Coupled analysis of floating wind turbines
FOREWORD

DNV GL recommended practices contain sound engineering practice and guidance.

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CHANGES – CURRENT

This is a new document.
Acknowledgement

This recommended practice is prepared based on results from the joint industry project *Coupled analysis of floating wind turbines*. In addition to their financial support, the companies below (list sorted in alphabetical order) are also acknowledged for their technical contributions through their participation in the project.

— Atkins
— Dr. Techn. Olav Olsen
— EDF
— Esteyco
— GICON®
— Glosten
— Ideol
— MARIN
— National Renewable Energy Laboratory (NREL)
— NAUTILUS Floating Solutions
— Ramboll
— SINTEF Ocean
— STX Solutions Europe
— UNICAN.
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SECTION 1 GENERAL

1.1 Introduction
This recommended practice (RP) gives guidance for modelling, load analysis and model testing of floating offshore wind turbines (FOWT). The RP is based on state of the art of modelling and load analysis of FOWT. The joint industry project (JIP) Coupled analysis of floating wind turbines has provided valuable input to the RP. The RP shall be read in conjunction with other standards such as DNVGL-ST-0437 for wind turbine loads and DNVGL-ST-0119 for design of FOWT structures.

1.2 Objective
This recommended practice specifies general principles and methods for the analysis of FOWTs, to be used in combination with the referenced standards. The objectives of this recommended practice are to:

— provide an internationally acceptable set of recommendations that fulfil the requirements of the referenced standards for the analysis and the design of FOWTs
— serve as a reference document between project stakeholders, to agree and align the methods for the design and the analysis of FOWTs
— serve as a guideline for designers, suppliers, purchasers and regulators
— specify procedures and methods for the analysis of FOWTs subjected to DNV GL certification
— serve as a guidance for planning and execution of ocean basin tests, having the purpose of calibrating and validating numerical models.

1.3 Scope
This document states recommendations for the following:

— analysis approach
— environmental conditions, models and parameter selection
— numerical models
— design load cases setup
— controller implementation
— model testing and numerical model validation.

The recommend practice considers different stages of the design:

— conceptual design
— prototype design
— site type design
— offshore wind farm design (project certification).

The recommended practice does not give specific recommendations for dynamic cable and anchor analysis. Definition and requirements for the certification of these design stages are given in DNVGL-SE-0422.

1.4 Application
The objective is to provide recommended practice for global analysis of floating offshore wind turbines, including substructures, and of separate components, i.e. wind turbine, floater and station keeping system. This recommended practice is applicable to the design of floating wind turbines with the following types of foundation;
- spar
- semi-submersible
- barge
- tension leg platform.

1.5 References
The DNV GL documents listed in Table 1-1 and Table 1-2 and the recognized codes and standards in Table 1-3 are referred to in this recommended practice.

Table 1-1 DNV GL standards and guidelines

<table>
<thead>
<tr>
<th>Document code</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNVGL-OS-E301</td>
<td>Position mooring</td>
</tr>
<tr>
<td>DNVGL-SE-0422</td>
<td>Certification of floating wind turbines</td>
</tr>
<tr>
<td>DNVGL-ST-0119</td>
<td>Floating wind turbine structures</td>
</tr>
<tr>
<td>DNVGL-ST-0361</td>
<td>Machinery for wind turbines</td>
</tr>
<tr>
<td>DNVGL-ST-0437</td>
<td>Loads and site conditions for wind turbines</td>
</tr>
<tr>
<td>DNVGL-ST-0438</td>
<td>Control and protection systems for wind turbines</td>
</tr>
<tr>
<td>DNV GL Technical note</td>
<td>Certification of Wind Turbines for Tropical Cyclone Conditions</td>
</tr>
</tbody>
</table>

Table 1-2 DNV GL recommended practices

<table>
<thead>
<tr>
<th>Document code</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNVGL-RP-C205</td>
<td>Environmental conditions and environmental loads</td>
</tr>
<tr>
<td>DNVGL-RP-F205</td>
<td>Global performance analysis of deepwater floating structures</td>
</tr>
<tr>
<td>DNVGL-RP-N103</td>
<td>Modelling and analysis of marine operations</td>
</tr>
</tbody>
</table>

The documents in Table 1-1 and Table 1-2 include requirements, acceptable methods and useful guidance to supplement the contents of this recommended practice.

1.6 Definitions and abbreviations

1.6.1 Definition of terms

Table 1-3 Definition of terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>accidental limit states</td>
<td>survival conditions in a damaged condition or in the presence of strongly nonlinear environmental conditions</td>
</tr>
</tbody>
</table>
| anchor                     | a structural device to transfer forces from mooring lines or tendons to seabed soils or rock For anchors attached to mooring lines, the anchor is rationalized as the anchor itself plus the embedded part of the mooring line.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>barge</td>
<td>Adopted expression from maritime vessel types for cargo hold and no means of self-propulsion. Herein a barge is a free-surface stabilized structure for carrying the wind turbine. It characterised by a large water plane area and relatively small draught.</td>
</tr>
<tr>
<td>catenary</td>
<td>mooring configuration that provides a restoring force mostly through the weight of the system. Typical shape of mooring line is free hanging. The catenaries are hanging horizontally at the seabed.</td>
</tr>
<tr>
<td>column-stabilized</td>
<td>a structure dependent on buoyancy of widely spaced columns for floatation and stability</td>
</tr>
<tr>
<td>deep water</td>
<td>characterized by wavelengths shorter than about twice the water depth</td>
</tr>
<tr>
<td>design life</td>
<td>the period of time over which the wind turbines, floating support structure and its station-keeping system is designed to provide an acceptable minimum level of safety</td>
</tr>
<tr>
<td>fatigue limit states</td>
<td>related to the possibility of failure due to the cumulative damage effect of cyclic loading</td>
</tr>
</tbody>
</table>
| floating offshore wind turbine | term used for the entire system consisting of wind turbine, floating support structure and station keeping system  
A system of two or more wind turbines mounted on the same floater is rationalised as one floating wind turbine unit. |
<p>| heel                | a tilt, as of a boat, to one side. Heel is used here in the context of wind heeling when floating stability is the issue.                     |
| high frequency      | frequency band relating to fast-varying responses with frequencies above the typical wave frequency range. Examples include ringing and springing responses in TLPs. |
| hub height          | height of centre of swept area of wind turbine rotor, measured from mean water level (MWL), see DNVGL-ST-0126                                   |
| lock-off tension    | the pre-stressing load transferred into a rock anchor immediately following proof-loading of the anchor. The lock-off tension is the permanent tensile lock-off load that a prestressed rock anchor will be subject to before hook-up of any tendon or mooring line. |
| low frequency       | frequency band relating to slowly varying responses with frequencies below the typical wave frequency range. Examples of such slowly varying responses include slowly varying surge and sway motions of column-stabilized and ship-shaped units and slowly varying roll and pitch motions of deep draught floaters. |
| Mathieu instability | a type of instability which is caused by coupling between the heave and pitch motions. MI typically occurs as the result of large heave motion if the natural period of a heave motion comes close to or equals half the natural period of pitch, causing the pitch motion to increase significantly. |
| mean water level    | long-term average water level, i.e. the arithmetic mean of all sea levels measured over a long period                                           |
| misalignment        | designates that the wind and the waves at a given point in time and space are not co-directional, i.e. they act or propagate in different directions. Misalignment is also used as a term for the deviation between the mean wind direction and the rotor axis. |</p>
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
</table>
| mooring line                  | strong slender line, such as chain, rope or wire, in catenary and taut mooring systems of floating units  
Note that tendons used for tension leg platforms are not referred to as mooring lines. |
| mooring system                | system made up of mooring lines, anchors and connectors, used for station keeping of a floating structure                                  |
| redundancy                    | the ability of a component or system to maintain or restore its function after a failure of a member or connection has occurred  
Redundancy may be achieved for instance by strengthening or introducing alternative load paths. For example, if one mooring line in a mooring system is lost and the remaining part of the mooring system meets the ALS criterion, which is survival for at least a one-year load, then the initial undamaged mooring system is said to be redundant. |
| return period                 | the average time between two events characterized by a given magnitude  
Measured in number of years, the return period is the inverse of the annual probability of exceedance of an event such as the occurrence of a wave height, i.e. a 50 year wave height has a 2% probability of being exceeded in any one year. |
| ringing                       | high-frequency transient resonant structural response due to higher-order wave loads                                                                 |
| semi-submersible              | a buoyancy and free-surface stabilized structure with a relatively shallow draught  
A number of large columns are linked to each other by bracings. The columns provide the ballast and flotation stability (column-stabilized). |
| serviceability limit states   | disruption of normal operations due to deterioration or loss of routine functionality, e.g. exceedance of normal operation criteria  
The SLS imply deformations in excess of tolerance without exceeding the load-carrying capacity, i.e., they correspond to tolerance criteria applicable to normal use and durability. Unacceptable deformations and excessive vibrations are typical examples of the SLS. |
| shallow water                 | waters characterized by wavelengths greater than 10 times the water depth                                                                  |
| spar                          | a weight-buoyancy stabilized structure with a relatively large draught compared to barges, semi-submersibles and TLPs  
A spar can consist of multi-vertical columns or a single column with or without moonpool (e.g. classic, truss and cell spar). |
| springing                     | high-frequency stationary resonant structural response due to sum-frequency wave loads                                                                 |
| station keeping system        | system to maintain a floating structure in a fixed position relative to a fixed point or within a defined sector relative to the fixed point  
The station keeping system includes the mooring lines or tendons, as applicable, as well as the anchor foundations that transfer forces from the system to the seabed. |
| still water level             | average water surface elevation at any instant, excluding local variations due to waves, but including the effects of tides and storm surges |
| support structure             | term denoting the support structure of a wind turbine, i.e. the tower, the substructure, the foundation for bottom-fixed substructures and the station-keeping system for floating substructures, but excluding the wind turbine (the rotor-nacelle assembly) itself |
| tendon                        | structural component used as part of the station-keeping system for a TLP, also referred to as tether                                           |
| tension leg platform          | a vertically moored floating structure whose station keeping system consists of tenders or tendons anchored at the seabed |
### 1.6.2 Verbal forms

