is also difficult because of the sheer height of all the moving parts. Vertical Axis Wind Turbines can overcome the disadvantages mentioned above by locating their main components at the base of the installation, providing easy access and a lower value of overturning moment, and are less sensitive to wind direction. Riegler (2003) and Ericsson et al (2008), provide some interesting analytical discussions for these different design philosophies.

The first design of a vertical axis wind turbine that was analytically documented, was the Darrieus wind turbine (Darrieus, 1931), which comprised of curved blades, forming an 'egg-shape' machine. Although this configuration is effective, the requirement for a bearing at the top of the tower and high cycle nature of the machine has negated the otherwise beneficial structural effects. The Savonius (Savonius, 1931), the Giromil (Brulle et al, 1975) and combinations of the former configurations, Darrieus-Savonius (Gavalda, 1990), wind turbines overcome some of the disadvantages referred to above.

Floating Support Structures

Research on floating structures for wind turbines is starting to yield preliminary full scale results, but these are still in the test phase (e.g. the Hywind project, by Statoil). Commercial scale structures have not yet begun, and a clear classification method has not yet emerged.

The oil & gas offshore industry has developed several floating support structure concepts during the last 50 years, such as the tension leg platform (TLP), semi-submersible vessel, self-elevating jack-up, single point mooring, SPAR, etc. Some of those can be re-utilized and adapted to the offshore wind energy industry, and a simple way to classify them has been proposed by Butterfield et al. (2005). This classification is based on the method used to achieve static stability with respect to the rotational degrees of freedom. Stability of a floating structure can be achieved through waterplane area (buoyancy), ballast or mooring lines.

Waterplane area mechanism is based on the fact that when a floating body rotates, the shape of the submerged volume changes, changing the position of the centre of buoyancy. Defining the metacentre *M* (small rotations) as the point of intersection of the lines of action of the buoyancy and with *G* the centre of gravity, the restoring moment is proportional to *GM* (positive when *M* above *G*). It is proportional to the waterplane area moment about the structure's centre of rotation.

In ballast stabilized floating structures, the weight force acts on the centre of gravity (*CG*) of the structure, downwards, while the buoyancy acts on the centre of buoyancy (*CB*), upwards. If an adequate volume of ballast is added to the structure to ensure that *CG* is below *CB*, the two forces will create a restoring set.

Finally, in mooring line stabilized floating structures, the mooring lines exert a moment on the structure, when it is displaced from its equilibrium state. The characteristics of this moment depend on the type of the mooring line. For catenary mooring systems, the restoring moment in pitch and roll is, roughly, the product of the weight of moorings in water and the draft of the fairleads. The amount of restoring moment given by this mooring line type is insufficient to support large wind turbines, therefore is not taken into account (equal to zero). Their function is essentially station-keeping. Tension leg mooring systems substantially augment the stiffness of the system in all 6 degrees of freedom, therefore, contrary to catenary systems, the restoring moment in pitch and roll can be sufficient (Patel, 1989).

Concepts of Structural Reliability

Fundamentals

Structural Reliability treats uncertainties in structural designs systematically, evaluating the levels of safety and serviceability of the structure. During recent decades, it has been established as a valuable tool for the characterization of the actual performance of the structure and lately forms the basic background for most modern design standards aiming to achieve uniform structural performance among different classes of structures (DNV, 1995).

Reliability of structures can be estimated based on the limit state function that describes the response of the structure under loading, distinguishing safe from unsafe limits of operation. A limit state is a condition beyond which a structure or structural component will no longer satisfy the design requirements (DNV, 2008). For each of the limit states examined, the n basic variables of the structure X_i that affect the response of the structure should be initially identified and their stochastic (statistical) representation should be determined. Following a mathematical notation, the limit state function can be described as:

$$Z = g(X_1, X_2, \ldots, X_n)$$

The critical surface can then be defined as:

$$Z = 0$$

This surface distinguishes the safe from the failure region when this equality is exceeded or not. Using $Z<0$ as an integration limit, the probability of failure of a member is given as:

$$P_f = \int \dots \int_{g(\ )<0} f_x(x_1, x_2, \dots x_n) dx_1 dx_2 \dots dx_n$$

