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## GLOBAL LIMIT STATES FOR THE DESIGN OF FLOATING WIND TURBINE SUPPORT STRUCTURES

**Mareike Leimeister**

Research associate, Fraunhofer IWES, Bremerhaven, Germany  
REMS EngD Fellow, Cranfield University, Cranfield, Bedfordshire, UK  
[mareike.leimeister@iwes.fraunhofer.de](mailto:mareike.leimeister@iwes.fraunhofer.de)

### ABSTRACT

**Reliability is an essential parameter for offshore wind turbines which are located some distance from the coast in mostly quite harsh environments. Limited weather windows for maintenance and repair work indicate the relevance for using reliability-based methods during the design process of wind turbine structures. This is even more crucial but also more challenging for floating devices due to the highly complex system dynamics and interactions. In this work, the use of global limit states for the design of floating support structures is elaborated. Reliability criteria which are essential for floating wind turbine systems are selected and their critical values are defined. Based on these, the global limit state functions can be set up. Furthermore, the dependencies and predefined boundary conditions of the parameters for the design of floating support structure have to be worked out, so that the modifiable variables can be identified and their effect on the global limit state functions and reliability criteria analysed. This study should serve as basis for developing a reliability-based optimisation tool for the design of floating wind turbine support structures, which uses global limit states and could be extended to consider local characteristics as well.**

### NOMENCLATURE AND ABBREVIATIONS

$D_R$	= Rotor diameter (m)
DLC	= Design Load Case
$g$	= Gravitational acceleration ( $\text{ms}^{-2}$ )
NREL	= National Renewable Energy Laboratory
OC3	= Offshore Code Comparison Collaboration
SWL	= Still Water Level

### INTRODUCTION

High and consistent winds, little restrictions regarding noise emissions and size permissions, and being beyond the range of vision are advantages of offshore wind energy over onshore. The challenge of deep but promising sites, which many countries have to face in association with offshore wind energy, can be overcome by utilising floating wind turbine systems. However, coupled motions, complex system dynamics, wave and current loads, as well as additional components for example for station-keeping, place high demands on the structure and entire floating systems. This is reinforced by the quite harsh offshore environment which only leaves certain limited weather windows for maintenance and repair work. Thus, any failure of the floating wind turbine system could cause long production downtimes and economic losses.

For this reason, reliability-based design methods can be of great benefit for floating wind turbine systems. Thus, the aim of this work is to elaborate reliability criteria and global limit state functions for the design of floating wind turbine support structures. The approach was kept deliberately simple at the first stage, so that it can be used afterwards for developing a reliability-based design optimisation tool which could further serve as basis for well-founded development of a more sophisticated optimisation tool that considers local criteria. In this paper, first, the methodology is shortly introduced. Afterwards, the results for the chosen reference framework and determined criteria and parameters are presented. Finally, a short conclusion outlines and critically evaluates the findings.

## METHODOLOGY

As this study should serve as basis for developing a reliability-based design optimisation tool for floating wind turbine support structures, an entire reference framework is set up. This comprises the floating wind turbine system, as well as the system parameters which are elementary for the design concept. Furthermore, the reliability criteria, on which basis the global limit state functions are defined, are selected. Additionally, a reference load case for testing the performance of the floating wind turbine system especially with respect to the chosen reliability-criteria is specified.

## RESULTS

### Floating Wind Turbine System

For the floating offshore wind turbine system, the Hywind spar-buoy concept from OC3 (Offshore Code Comparison Collaboration) phase 4 [1] is chosen. The spar consists of two cylindrical elements with one tapered part between them and is partially filled with ballast. The floating platform carries the upwind, three-bladed NREL (National Renewable Energy Laboratory) 5MW wind turbine [2] with an offshore adapted tower and modified control system. The entire floating system is moored with three evenly spaced catenary lines to the seabed. Some main properties of this offshore wind turbine system are presented in Table 1. Elevations are given as distance above the still water level (SWL), while depths are specified as distance below SWL.