**Table 1-4 Definition of verbal forms**

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>shall</td>
<td>verbal form used to indicate requirements strictly to be followed in order to conform to the document</td>
</tr>
<tr>
<td>should</td>
<td>verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others</td>
</tr>
<tr>
<td>may</td>
<td>verbal form used to indicate a course of action permissible within the limits of the document</td>
</tr>
</tbody>
</table>

### 1.6.3 Abbreviations

Abbreviations as given in **Table 1-5** are used in this offshore standard.

**Table 1-5 Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALS</td>
<td>accidental limit state</td>
</tr>
<tr>
<td>API</td>
<td>American petroleum institute</td>
</tr>
<tr>
<td>BEM</td>
<td>blade element momentum</td>
</tr>
<tr>
<td>CFD</td>
<td>computational fluid dynamics</td>
</tr>
<tr>
<td>COG</td>
<td>centre of gravity</td>
</tr>
<tr>
<td>DAE</td>
<td>differential-algebraic-equation</td>
</tr>
<tr>
<td>DEL</td>
<td>damage equivalent load</td>
</tr>
<tr>
<td>DLC</td>
<td>design load case</td>
</tr>
<tr>
<td>DLL</td>
<td>dynamic link library</td>
</tr>
<tr>
<td>DOF</td>
<td>degrees of freedom</td>
</tr>
<tr>
<td>DP</td>
<td>design position</td>
</tr>
<tr>
<td>EOG</td>
<td>extreme operating gust</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>ESS</td>
<td>extreme sea state</td>
</tr>
<tr>
<td>EWM</td>
<td>extreme wind speed model</td>
</tr>
<tr>
<td>FE</td>
<td>finite element</td>
</tr>
<tr>
<td>FEM</td>
<td>finite element method</td>
</tr>
<tr>
<td>FLS</td>
<td>fatigue limit state</td>
</tr>
<tr>
<td>FOWT</td>
<td>floating offshore wind turbine</td>
</tr>
<tr>
<td>GDW</td>
<td>generalized dynamic wake</td>
</tr>
<tr>
<td>GM</td>
<td>metacentric height</td>
</tr>
<tr>
<td>GML</td>
<td>longitudinal metacentric height</td>
</tr>
<tr>
<td>GMT</td>
<td>transverse metacentric height</td>
</tr>
<tr>
<td>HF</td>
<td>high frequency</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td>IPC</td>
<td>individual pitch controller</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization of Standardization</td>
</tr>
<tr>
<td>JIP</td>
<td>joint industry project</td>
</tr>
<tr>
<td>JONSWAP</td>
<td>joint north sea wave project</td>
</tr>
<tr>
<td>KC</td>
<td>Keulegan–Carpenter number</td>
</tr>
<tr>
<td>LF</td>
<td>low frequency</td>
</tr>
<tr>
<td>LHS</td>
<td>latin hypercube sampling</td>
</tr>
<tr>
<td>LQG</td>
<td>linear quadratic gaussian</td>
</tr>
<tr>
<td>MI</td>
<td>Mathieu instability</td>
</tr>
<tr>
<td>MIMO</td>
<td>multi-input multi-output</td>
</tr>
<tr>
<td>MPC</td>
<td>model predictive control</td>
</tr>
<tr>
<td>MSL</td>
<td>mean sea level</td>
</tr>
<tr>
<td>MWL</td>
<td>mean water level</td>
</tr>
<tr>
<td>NMP</td>
<td>non-minimum phase</td>
</tr>
<tr>
<td>NSS</td>
<td>normal sea state</td>
</tr>
<tr>
<td>OWF</td>
<td>offshore wind farm</td>
</tr>
<tr>
<td>PID</td>
<td>proportional-integral-differential control algorithm</td>
</tr>
<tr>
<td>QTF</td>
<td>quadratic transfer function</td>
</tr>
<tr>
<td>R</td>
<td>restrained</td>
</tr>
<tr>
<td>RAO</td>
<td>response amplitude operator</td>
</tr>
<tr>
<td>RNA</td>
<td>rotor nacelle assembly</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>RP</td>
<td>recommended practice</td>
</tr>
<tr>
<td>SISO</td>
<td>single-input single-output</td>
</tr>
<tr>
<td>SLS</td>
<td>serviceability limit states</td>
</tr>
<tr>
<td>SSS</td>
<td>severe sea state</td>
</tr>
<tr>
<td>SWL</td>
<td>still water level</td>
</tr>
<tr>
<td>TLP</td>
<td>tension leg platform</td>
</tr>
<tr>
<td>TSR</td>
<td>tip speed ratio</td>
</tr>
<tr>
<td>ULS</td>
<td>ultimate limit state</td>
</tr>
<tr>
<td>VP</td>
<td>verification position</td>
</tr>
<tr>
<td>VIM</td>
<td>vortex induced motions</td>
</tr>
<tr>
<td>VIV</td>
<td>vortex induced vibrations</td>
</tr>
<tr>
<td>WF</td>
<td>wave frequency</td>
</tr>
<tr>
<td>WT</td>
<td>wind turbine</td>
</tr>
</tbody>
</table>
1.6.4 Definition of symbols