Computation of the Probability of failure P_f, using the above fundamental equation of reliability analysis, is called the full distributional approach. In the above integral, $f_x(x_1, x_2, \dots x_n)$ is the joint probability density function of the basic random variables$(X_1, X_2, \dots, X_n)$. Accurate estimation of the joint probability density function is a very complicated procedure and therefore indirect methods are often used. An equivalent term often preferred in the reliability methods is that of the reliability index that is expressed as follows:

$$P_f = \Phi(-\beta)$$

Where the notation Φ stands for the inverse cumulative distribution function of the standard normally distributed variable β.

Calculation of Structural Reliability

In order to simplify the integration process, Taylor series expansions can be employed in order to linearize the limit state functions. First and second order Taylor series approaches are employed, for the First and Second order reliability methods (FORM/SORM). FORM methods allow direct geometrical approximation of the reliability index as the closest distance between the limit state surface and the zero point of the normalized U-dimensional space following an iteration process. In cases where the limit state function is non linear, having large curvatures, or has multiple minimal distance points, First Order Reliability Methods may give inaccurate results. To overcome this problem, the Second Order Reliability Methods might be employed, using second order terms of Taylor expansion series. The geometrical interpretation of the SORM approximation is that the limit state function is approached by an asymptotic curve rather than a straight line.

Monte Carlo Simulations, also known as the simple random sampling method, is based on realizations of randomly generated sampling sets for uncertain variables. Following several iterations where stochastic variables are represented by random values and the probability calculation integral is approximated deterministically, the problem diminishes to calculation of the ratio between the realizations of the limit state inequality for the random sets of numbers over the total sampling number. The Monte Carlo Simulation method has the advantage that it can accommodate any type of random variable as long as the probability density function is known. Its disadvantage is that it demands large numbers of iterations for the numerical integration, making the method inefficient when very small values of probability of failure need to be estimated. Methods of biased selection of random numbers can partially overcome this increased demand in computational requirements.

Limit States of Floating Structures

General

Existing standards propose different limit states that should be considered in order to derive a comprehensive design of a structure. Both on a local (members-elements) and a global level, potential failure modes should be identified and corresponding limit states formulated in order to allow stochastic representation of the basic variables.

For a floating structure, two basic global limit states can be distinguished. Capsizing (or stability), is the equivalent of failure due to overturning for a fixed structure (push-over analysis), while mooring failure is equivalent to failure due to inadequate piling. In the following paragraphs, derivation of the two limit states will be described, considering excitation of the floating structure as an input to the calculation.

Capsizing-Stability Limit State

In order to perform a stability check for a floating structure, the basic degrees of freedom are shown in Figure 1.

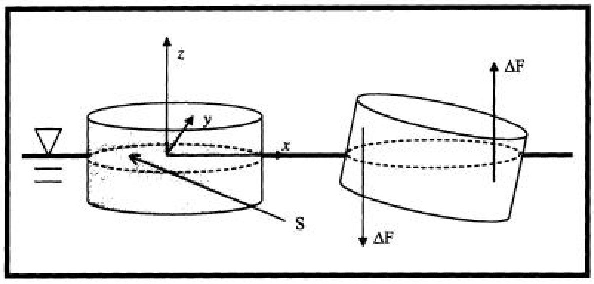

Fig. 1: Pitching of Floating Structure (Wayman, 2006)

The system's steady-state pitch, ξ_5, is determined by the steady-state moment exerted on the system in pitch, F_5, and the system's restoring properties in pitch, C_{55}, as given in the following equation:

$$\xi_5 = \frac{F_5}{C_{SS}} \rightarrow C_{SS} = \xi_5 \cdot F_5$$

For a HAWT, F_5 is the moment that the thrust force, F_{Thrust}, makes about the origin by exerting a force at the location of the (equivalent) hub, Z_{Hub}. For a VAWT usually the total overturning moment F_5 is the sum of the overturning moment and the thrust force (evaluated at the root of the rotor) multiplied by the height of the root of the rotor above the mean waterline.