**Table 1.** Properties of the spar-buoy floating wind turbine system from OC3 phase 4 [1,2]

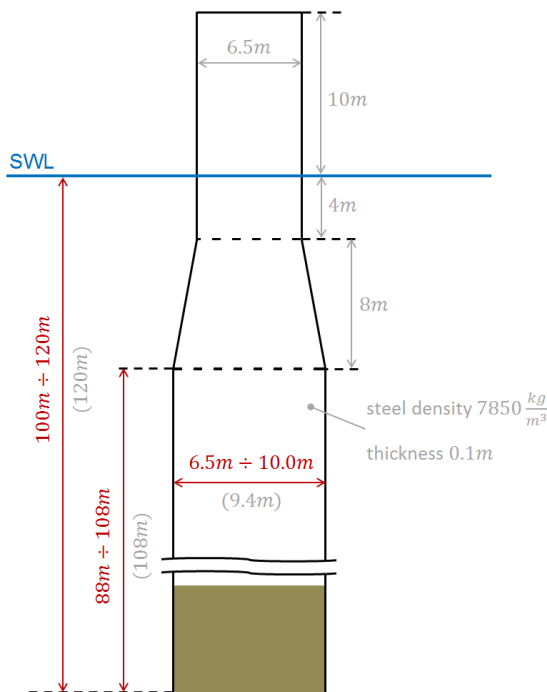
Part	Parameter	Value
Rotor-nacelle assembly	Rotor diameter	126.0m
	Hub height	90.0m
	Mass	350,000kg
	Cut-in, rated, cut-out wind speed	$3.0 \frac{m}{s}$ , $11.4 \frac{m}{s}$ , $25.0 \frac{m}{s}$
Tower	Top elevation, diameter, thickness	87.6m, 3.87m, 0.019m
	Base elevation, diameter, thickness	10.0m, 6.5m, 0.027m
	Mass	249,718kg
Floater	Top elevation, diameter	10.0m, 6.5m
	Depth range of taper	4.0m to 12.0m
	Base depth, diameter	120.0m, 9.4m
	Mass (including ballast)	7,466,330kg
Mooring system	Fairleads depth, radius from centerline	70.0m, 5.2m
	Anchors depth, radius from centerline	320.0m, 853.87m
	Mooring line length (unstretched), diameter	902.2m, 0.09m

### Design Parameters

As the purpose of this work is reliability-based design of a floating wind turbine support structure, the modifiable parameters relevant to the design concept have to be defined. The focus lies on the floating platform, meaning that wind turbine (tower and rotor-nacelle assembly) and station-keeping system remain unchanged, while some of the floater design parameters are free to be altered.

#### Geometric Design Parameters

Geometric parameters are diameters, thicknesses, and lengths of the floater parts. Top diameter and elevation should retain their original values to ensure that the floater top fits the tower base and the hub height remains the same. Furthermore, the total length of the top cylindrical part and the taper length are kept as well, to avoid significant changes in wave impact effects on the upper part of the structure. Thus, the top of the bottom cylindrical part remains at 12m below SWL. However, length and diameter of the bottom cylindrical part are chosen to be the two modifiable geometric design parameters, as it is also intended to decrease the outer dimensions while still fulfilling reliability criteria without losing performance. The lower bound for the base diameter is prescribed by the diameter of the upper cylindrical part. The current base diameter is 9.4m (Table 1). Not aiming for significant larger dimensions, the maximum tolerated value for the base diameter is set equal to 10m. To allow a reduction in the total length by up to 20m, corresponding to a total draft of just 100m, the range for the height of the bottom cylindrical part is defined between 88m and 108m. Finally, as structural integrity checks are not performed at this stage, the wall thickness of the floater is fixed at a conservative value of 0.1m. Figure 1 schematically shows the fixed and modifiable parameters of the floating support structure.



**Figure 1.** Schematic of the fixed/original (grey) and modifiable (red) parameters of the spar-buoy.

### Ballast Design Parameters

Modified geometric parameters imply changed structural mass, displaced water volume, and resulting buoyancy. To maintain the hub height and hence the 10m elevation of the floater top, but also to allow for a variable center of mass, influencing the system performance and affecting the reliability criteria, ballast amount and density are set as modifiable. The required ballast mass is determined from the chosen geometric design parameters and predefined dimensions. For the ballast density range it is decided to make use of common and cheap materials, such as sand with a density range from around  $1281 \frac{kg}{m^3}$  to  $2082 \frac{kg}{m^3}$  depending on the water content [3], concrete with a density between  $1750 \frac{kg}{m^3}$  and  $2400 \frac{kg}{m^3}$  [4], or other rocks like sandstone with a density of  $2600 \frac{kg}{m^3}$  [5]. Thus, the ballast density range is chosen to be between  $1281 \frac{kg}{m^3}$  and  $2600 \frac{kg}{m^3}$ . With a selected density, the ballast height can be calculated from the required ballast mass. Then it has to be checked that the computed value lies within 0m and the height of the bottom cylindrical part. If this is not the case, another density has to be selected until the height criterion is fulfilled.