Table 1-6 Latin characters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_D$</td>
<td>drag coefficient</td>
</tr>
<tr>
<td>$c$</td>
<td>stiffness</td>
</tr>
<tr>
<td>$c_D$</td>
<td>drag coefficient</td>
</tr>
<tr>
<td>$d$</td>
<td>damping</td>
</tr>
<tr>
<td>$d_{crit}$</td>
<td>critical damping</td>
</tr>
<tr>
<td>$Eu$</td>
<td>Euler</td>
</tr>
<tr>
<td>$f$</td>
<td>frequency</td>
</tr>
<tr>
<td>$f_n$</td>
<td>modal frequency</td>
</tr>
<tr>
<td>$Fr$</td>
<td>Froude number</td>
</tr>
<tr>
<td>$g$, $g_0$</td>
<td>acceleration of gravity</td>
</tr>
<tr>
<td>$k$</td>
<td>wave number</td>
</tr>
<tr>
<td>$KC$</td>
<td>Keulegan-Carpenter number</td>
</tr>
<tr>
<td>$L$</td>
<td>length</td>
</tr>
<tr>
<td>$L_{EQ}$</td>
<td>1 Hz DEL</td>
</tr>
<tr>
<td>$L_i$</td>
<td>load range of the $i^{th}$ bin of the fatigue load spectrum</td>
</tr>
<tr>
<td>$m$</td>
<td>mass</td>
</tr>
<tr>
<td>$m$</td>
<td>material slope of the S-N curve</td>
</tr>
<tr>
<td>$N_{ref}$</td>
<td>reference number of cycles</td>
</tr>
<tr>
<td>$n_i$</td>
<td>number of cycles in the $i^{th}$ bin</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
</tr>
<tr>
<td>$u$</td>
<td>wind speed</td>
</tr>
<tr>
<td>$z$</td>
<td>height, vertical distance</td>
</tr>
<tr>
<td>$H$</td>
<td>wave height</td>
</tr>
<tr>
<td>$H_S$</td>
<td>significant wave height</td>
</tr>
<tr>
<td>$N$</td>
<td>number of sea states</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$St$</td>
<td>Strouhal number</td>
</tr>
<tr>
<td>$T$</td>
<td>wave period</td>
</tr>
<tr>
<td>$T_P$</td>
<td>peak period</td>
</tr>
<tr>
<td>$T_R$</td>
<td>return period</td>
</tr>
<tr>
<td>$T_S$</td>
<td>duration of sea state</td>
</tr>
<tr>
<td>$T_Z$</td>
<td>zero-upcrossing period</td>
</tr>
<tr>
<td>$U_{10}$</td>
<td>10 minute mean wind speed</td>
</tr>
<tr>
<td>$V$</td>
<td>wind speed</td>
</tr>
</tbody>
</table>
\( V_{\text{gust}} \) : reference wind speed for gust

\( We \) : Weber number.

**Table 1-7 Greek characters**

- \( \zeta \) : damping ratio
- \( \delta \) : logarithmic decrement
- \( \gamma_f \) : load factor
- \( \gamma_f,E \) : load factor for environmental loads
- \( \gamma_f,G,Q \) : load factor for permanent loads and variables functional loads
- \( \lambda \) : wavelength
- \( \lambda \) : scale factor
- \( \nu \) : dynamic viscosity
- \( \omega \) : angular wave frequency.

### 1.6.5 Definition of degrees freedom

For the floaters listed in **Table 1-8**, the six referenced degrees of freedom relate to the floater, i.e. the surge and sway axes follow the orientation of the floater. For example, for a barge floater, the surge axis is the longitudinal axis. For a spar, which is axisymmetric, the surge and sway axes of the floater are not predefined by the spar structure itself, but their orientation may be dictated by the station-keeping system as this is usually not axisymmetric.

In some contexts, it is convenient to refer the six degrees of freedom to the orientation of the wind turbine rather than to the orientation of the floater. This is the case, for example, when reference is made to the control system of the wind turbine as this refers to the orientation of the turbine. This gives two coordinate systems, one for the floater and one for the turbine, and they are not necessarily the same. In particular, the coordinate system referring to the turbine will yaw with the turbine when the direction of the wind changes, while the coordinate system of the floater will remain unchanged.

**Figure 1-1** shows a FOWT with the six degrees of freedom marked out. As indicated in the legend in **Figure 1-2**, the surge and sway axes follow the orientation of the floater.
Figure 1-1 DOFs of a floating wind turbine

<table>
<thead>
<tr>
<th>DOF</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>Translation along the longitudinal axis</td>
</tr>
<tr>
<td>Sway</td>
<td>Translation along the lateral axis</td>
</tr>
<tr>
<td>Heave</td>
<td>Translation along the vertical axis</td>
</tr>
<tr>
<td>Roll</td>
<td>Rotation about the longitudinal axis</td>
</tr>
<tr>
<td>Pitch</td>
<td>Rotation about the lateral axis</td>
</tr>
<tr>
<td>Yaw</td>
<td>Rotation about the vertical axis</td>
</tr>
</tbody>
</table>

1.7 Document assumptions and boundary conditions

1.7.1 General

This document reflects current industry experience, and is based on a range of design solutions and wind turbine sizes. The type of experience used as background for this document is listed in paragraphs [1.6.2] and [1.7.2]. When the design boundary conditions are different from the referenced list, specific considerations may be needed.

1.7.2 Types of floaters considered and boundary conditions

Support structures for FOWTs may either be compliant, or restrained for some of the global modes of motions, also referred to as degrees of freedom (DOF): surge, sway, heave, roll, pitch and yaw. For easy reference, Table 1-8 shows the different floater types considered in this RP. Restrained modes shall not imply a total fixation, but displacements in the order of centimetres may occur (e.g. an elastic stretch of a TLP tendon) compared to displacements in the order of meters for a compliant mode. In Table 1-8, C denotes compliant and R denotes restrained. The floater types considered in the RP are shown in Figure 1-2.
Table 1-8 Floaters considered in this RP, and boundary conditions

<table>
<thead>
<tr>
<th>Type</th>
<th>Surge</th>
<th>Sway</th>
<th>Heave</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spar</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Semi-submersibles</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Barges</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Tension leg platforms (TLP)</td>
<td>C</td>
<td>C</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>C</td>
</tr>
</tbody>
</table>

Figure 1-2 Four common floater types for wind turbines

This recommended practice is based on experience with floating wind projects on a water depth range of 30 m - 300 m. Considerations on deeper waters are made based on experience in other industries and on numerical simulations.

For the analysis of station keeping systems, not only the depth should be considered, but also the vertical distance between the anchor attachment and the fairlead.

Unless differently specified, three-bladed, pitch-controlled, horizontal axis wind turbines are considered in this document.

At the moment of developing this document, FOWT structures had been designed for a range of 2 MW to 8 MW. Furthermore, research projects have developed designs for 10 MW wind turbines (see http://
lifes50plus.eu/ and http://www.innwind.eu/. It is foreseen that larger wind turbines may be used for floating applications in the coming years.

Given the boundary conditions in this subsection, the typical ranges of natural periods for the different types of floating foundations are given in Table 1-9.