Restoring the pitch moment is achieved through three general mechanisms as described above.

Restoring from a structure's waterplane area is provided by the moment of the structure's waterplane area about the structure's centre of rotation, which is assumed to coincide with the structure's coordinate system origin. Waterplane area moment about the x and y axes is given by the equations below:

$$M_{WP,y} = \iint x^2 ds \text{ and } M_{WP,x} = \iint y^2 ds$$

Where, S represents the water plane area surface when the structure is not offset in pitch or roll.

Simplifying the geometrical considerations, for the case of a cylindrical object:

$$M_{WP,R} = \frac{\pi . R^4}{4}$$

When the structure is perturbed in pitch, one side of the structure is submerged, and the other side is elevated from the water. The submerged side experiences an increase in buoyant mass, as a larger volume of water is displaced on that side, while the other side experiences the opposite response. These increases and decreases in buoyant mass result in increases and decreases in buoyant force, *ΔF*. The moment the waterplane area makes about the y axis determines the moment that results from these *ΔF* forces. This moment opposes the moment exerted on the body to displace it in pitch, and results in a restoring moment.

Accordingly, the restoring moment is given for 2D geometries.

$$M_{Restoring,WP,y} = \left(\rho \cdot g \iint x^2 ds\right) \sin \xi_5$$

$$M_{Restoring,WP,x} = \left(\rho \cdot g \iint y^2 ds\right) \sin \xi_4$$

Applying the principle of small angles:

$$M_{Restoring,WP,y} = \left(\rho \cdot g \iint x^2 ds\right) \xi_5$$

$$M_{Restoring,WP,x} = \left(\rho \cdot g \iint y^2 ds\right) \xi_4$$

For cylindrical cross sections:

$$M_{Restoring,WP,R} = p \cdot g \cdot \pi \cdot \frac{R^4}{4}$$

Restoring by ballast is achieved when enough ballast is added to the structure lowering the centre of gravity to a location below the centre of buoyancy. Restoring is then provided by the vertical separation between the structure's centre of gravity and the structure's centre of buoyancy. The restoring effect due to ballast then combines with the restoring effect of waterplane area to form hydrostatic and inertial restoring.

When the system is offset in pitch, the buoyant force acting on the centre of buoyancy creates a moment about the origin, and the gravitational force acting on the centre of gravity creates a moment in the opposite direction about the origin. For a freely floating structure, the gravitational force is equal to the buoyant force, and the vertical distance between the centre of buoyancy and the centre of gravity results in a net moment that has the tendency to restore the system to its vertical position when the system is offset in pitch. The combined hydrostatic and inertial restoring moment is given by the equation below.

$$M_{Restoring,ballast,x} = M_B \cdot g \cdot Z_{CB} \cdot \sin \xi_5 - M_G \cdot g \cdot Z_{CG} \cdot \sin \xi_5 + \left(\rho \cdot g \iint x^2 d5\right) \sin \xi_5$$

Where M_G, M_B, Z_{CG}, Z_{CB} represent, respectively, the gravitational and displaced masses, the centre of gravity, and the centre of buoyancy.