### Global Limit States

System rotational stability, translational displacements, and nacelle acceleration make up the reliability criteria used for setting up the global limit state functions. Their descriptions and critical values are given hereinafter.

#### System Rotational Stability

The stability criterion is represented by the maximum combined rotation angle. Based on conventional values [6,7], the maximum allowable total inclination is set equal to  $10^\circ$ .

#### Translational Displacements

Floating wind turbines should not drift too far away from their initial position. This becomes especially relevant within a wind farm. Due to the fact that the spar-buoy is moored with catenary lines, translational motion restrictions are not as stringent as they are for tension leg platforms which use tendons for station-keeping, elaborated in [8]. There are no specific limits for translational displacements of a floating spar-type wind turbine available; however, Johnson [9] assesses three and eight rotor diameters ( $D_R$ ) as credible minimum spacing between turbines in a row and rows in a wind farm, respectively. Furthermore, he determined the average turbine spacing in a region in the middle of the United States to be  $4D_R$  crosswind and  $10D_R$  downwind. Even if these values are just based on one local study on onshore wind farms, this information is used for specifying the upper limits for translational motions of the floating wind turbine. Considering only one turbine moving, this would leave an allowable displacement of  $1D_R$  in sway and  $2D_R$  in surge direction. However, it is more realistic if both turbines in a row or line move in the same direction, but maybe with a different amount. Worst case on the other hand is motion in different directions, which would then require half of the tolerated displacement, thus  $0.5D_R$  in sway and  $1D_R$  in surge direction. With the NREL 5MW turbine, having a rotor diameter of  $D_R = 126m$  [2], the most conservative approach yields an allowable motion of 63m in sway and 126m in surge direction. Despite the more realistic assumption of  $1D_R$  crosswind and  $2D_R$  downwind motion for the boundaries, the more conservative values of 63m and 126m are taken as limit states for the sway and surge displacements, because of the not equivalent and insufficient information on which those numbers are based.

#### Nacelle Acceleration

As the nacelle contains sensitive components such as gearbox, generator, and bearings, its motion has to be restricted. A commonly used upper bound for the nacelle acceleration is  $0.2g$  [10], corresponding to  $\approx 1.962 \frac{m}{s^2}$ .

## Design Load Case

In order to analyse wind turbine system performance and evaluate global limit state parameters, at least the design load cases (DLCs) defined in the IEC standard 61400-3 [11] have to be considered in general. However, as not every DLC is relevant for the specific reliability criteria and with respect to the computational effort and time in a subsequent optimisation process, it is decided to specify one most critical DLC. The choice is based on the following approach:

- First, all DLCs given in [11, p. 36-38] are simulated for the reference floating wind turbine system. As the reliability criteria focus on global extreme system behaviour without considering structural loads and integrity, the DLCs defined for fatigue analysis can directly be excluded and only the DLCs for ultimate loads used.
- All simulated DLCs are evaluated regarding the selected reliability criteria. Based on this, the DLC(s) yielding the most critical results are determined.
- If all reliability criteria are most critical in one and the same DLC, this load case is directly taken. However, if different DLCs yield the most critical reliability criteria, an appropriate DLC combining all these worst load case conditions is defined and used for the subsequent analysis.

## CONCLUSIONS

The proposed methodology for reliability-based design of a floating wind turbine support structure, using global limit states, has to be seen as initial simple approach towards design optimisation. One has to keep in mind that structural integrity is not yet monitored and assumptions, such as the wall thickness value, have to be verified. Additionally, system design changes will affect the performance and response, and may require adaption of the controller, which is especially relevant for floating systems. Further design parameters may be added to meet the reliability criteria; for example a modified mooring system could restrict large translational motions, while other or more parameters would need to be specified for a different floating wind turbine system considered. Furthermore, a sensitivity analysis on the impact of the design parameter constraints on the overall design has to be included. Finally, the suitability and representative nature of the defined DLC have to be validated. Nevertheless, the presented approach can directly be used to develop a reliability-based design optimisation tool, which, in turn, could serve as basis for a more advanced tool including local limit states.

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