### Table 1-9 Typical natural periods of different floater types

<table>
<thead>
<tr>
<th>Type of motion</th>
<th>Spar</th>
<th>Semi-submersible</th>
<th>TLP</th>
<th>Barge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>[s]</td>
<td>[s]</td>
<td>[s]</td>
<td>[s]</td>
</tr>
<tr>
<td>Surge</td>
<td>~100 (catenary)</td>
<td>~100 (catenary)</td>
<td>15-60 $^2$</td>
<td>~100</td>
</tr>
<tr>
<td>Heave</td>
<td>25-40 $^3$</td>
<td>15-25 $^3$</td>
<td>1-2</td>
<td>5-10</td>
</tr>
<tr>
<td>Pitch</td>
<td>25-40 $^3$</td>
<td>25-40 $^3$</td>
<td>2-5</td>
<td>9-16</td>
</tr>
<tr>
<td>Yaw</td>
<td>5-20 $^1$</td>
<td>50-80 $^1$</td>
<td>8-20$^2$</td>
<td>50-100 $^1$</td>
</tr>
</tbody>
</table>

1) Yaw frequency is sensitive to mean line tension, water depth and mooring attachment point. Dependency maybe higher for shallow water (catenary).
2) The large range in TLP periods reflect the sensitivity to water depth.
3) Typically try to avoid wave frequency range.

### 1.7.3 Target safety

Target safety shall be in accordance to the DNVGL-ST-0119.

### 1.7.4 Limit states

A limit state is a condition beyond which a structure or structural component will no longer satisfy the design requirements.

The following limit states are considered in this RP:

— Ultimate limit states (ULS) corresponding to the maximum load-carrying resistance including.
— Fatigue limit states (FLS) corresponding to failure due to the effect of cyclic loading.
— Accidental limit states (ALS) corresponding to survival conditions in a damaged condition or in the presence of abnormal environmental conditions.
— Serviceability limit states (SLS) corresponding to project-defined criteria applicable to the intended use.
SECTION 2 GENERAL DESIGN CONSIDERATIONS

2.1 Introduction
The development of FOWT may be divided into different levels, see DNVGL-SE-0422:

— Concept level
  Feasibility evaluation may be carried out for a generic site e.g. in App.A or according to specific site conditions defined by the developer.

— Prototype level
  A full scale prototype may be built to develop a type certified design. Different tests are carried out to validate the design.

— Site type level
  The focus is on the design validation of the floater, the station keeping system, individual floating components or the full FOWT including a type certified RNA.

— Project level
  This is relevant for a farm consisting of a single or several floating wind turbines.

In general, a site-specific load analysis based on the design basis shall be performed. The load analysis shall include aero-elastic and hydrodynamic effects. This analysis may be performed for one or a few locations only, see [2.2].

Testing requirements at different design stages may be found in DNVGL-ST-0019 and DNVGL-SE-0422.

2.2 Design position definition

2.2.1 Selection of representative design position in an offshore wind farm
For large wind farms, in the detailed design of substructures typically representative positions within an offshore wind farm (OWF) are applied in the loads analysis, i.e. the simulation of design load cases to determine ULS, FLS, ALS and SLS loads. The chosen positions shall ensure that the loads derived yield a conservative design of all FOWT support structures in the OWF.

The selected representative positions define a load cluster group. This means all systems within this cluster are designed applying the same loads. However, the individual designs within a cluster may still differ significantly in certain parameters e.g. differences in water depth or soil conditions.

Design positions (DPs) are defined to simulate the loads which are used to design other positions in the same cluster within the OWF. A verification position (VP) may additionally be used to verify that the loads from the DP are conservative.

The clustering is used for larger wind farms to limit the load simulations to be performed. That means only for the selected clusters, the loads for the required design load cases are computed. The clustering also limits the positions where detailed wave, wind and current climate information is required.

Parameters analysed to determine the clustering are typically related to values which are known to have a significant influence on the design loads. Depending on floating support structure and wind turbine designs, these parameters may be different. For example, design load drivers for a direct drive wind turbine will not be identical to a geared machine.

The designer shall demonstrate, by means of sensitivity studies, that the selected clustering parameters are representative for the investigated support structure type.

Different platform orientations may also have an effect on secondary structure design and alignments. This may result in differing support structures in regards to their secondary structure and shall be considered when planning a wind farm layout, as fabrication may become more difficult.

Generally, the clustering parameters may consist of a set of values which cover the following items:

— Mooring system
In floating OWFs, the compliant mooring systems may be oriented differently for each individual position. The orientation of the mooring system therefore should be taken into account for the clustering, particularly regarding the loads of the mooring system itself, which are influenced by the orientation. Changes in mooring stiffness across positions in wind farm may influence fatigue loads (by e.g. changing the system global fore-aft mode).

— Natural frequency
The natural frequency is a parameter to determine the degree of dynamic excitation with regards to resonance phenomena. The support structure natural periods may depend on position specific parameters. This e.g. may also be a structural mode shape parameter indicating the exposure to wind, wave and current excitation. The larger the deflection of the mode shape is, the more energy is transferred into the structure and fatigue prone areas. This is most relevant for structures which may not be considered rigid.

— Water depth
The wave and current conditions, and thus the hydrodynamic loads, support structure motions and thus overall system loads, depend on water depth. Particularly in shallow water sites, absolute water depth differences may result in significant relative depth differences and in significant variation of design wave heights and current speeds across the wind farm.
Water depth may be important also for the design of the mooring system. If mooring characteristics are sufficiently different or if wave heights are different, water depth should be considered in clustering. However, even if the same system characteristics (e.g. eigenperiods and restoring characteristics) are achieved across the OWF, water depth may influence mooring line dynamics and possible excitations of the eigenmodes.

— Position within the OWF
Wind turbines at positions inside a wind farm typically experience wakes from neighbouring wind turbines and thus increased loading, particularly in fatigue. Additionally, soft yaw stiffness of floaters may lead to increased fatigue loads for internal positions due to partial wake inflow conditions. Proximity to land may lead to differences in extreme wave heights that are large enough to lead to significant ULS load differences.

— Soil conditions
For catenary moored systems generally soil conditions do not require any clustering in load calculations. However, depending on the design, soil condition variations across the OWF may influence the loads. For TLP systems, the pretension may vary depending on the soil conditions (anchor holding capacity). For design of anchors, which is not covered by this RP, clustering based on soil conditions (in addition to design loads) may be necessary.

2.2.2 Considerations on frequencies and dynamic effects
The eigenfrequencies of a FOWT system, including the substructure as well as the system's tower, drive train, blade and mooring system modes, may significantly influence the loads if resonances with exciting loads (environmental and from wind turbines) are present. Therefore, an analysis of frequencies and dynamic effects during the design process is required.

The analysis may be performed following the outlined procedure:

— In an initial analysis, the Response Amplitude Operators (RAOs) should be determined for the floating substructure only. A boundary element potential flow based method of the substructure should be applied considering a linearized mooring system stiffness, appropriate mass properties of the tower and RNA and appropriate damping. For systems, which experience strong coupling between rigid body motions and tower structural modes (e.g. TLPs) the effect of structural vibrations shall be investigated and if appropriate included in the calculation of the RAOs.

— The RAOs shall be analysed in order to ensure the excitation for the location (design position) specific wave spectrum is limited (either out of the main energy range or sufficiently damped). RAOs may also be retrieved from time-domain simulation. The aerodynamic damping of the rotor is higher in fore-aft direction when the turbine is in operation than in idle or parked condition. Depending on the substructure and mooring, this may affect the RAOs, see /1/.
— Response spectra may also be directly determined for the appropriate design position wind and wave spectra for relevant interface loads of the FOWTs such as tower base moment, nacelle acceleration, velocity and displacement.

In a next step, the global system shall be analysed.