Using the small angle approximation:

$$M_{Restoring,ballast} = \left(M_B \cdot g \cdot Z_{CB} - M_G \cdot g \cdot Z_{CG} + \rho \cdot g \iint x^2 ds\right) \cdot \xi_5$$

Considering that the structure should be able to float by itself, as a certification requirement, the effect of moorings will be neglected for this stability check. Therefore the total restoring moment and restoring coefficient expressed analytically as:

$$M_{Restoring} = \left(M_B \cdot g \cdot Z_{CB} - M_G \cdot g \cdot Z_{CG} + \rho \cdot g \cdot \iint x^2 ds\right) \cdot \xi_5$$

$$C_{ss,min} = C_{55} = \left(M_B \cdot g \cdot Z_{CB} - M_G \cdot g \cdot Z_{CG} + \rho \cdot g \cdot \iint x^2 ds\right)$$

For the simplified case of a hollow cylindrical cross-section:

$$C_{55} = M_B \cdot g \cdot Z_{CB} - M_G \cdot g \cdot Z_{CG} + \rho \cdot g \cdot \pi \cdot \frac{R^4 - r^4}{4}$$

The limit state function derived is:

$$C(X) = C_{55} - C_{55,min}$$

The zones derived by the limit state function are:

- $C(X) > 0$ Failure Region
- $C(X) < 0$ Safe Region
- $C(X) = 0$ Critical Region

In the following section, a numerical example for the calculation of reliability based on the limit state is presented, including the consideration of all relevant random variables.

Mooring Failure Limit State

Following the same procedure, the limit state of the mooring line failure is formed as the function of the difference between the resistance of the mooring line (allowable stress) and the actual stress towards the length of the line. Definition of the problem is presented in Figure 2, considering the unit length weight of the line with *q*, the total length *S* and a set of forces that account for the excitation from the floating structure F_x and F_y. For reasons of simplicity, the contribution of the current and lateral stiffness to the response of the mooring line has been neglected; however it can be easily considered applying a horizontal distributed shear load and taking into account the added mass and other relevant fluid effects.

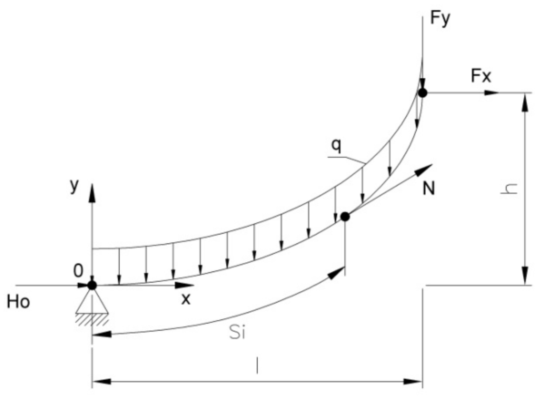

Fig. 2: Mooring Chain Definition

Based on fundamental equilibrium equations an expression of the actual stress can be derived as follows:
Equilibrium from *O* to *A*:

$$\sum F_x = 0 \rightarrow H_o + F_x = 0$$
$$\sum F_y = 0 \rightarrow F_y - s \cdot q = 0$$
$$\sum M_o = 0 \rightarrow F_x \cdot h + F_y \cdot l + s \cdot q \cdot \frac{s^*}{2} = 0$$

Where, s^* is the projection of *s* to the *x*-axis.
Equilibrium from *O* to *P*:

$$\sum F_x = 0 \rightarrow H_o + N \cdot cos\theta = 0$$
$$\sum F_y = 0 \rightarrow N \cdot sin\theta - s_i \cdot q = 0$$

Where, s_i is the inverse of x function towards *s* direction. In order to express s^* to $s = f(x)$:

$$tan\,\partial = \frac{qs}{H} = \frac{dy}{dx}$$
$$x = \frac{Ho}{q} \cdot ln \cdot \left(\frac{qs}{Ho} + \left(1 + \left(\frac{qs}{Ho}\right)^2\right)^{1/2}\right)$$

Solving for *s*, using approximate integration:

$$s_i = \frac{Ho}{q} \cdot \left(\frac{e^{qx/Ho} - e^{-qx/Ho}}{2}\right)$$
$$y(x) = \frac{Ho}{q} \cdot \left[\frac{e^{qx/Ho} + e^{-qx/Ho}}{2} - 1\right]$$
$$\sum M_o = 0 \rightarrow$$
$$N \cdot cos\theta \cdot y - N \cdot sin\theta \cdot x + s_i \cdot q \cdot \frac{x}{2} = 0$$

s_i can be expressed as *f(x)* and therefore axial force can be derived as a function of the location on the mooring line, *N(x,y)*. The maximum value of N, will obviously occur in the location where $x=x_{max}$ and $y=y_{max}$.