— Determine the coupled system natural frequencies (damped and undamped) of FOWT:

At least combined tower and floater flexibility, blade and drivetrain flexibility, mooring system and floating substructure hydrostatics and hydrodynamic added mass shall be considered.

The frequencies may be determined either from a modal reduced linearized coupled model or from a Fast Fourier Transform analysis of time domain simulations. In the second case, determination of the system modes may require analysis of multiple sensor outputs.

Appropriate damping from structural damping of tower, blades and drivetrain, aerodynamic damping of at least the rotor and tower (and optionally the dry parts of the substructure), hydrodynamic viscous and radiation damping of the substructure, and mooring line viscous hydrodynamic damping should be considered in the analysis. Viscous drag coefficients should be carefully defined, particularly for the substructure. They shall be, if available, based on experimental data.

The effect from rotational speed on system natural frequencies (whirling) should generally be considered. This limitation may be resolved with time domain approach.

— Develop a Campbell diagram (frequency over rpm) covering:

The considered frequencies shall be from zero to at least 6P (six times rotational speed). The range of main system natural periods of the FOWTs shall be covered. Furthermore, at least following frequencies shall be included:

— first and second global tower bending
— floating substructure surge, sway, heave, roll, pitch and yaw
— first tower torsion
— first drivetrain torsion
— major global rotor modes (collective/differential flapwise, edgewise blade, considering rotation effects).

— Analysis of the Campbell diagram:

The Campbell diagram is used to identify where, during operation, a structural natural frequency coincides with an expected excitation frequency, namely at the harmonics of the rotor rotational frequency but additionally the wave energy spectrum range may be overlaid. These are potential operating points that may experience resonance. In practice the level of turbulence also affects the amount of time being spent at problematic frequencies as it causes rotor speed fluctuations with typically lower turbulence leading to more severe resonances.

Floating foundation and mooring structural mode frequencies should at least be estimated to ensure there is no risk of lock-in. A safety margin of at least +-5% to crossings of structural eigenfrequencies with 1P, 3P and 6P excitation should be kept.

2.3 References

SECTION 3 ENVIRONMENTAL CONDITIONS

3.1 Wind

3.1.1 General

Wind loading is important for the prediction of global motion responses of FOWT. Accurate modelling of the wind effects is therefore essential. For some floating systems and in some load cases, the wind loads may be the dominating excitation.

Wind conditions vary with time and space. In time they are generally considered stationary over a 10 minute period with variations within this time referred to as turbulence and variations longer than this time period described by a long term wind speed distribution. In space, conditions vary with height known as wind shear (speed) and wind veer (direction). Turbulence also has some coherence in space generally described by the wind turbulence model and proximity to the support structure will cause local disturbances in wind conditions known as tower influence.

In wind data documentation for wind turbines, hub height is frequently used as reference height for the 10 minute mean wind speed. In the offshore industry, a reference height of 10 m is normal. Careful interpretation of the wind data is therefore necessary.

The selection of the proper wind speed and direction shall be carried out according to the standards DNVGL-ST-0437, IEC 61400-3-1 and IEC 61400-3-2 in accordance with the load case to be simulated. With this in mind the wind model shall be capable of including:

— turbulence (varying level, resolution and grid variables)
— gusts (stochastic and deterministic)
— wind shear
— tower shadow
— wake effects from neighbouring wind turbines or structures.

Turbulence is described in more detail in [3.1.3]. A widely-accepted turbulence model is to assume stationary wind for 10 minutes. However, for analysis of FOWT in irregular sea state significantly longer simulation times are usually necessary.

Rotational sampling should be taken into account when selecting the wind spectrum. This phenomenon describes the low frequency energy transfer towards high frequency loading of the wind turbine. Therefore, it is necessary to have adequate low-frequency range representation in the turbulence spectra.

For requirements to spatial resolution, see IEC 61400-1, ed. 4, section 7.5, footnote 12.

Design gusts that are described in DNVGL-ST-0119 and IEC 61400-3-2 consist of deterministic changes in mean wind speed, direction and shear. The period of the gusts, as well as those already suggested, should be chosen to produce the largest rigid body platform response which as a first pass may coincide with critical natural frequencies of the floater. The corresponding intensity of the gust may be considered the same as the ones defined in IEC 61400-1, except for EOG, which shall be calculated according to DNVGL-ST-0119 and IEC 61400-3-2.

Varying approaches to mean wind shear profiles are described in DNVGL-RP-C205. Commonly wind turbine load calculations are carried out using a simple power law profile with common exponents given in IEC 61400-1. This approach is acceptable where measured site data is not available.

The model of the tower shadow shall be applied to the wind speed experienced by the wind turbine blades and shall depend on whether the blade is upwind or downwind of the shadowing support structure. Upwind this may be described by a potential flow model and downwind via an empirical wake model.

3.1.2 Wind time series from measurements

In certain cases, it may be required to apply different methods when analysing loads due to extreme wind conditions instead of normal wind conditions. As an example, it may be relevant to apply measured time
series of wind speeds rather than wind speeds generated from generic wind spectra. Some guidance on how
to analyse the event of a squall/gust when analysing for use in a mooring system analysis is given in DNVGL-
OS-E301.

3.1.3 Turbulence models

Atmospheric turbulence is the small scale natural variability of wind speed and is generally described through
turbulence models. These models may address up to three general properties that describe the variation in
wind speed:

— Spectra: at a single point in space wind speed variations may be described in the frequency domain, this
is the power spectral density of wind speed.
— Coherence: wind speed varying with time also varies in space, the coherence describes the similarity in
wind speed between two points in space.
— Correlation: it describes the interactions between wind speed variations in each direction.

There are various commonly used spectral models of the wind, most of which are described in detail in
DNVGL-RP-C205. General properties are given in Table 3-1 which may be used to assist in selecting an
appropriate model for FOWT calculations. All the turbulence models described here have been derived based
on neutral atmospheric stability conditions although practically they may be tuned to represent a slightly
broader range of atmospheric stability conditions. In case of discrepancies between the turbulence model and
site measurements, further adjustments may be required.

Table 3-1 Summary of various commonly used turbulence models

<table>
<thead>
<tr>
<th>Turbulence model</th>
<th>No. components</th>
<th>Industry source</th>
<th>Reference</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaimal</td>
<td>3D 1)</td>
<td>Wind turbine</td>
<td>IEC 61400-1</td>
<td></td>
</tr>
<tr>
<td>Frøya</td>
<td>1D</td>
<td>Oil and gas</td>
<td>DNVGL-RP-C205</td>
<td>Also referred to as NPD.</td>
</tr>
<tr>
<td>API</td>
<td>1D</td>
<td>Oil and gas</td>
<td>API</td>
<td></td>
</tr>
<tr>
<td>ESDU</td>
<td>3D 1)</td>
<td>Wind turbine</td>
<td>ESDU</td>
<td>Modified form of von-Kármán. Also, referred to as 'improved von Kármán'.</td>
</tr>
<tr>
<td>Mann</td>
<td>3D 1)</td>
<td>Wind turbine</td>
<td>IEC 61400-1</td>
<td>Might be a problem to produce long wind files in practice, due to 3D coherence.</td>
</tr>
</tbody>
</table>

1) 3D: correlation of u, v and w components of wind speed in space.
Figure 3-1 Normalised spectra comparison for the most commonly used turbulence models at a wind speed of 10 m/s

Figure 3-2 Normalised spectra comparison for the most commonly used turbulence models at a wind speed of 50 m/s
In choosing an appropriate turbulence model the following considerations are important and should be taken into account:

— Firstly the 3-dimensional nature of turbulence is considered important when calculating loads on wind turbines and it is not considered acceptable to neglect this when interested in wind turbine loading.

— Secondly the spatial variation of the wind field (coherence) may affect loading resulting from simulations and platform response, depending on the size of the structure. The length scale of the wind speed gives a measure of the average gust size.

— Atmospheric stability is more likely to vary from neutral conditions. If measurements are available, site specific atmospheric stability may be taken into account.

— Frequencies at which energy of the spectra resides and the frequency applicability range are key factors. For this it is therefore important to understand the particular floating system being examined in terms of eigenfrequencies. Low frequency representation are typically essential for the loading of FOWT. Important frequencies of the system should not lie outside the applicability range of the spectra model to be used.

The research in turbulence modelling is ongoing. According to today's knowledge the Mann model may give a good representation of the average wind conditions offshore. In case high frequency measurements are available, adaptation of the shear distortion (anisotropy) parameter, dissipation factor and the length scale under consideration of stability are recommended. Other models may be applied but the parameters should be carefully adjusted to the site conditions.

### 3.1.4 Altering sample lengths for turbulent wind time series

Design wind conditions used in simulations may come from site measurements, or some assumed conditions, based on a sample length for which the turbulence properties may apply. Typically, this is of 10 minutes, however, may be another period such as one hour. This sample length shall be known by the designer in order to use the data appropriately and shall be referred to here as the 'design sample length'. It should also be noted that a distinction is made herein between the 'wind time series length' and 'simulation length' which may differ.

When creating wind time series for use in simulations whose length matches the design sample length, the turbulence properties are applicable and can be used directly with no further processing. However, when
creating wind time series for different sample lengths then conversions may be required depending on the intention of the load case. For load cases where turbulent wind is used, following shall be considered:

Load cases modelling transient events such as wind turbine faults or shutdowns typically occur over time periods shorter than the design sample length. For these events the wind time series length should match the design sample length, although the simulation length itself may be shorter.

For extreme load cases using the EWM it is important to preserve the highest wind speed gust, during which the largest loads are expected to occur, and therefore the mean wind speed shall be adjusted if the wind time series length differs from the design sample length. The conversion may depend on the turbulence model being used with guidance on how to convert from a 10 minute mean wind speed to other averaging periods found in IEC 61400-3-1 (for IEC recommended turbulence models) or DNVGL-RP-C205 (for the Frøya turbulence model).

**Guidance note:**

In the case where the design sample length is shorter than the intended simulations an alternate approach may be applied whereby the wind time series created for the simulation is matched with the design sample length and then repeated during simulations to make up the entire simulation length. If an inverse Fast Fourier Transform approach was used to create the wind time series, then it is directly repeatable without further processing. However, if a simple repetition does not create an unphysical jump in wind speed between the last time step on the first time series and the first time step on the succeeding time series. One method to remedy this, is to reverse every other time series, and merge the first time step of a time series with the last time step of the succeeding time series. The turbulence file can be recycled by looping from the end back to the beginning.

To properly represent statistical variation, a higher number of seeds may be necessary for this method compared to generating wind and simulation time series of equal length. Also, to maintain the statistical properties of the wind the simulation length should only be a multiple of the wind time series length and it should be ensured that no low frequency excitation is caused by the repetition of the wind.

---end of guidance note---

For other extreme and fatigue load cases the wind is assumed to be stationary in time whereby the statistical properties do not change. For these cases the mean wind speed may be set equal to that of the design sample length.

For all cases where the wind time series length differs from the design sample length the turbulence intensity (or standard deviation of the wind speed) applied shall be adjusted. The intention should be to preserve the turbulence spectrum over the frequency range resolvable from the design sample length where, in practice, only the low frequency end is of importance (inverse of the design sample length). For example, when creating wind time series which length is larger than the design sample length non-negligible low frequency variations, present in the turbulence spectrum, are introduced. This means that the standard deviation over that longer time period is expected to be larger for a given turbulence spectrum.

While pre-generating longer wind time histories it shall be ensured that the grid spacing in the turbulence model definition in the aero-elastic code is consistent with that of the pre-generated grid model. Further, the turbulence grid shall cover the entire rotor even in situations with large offsets from the starting position.

**Guidance note:**

Producing turbulent wind time histories for long simulations may be a computationally expensive activity, in some cases prohibitively so. In such situations careful choice of spatial and temporal resolution is advised.

Given the lower energy content towards higher frequencies, the time step of the turbulent wind should be chosen carefully. In general a time step of less than 0.1s is advised from a wind turbine loading perspective. However, if the interest of the simulations is for the floater or moorings then a longer step may be justified backed up with a convergence study.

The spatial resolution of the wind file may need reducing towards the coarsest advisable, as discussed in [3.1.1].

---end of guidance note---

### 3.1.5 Tropical cyclones and typhoons

Many sites that are suitable for the application of FOWTs also experience tropical cyclones. Where applicable, guidance on how to model these conditions may be found in DNV GL Technical Note *Certification of Wind Turbines for Tropical Cyclone Conditions*, see [www.dnvgl.com](http://www.dnvgl.com). There is also potential that at these sites
the upper tail of the Weibull distribution does not give a good representation of the long-term wind speed conditions and may need modification based on site data.

### 3.1.6 Wakes

In a wind farm neighbouring wind turbine’s wakes may influence the wind flow and thus the inflow on every turbine. The effect is complicated and varies in time and space. To catch this effect several models have been developed with different level of complexity. Two models are presented in IEC 61400-1 edition 4, Annex E, a simple added wake turbulence method and the meandering wake model.

The added wake turbulence method suggested by Frandsen, see [7], is a model where all effects are summed up in one parameter: the additional wake turbulence. This additional turbulence, is artificial with limited physical background and meant to derive similar load levels as if the complex wake flow on the turbine would apply.

The dynamic meandering wake model is a more physical representation of the waked-flow behind an operating wind turbine than the added wake turbulence model. The theory behind the model is that low frequency eddies (of equivalent size to the wake deficit) within the ambient turbulence field interact and move the wake as it travels downstream, thus creating a meandering wake motion. The meandering wake model is described in detail in the Informative Annex E of IEC 61400-1 edition 4. Other useful references for wake meandering may be found in e.g. [4], [5], [6] and [8].

The low frequencies of the meandering motion could come close to those of the mooring dynamics of floating turbines. From numerical simulation of dynamic wake meandering, low frequency cycles are experienced in turbine thrust load components and additional fatigue is seen in structural torsional loads. This could impose significant extreme and fatigue loads on yawing and station keeping systems.

The decision, which model to use shall be made under consideration of the different effects that shall be analysed and the significantly increased computational effort connected with application of the meandering wake model.

### 3.2 Waves

#### 3.2.1 General

Waves are irregular and random in shape, height, speed of propagation and direction. Such an irregular sea state is typically described by a frequency spectrum defined in terms of the significant wave height, the peak wave period, the main wave direction and some spreading function. Typically, a real sea state may consist of several such irregular sea states. Sea states may be classified into:

- Wind seas: these are generated by the local wind, and are typically irregular and short-crested.
- Swell seas: these have no relation to the local wind conditions, and are typically long (in terms of wavelength) and more regular and long-crested than wind sea waves.

In coupled analysis of a floating system, a variety of wave theories may be used, some of which are mentioned in DNVGL-RP-C205. Further environmental sea conditions, such as marine growth, are specified in DNVGL-ST-0119 and DNVGL-ST-0437 standards.

#### 3.2.2 Wave kinematics

The most commonly used wave models for coupled analysis are irregular Airy waves.