The corresponding limit state function is formed as:

$$N_{max} - N_{all} < 0$$

Values for N_{all} can be derived from handbooks and standards, mainly as a function of the diameter of the mooring line (DNV, 2008b). In a stochastic consideration of loads, input into the limit state function should be the length and diameter of the mooring line, and the forces imposed from the floating structure, as a function of the external excitation which should account for the wind and wave loads as well as the rotational loads of the VAWT.

Example of Reliability Calculation for the Stability Limit State

As discussed above, once the limit state equations have been formulated, the next step for the calculation of the probability of failure integral is to define stochastically the participating variables. Table 1 presents those variables and the values used. A normal distribution is selected since most of the variables are geometrical. The excitation has been calculated based on the characteristics of the VAWT (considering thrust force and overturning moment), and using the response surface method, it can be expressed as a second order polynomial function of the basic variable which is the wind speed as:

$$C_{55} = 1670401 \cdot V_s^2 - 0.0456 \cdot V_s + 0.334$$

Table 1: Stochastic modeling of design variables for the stability limit State (Normal Distribution)

Variable	Mean Value	Standard Deviation	Unit
v_s	15.0	5.0	m/sec
F_B	343138.8	0	kN
Z_{CB}	9.0	0	M
M_{tot}	34498.0	1400.0	tn
g	9.8	0	m/sec^2
Z_{CG}	-9.0	0	M
ρ	1025.0	55.0	kg/m^3
R	35.6	1.0	M
r	25.9	1.0	M

The simulation was executed using commercial software DNV SESAM PROBAN to derive the values of the reliability index. Both deterministic, FORM/SORM and simulation methods (Axis-orthogonal) were used and the results are presented in Table 2. Due to the simplicity of the limit state function, sufficient matching of the results was expected and can been observed. Figure 3, presents a chart with the important factors of the case examined. The contribution of the inner and outer radius dimensions is seen to dominate the determination of the reliability index values.

Table 2: Results of calculation of Reliability Index *β* and Probability of Failure P_f

Method	*β*	P_f
FORM	6.8526	3.6272×10^{-12}
SORM	6.8074	4.9696×10^{-12}
Axis Orthogonal Sim.	6.8172	4.6416×10^{-12}

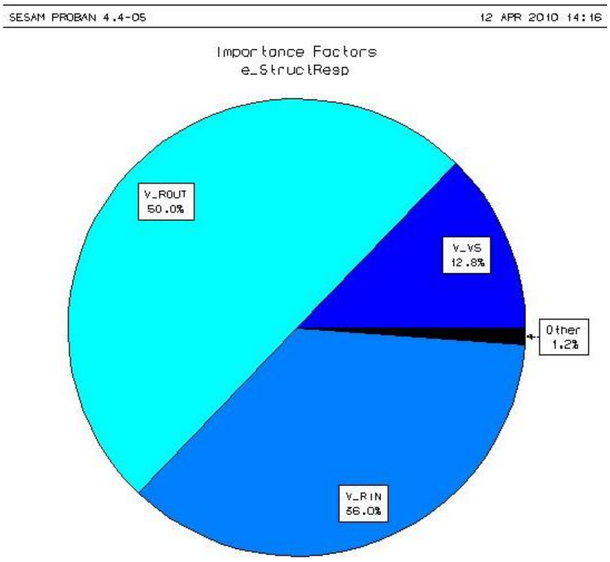

Fig. 3: Importance Factors of the variables on the calculation of the reliability index