When irregular Airy waves are applied with strip theory (see [4.7.2.2]) a relevant stretching should be applied. More details on stretching of waves may be found in DNVGL-RP-C205.

In the process of the floater design analysis, it is recommended that the wave theory applied is adjusted to the actual stage in the design process. For an initial screening it may be sufficient to apply Airy wave theory for most cases, whereas for a more detailed design the wave theory should be chosen to be applicable with
the governing design conditions. More details on the different wave theories are offered in DNVGL-RP-C205. For recommendations regarding the selection of the correct theory to a specific project, see DNVGL-ST-0437. The effect of the seabed slope on the wave kinematics should be evaluated for shallow water sites and in cases of a significant seabed gradient.

### 3.2.3 Short-term wave conditions

Unless site data indicate otherwise, short term stationary irregular sea states may be described by a wave spectrum, i.e. the power spectral density function of the vertical sea surface displacement. The Pierson-Moskowitz spectrum and JONSWAP spectrum are often applied for wind seas. JONSWAP extends Pierson-Moskowitz to include fetch limited seas, describing developing sea states. The JONSWAP and the Pierson-Moskowitz spectra may be found in DNVGL-RP-C205. The site dependency dictates whether a standard spectrum may be used.

Long natural periods may be excited by swell seas, thus in general, a two-peaked power spectrum, e.g. Torsethaugen (see DNVGL-RP-C205) should be applied to model irregular sea states with significant swell content. See Figure 3-1 for sample spectra of Pierson-Moskowitz, JONSWAP and Torsethaugen. Using two JONSWAP spectra may be an alternative for modelling combined wind driven and swell waves.

Directionality of the sea state may be of importance, too. The mean direction of wind and swell may differ. Wind sea and swell sea may come from different directions. Further, the individual wave direction around the mean direction of the sea state is spreading (short crested sea state), the spreading functions are different for wind sea and swell seas, see DNVGL-RP-C205 [3.5.8]. Often, for computational reasons the spreading is ignored and the simplification that all waves travel in the same mean direction is made (long crested sea). However, applying a two-peaked spectrum together with assigning long crested waves imposes the assumption that they are unidirectional. This approach may be conservative for many symmetric structures. For floating wind turbines an evaluation of the natural periods of the system, the system’s sensitivity to wave directions and the site data shall be performed before selecting the short-term sea state model.

Sufficient number of the wave components in the spectrum shall be considered.

Figure 3-4 Wave power spectrum comparison for $H_s = 8$ m and $T_p = 10$ s
3.2.4 Simulation time for extreme sea states

In extreme irregular sea states, it is important to have a good statistical basis for estimating the characteristic load effect. Structures with slowly varying responses need a longer total simulation time than structures with more high frequent responses. Thus, for most FOWTs, longer total simulation time than what is practice for bottom-fixed wind turbines shall be expected. The total simulation time is the product of the number of seeds simulated and the simulation length of each individual seed.

Common practice for analysis of bottom-fixed structures is to assume 10 minute stationary waves. In structures with slower response characteristics, waves are usually assumed stationary in reference periods of 1 or 3 hours. Conversion of significant wave heights between different reference periods may be performed according to equation (3.3) in DNVGL-ST-0437. After simulation, it shall be verified that the required wave statistics were obtained. Further aspects of adjusting suitable simulation length in design load cases are given in Sec.5.

3.2.5 Nonlinear waves

The validity of the Airy wave theory may be questioned for shallow water and/or when the waves become steep.

For moderate water depth and in deep water 2nd order irregular waves may be applied to model high sea states. Nonlinear wave theories shall be used to simulate strongly nonlinear effects like impact from breaking waves. Numerical tools that model nonlinear wave theories, generally do not apply to the calculation of wave loads on large-volume structures pertinent to FOWTs. For moderate and deep water depths 2nd order irregular waves may be applied to model high or steep sea states. It shall be kept in mind, that tools used to calculate wave loads on large-volume structures (see [4.7.2.4]) are, in general, not able to consider higher order effects. In some cases, 2nd order waves are included in potential wave theory models. Nonlinear wave theories should be used to simulate strongly nonlinear effects like impact from breaking waves. In that case hybrid or dual methods (see [4.7.2.1]) should be used (e.g. to consider wave impact load).

In very shallow water the waves may significantly change their behaviour and become more nonlinear for high crests. For bottom-fixed wind turbines, high crests may be modelled using a nonlinear stream function or 5th order Stokes waves embedded in the irregular Airy wave model to give more accurate wave kinematics around the high crest. The embedded wave approach does not apply to floaters modelled with large volume wave loads.

Second order wave loads shall be included in the simulations as difference and sum frequency components, unless found to be negligible. More details of these effects may be found in DNVGL-RP-C205 and in [4.7].

In very shallow water the wave height might be limited by breaking. In this case, the maximum wave height depends on the water depth, beach slope and the wave length. See DNVGL-RP-C205 for further guidance.

3.3 Current

Current is of interest for FOWT as it produces slowly varying loadings that need to be balanced by the station keeping system. A steady current gives rise to steady forces in the horizontal plane. Dynamic loads due to vortex shedding may occur and may interact with the floater giving vortex induced motions (VIM). Slender structures, e.g. mooring lines, may be subjected to vortex induced vibration (VIV) which may lead to fatigue issues and should be considered (see also [4.7.7]).

An accurate modelling of the current conditions is important for determining forces on mooring lines, which could be comparable to the current loads on the hull. For structures with large drafts the current forces acting on the hull structure itself may also be significant and in some cases dominant compared to the environmental loads.

Current may be categorized into:

— wind induced currents
— tidal currents
— storm surge currents
— ocean currents (geostrophic currents)
— loop and eddy currents
— coastal currents (longshore currents).

The variation of currents with depth shall be considered and adapted to the site conditions. Site conditions data generally allow to reach such description, if detailed measurements do not exist, this may be done by:

— Assigning standard current profiles (DNVGL-ST-0437 or DNVGL-RP-C205). Typically, the tidal component may be assumed to vary according to a power law, whereas the wind-induced component may be assumed to vary linearly down to some distance between the still water level and the seabed.
— Using numerical models: for example, the tidal current may be addressed by a large domain computation with detailed bathymetry.

Currents are in general unsteady, i.e. the velocity, the level of turbulence and the direction vary with time. It is a common assumption in station keeping analysis to assume that the current is stationary. For most applications involving global performance of a floater this is a valid assumption. Nonetheless, if current variation is significant at a time scale of one sea state, or at a time scale relevant with respect to the structure’s response, this assumption should be revised when performing the analysis for detailed design. Typically, horizontally homogeneous but time-varying currents could be considered. Such considerations usually require current measurements on the actual installation site to be available. In most cases, it is still expected that assuming stationary currents is applicable also in detailed design, since the global performance of the floater typically is relatively insensitive to local current fluctuations.

### 3.4 Wave-current interaction

For strong currents and relatively steep waves the wave-current interactions should be taken into account when considering air gap and wave impact (slamming) problems, see DNVGL-RP-C205. If, for example, the current direction is opposite of the wave direction this may tend to steepen the waves.

In general, in the offshore wind field, a stationary depth-independent current is used to compute wave-current interaction using well known Stokes theories or stream function. For irregular waves, an Airy model is generally used with a modification of the dispersion relation to account for current effects, higher order methods (HOS for example) may be used even if more CPU time is needed. Taking into account a current profile on the water column may be necessary in shallower water, but in that case the irrotational hypothesis is lost and a Poisson equation shall be solved /1/ to determine the free surface elevation and the wave kinematics.