Dynamics of an offshore floating support structure for a VAWT

Coupled Model of Dynamics for HAWT

A review of the research concerning the development of offshore wind turbines revealed several dynamic models to describe the coupled aero-hydro-servo-elastic behavior of floating HAWTs. A simple approach based on Wayman (2006) and Wayman et al. (2006b) proposes a methodology that consists of the following steps:

- the body mass matrix of the wind turbine (including the rotor, the nacelle, the drive train and the tower) is added to the body mass matrix of the floating structure,
- rotor damping and restoring matrices, due to the aerodynamics and to gyroscopic effects, are added to the hydrostatic and hydrodynamic restoring and damping matrix of the floating structure,
- the influence of the mooring system is taken into account estimating a mean offset displacement, and in this state the linearized restoring coefficient are added to the global restoring matrix
- the aeroelasticity of the rotor is ignored

Utilizing a frequency domain analysis, the aim of the dynamic optimization is to demonstrate that the Response Amplitude Operator (RAO) peaks of this coupled system do not overlap with the wave spectrum of the operational site, and therefore the wave response of the whole structure is minimized.

This frequency domain linear analysis is not able to take into account transient loads and/or nonlinear dynamic characteristics, factors influencing the turbine analysis, and new, more advanced approaches that have been proposed (Jonkman, 2007; Henderson and Patel, 2003).

Coupled Model of Dynamics for VAWT

Currently, a coupled model for the dynamics of floating VAWT systems has not been developed to the same extent. Given that this is the case, a similar approach is proposed in this paper. With regard to the purpose of the present work, the aim is to calculate the heel angle as a function of the environmental variables linked to the wind and wave loading and assessing the probability that the heel angle will not exceed a predetermined maximum allowable value.

To calculate the static and dynamic heel angle (θ) of VAWT floating systems some important differences with respect to the HAWT have to be considered. Regarding the static heel angle, a seawater ballast tank control system can be considered, able to counteract the constant fraction of the overturning moment: in this case the static heel angle can be considered equal to zero. Nevertheless, load cases with a failure of the control ballast tank system should be considered, therefore in general the static heel angle (θ_s) is not equal zero.

Regarding the dynamic heel angle due to aerodynamic forces, for a given wind direction and speed U, the thrust and the overturning moment acting on VAWTs is not constant, but oscillates varying the azimuth angle (horizontal angle between a rotating body axis system and a fixed horizontal direction), according to the rotational speed of the rotor. If F_1 is the thrust force and F_5 is the overturning moment (these are a function of the wind speed U and the azimuth angle φ) then the resulting heel angle oscillation due to the aerodynamic F_1 and F_5 is a function of U and φ.

The dynamic angle due to hydrodynamic forces (waves), in the frequency domain linear analysis depends on the frequency (ω) and on the amplitude (A) of the incoming wave, and can be calculated estimating the pitch/roll RAOs of the wind turbine-floating structure coupled system.

Therefore the heel dynamic angle function can be written as:

$$\theta = \theta_o + \theta_{hyd}(A, \omega) + \theta_{aer}(U, \varphi)$$

where θ_0 is the static heel angle, θ_{hyd} is the dynamic angle due to hydrodynamic forces, and θ_{aer} is the dynamic angle due to aerodynamic forces.

Coupled Dynamics and Reliability

Following these considerations, the calculated value for the heel dynamic angle, will act as an input to the two limit states. For the stability-capsizing check, it will control the value of ξ_5, while for the mooring line limit state, it will determine the relative down force applied by the moorings (F_x, F_y).

Conclusions

In this paper, the consideration of the global reliability of floating support structures for Vertical Axis Wind Turbines has been discussed. After a review of the background literature concerning VAWTs, the available floating support structures concepts and fundamentals on structural reliability, limit states for stability check as well as failure of mooring lines have been explicitly derived. A numerical example for the determination of the reliability of a simplified, cylindrical floating structure has been presented and solved by deterministic and simulation methods. Finally, the issue of coupling the aero-hydro-servo-elastic induced dynamics of a VAWT system and its interaction with reliability estimation has been discussed and a simplified model proposed.

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