For strong currents and/or short waves where typically Brard numbers (see DNVGL-RP-C205 [8.2.7.1]) are higher than a critical value of 0.25, see /9/, current may produce significant changes in wave loads and should be considered. For certain conditions this effect may be estimated by diffraction/radiation solvers under the assumptions of small steepness, small Froude number and small Brard number. Regarding wave loads, it shall be noted that floater horizontal motions and current may be regarded as two equivalent problems and encounter frequency is computed in the same way, see [4.7.3.3]. Strong currents should also be taken into account when considering air gap and slamming, see DNVGL-RP-C205.

### 3.5 Tide level

Tides are seen at a local level as currents (see [3.3]) and changes in sea level caused by predictable astronomical effects and local weather conditions such as storm surges. The sea level is of concern in this context and may simply be modelled as a change in water level that may be assumed constant throughout a simulation but may vary between simulations.

In shallow waters, tidal variations may have a significant impact on static mooring loads or natural frequencies.

Further, a change in the water level may impact upon the hydrodynamic loading in various ways and should be considered when changing the water depth between simulations.
— the water level may influence whether the wave particle kinematics fall under the deep or intermediate water depth definition
— in a taut moored structure, the submerged volume varies with water level, which influences the tendon tension and the overall system behaviour. Changes to the hydrodynamic loading on the floater due to the different draught shall be taken into account.
— tides and storm surges may impact sub-surface currents
— the highest and lowest astronomical tides are derived from superposition of the tidal variations and storm surges.

3.6 Seismicity
In regions, which are considered seismically active, consideration of earthquake events should be made applying a guide to determine levels of seismicity, available in ISO 19901-2 /3/. Seismic events affect the floating system differently depending on the arrangement of the station keeping which may be divided into two main categories, taut and catenary. For catenary lines, it is expected that these events will cause dynamic mooring line tension loading that may be important for the station keeping system, however, have minimal impact on the floater and turbine. For taut systems, earthquake motions may also be directly transferred into the floating structure. Furthermore, geotechnical conditions for the anchors should be checked to determine dynamic soil properties and liquefaction potential (ISO 19901-4).
Earthquake events may be modelled through horizontal and vertical ground acceleration spectra for the specific region. Given how loading is transferred through the station keeping system, where generally a single line will not transfer moments or shear, consideration of various degrees of freedom may become important, although this may be assessed case by case. It is not expected that earthquakes will be dimensioning for catenary mooring lines. TLPs may be sensitive to ground accelerations and extreme displacements and earthquake loading shall be evaluated, see ISO 19901-2.

3.7 Tsunamis
Tsunamis are very long period waves generated by vertical movement of the seabed as a result of an earthquake. Tsunamis shall be considered only for sites prone to tsunamis. Their influence may be modelled as a variance of water surface elevation and a horizontal current following the advice in Annex L of IEC 61400-3-2.
The effect of tsunamis is therefore related to water depth. In deep waters, tsunami wave crests will usually be very small. As the tsunami travels from deep waters to shallower waters, the height of these waves may be increased by shoaling and refraction which is important to consider for sites with shallow water or complex bathymetry.
The effect of tsunamis is also related to which modes of motions are restrained. It should be checked whether resonant periods of the station keeping system coincide with the period of expected tsunami waves. If available, a tsunami warning system may be used to shut-down the turbine.

3.8 Sea ice
In areas where sea ice may occur, there are several sea ice scenarios that give potentially significant loads on the substructure. In general, there is a lack of experience and relevant standards in the industry for calculation of accurate sea ice loads and load effects on floating structures. Therefore, the main effects that should be included are only briefly mentioned here. It is recommended to assess the possibility and effect of the following ice scenarios:
— interaction with drifting level ice. Depending on the ice characteristics and the shape of the substructure, different failure modes of the ice (e.g. crushing or bending) may occur. Dynamic effects such as frequency lock-in and ice induced vibrations/motions should be considered.
— interaction with ridged ice
— vertical ice loads due to water level fluctuations
— loads and changes of floater properties due to accretion and adherence of ice on the substructure
— loads due to expansion of ice jammed between structure and land, either due to thermal expansion or arch effects (caused by water level fluctuations).

IEC-61400-3 and DNVGL-ST-0437 specify a number of load cases for the design against sea ice. It is recommended to also consider ISO 19906 /2/, as this is widely recognized as the most updated design standard to date for the determination of loads and load effects of sea ice.

IEC-61400-3 and DNVGL-ST-0437 specifies a number of load cases for design against sea ice. The load cases have been developed for fixed offshore wind turbines, and are therefore not automatically valid for floating wind turbines. It is recommended to also consider ISO 19906, as this is widely recognized as the most updated design standard to date for determination of loads and load effects of sea ice. As a minimum, the following should be addressed in design of such structures:

— Analysis of the occurrence of ice at the location of the structure. This analysis should include an assessment of the design ice conditions, preferably based on historical data of the location.
— Assumed failure of the ice (i.e. bending or crushing) and the limiting mechanism (i.e. limit stress, limit force and limit energy).
— Any interaction effects and feedback between the ice load and floater motion should be given particular attention. For instance for structures with downward slope in the water line, the effective angle of inclination between the structure and the ice may influence the failure mode of the oncoming ice sheet. This may further influence the ice load when the floater moves in e.g. pitch or roll. This interaction effect should be analysed dynamically.

Loads and load effects due to interaction with sea ice often governs the loads in areas where sea ice may occur. It is recommended to consider the ice loads at an early stage of the conceptual development.

### 3.9 References

SECTION 4 NUMERICAL MODEL

4.1 Introduction

4.1.1 Coupled dynamic modelling

It is established in the FOWT industry that the coupling between the forces on the wind turbine and the motions of the floater is crucial to account for, and this applies for all types of concepts.

The interfacing scheme applied by Jonkman, see /10/, to obtain a coupled aero-hydro-servo-elastic analysis model is illustrated in Figure 4-1. The term aero-hydro-servo-elastic coupling implies a coupling between the aerodynamic loads and responses, the hydrodynamic loads and responses, the control system and the deformation response of the structure due to elasticity. In a specific load simulation, typically, no coupling effects between the models of the external conditions are considered.

A description of different coupling strategies is given in /18/.

![Figure 4-1: Example of interfacing modules applied to achieve aero-hydro-servo-elastic coupled analysis /10/](image)

It shall be noted that in a coupled analysis, all forcing and response equations are solved simultaneously i.e. at each time step. Various time stepping methods exist to evolve the solution in the time domain. These differ with respect to efficiency, accuracy and stability. Common methods include time integration schemes like Euler, Runge-Kutta and Newmark-beta. Different time stepping methods may be relevant for the various sub-problems in the analysis. Differential-algebraic-equation (DAE) solvers are often needed in coupled problems, see /22/.

For an FOWT, there is a strong coupling between the floater motions and the turbine forces. This coupling may briefly be outlined as follows:

— The motion of the floater influences the aerodynamic inflow conditions to the turbine and introduces inertial loads on the turbine.
— The forces acting on the turbine influence the motion of the floater mainly through excitation and damping forces.

The aerodynamics of the wind turbine may contribute to the floater stability with a positive or negative damping, depending on the external conditions and the control system. A description of the effects of the aerodynamic loads on the platform motion is given in /13/. Specific motion effects of spar buoy floaters are given in /14/, and for barge type floaters in /11/.

For some types of installations there may also exist an important coupling between the station keeping system and the motions of the floater. This coupling may briefly be outlined as follows:

— The wind and wave induced motion of the floater influences the forces in the mooring system.
— The motion of the station keeping system exerts forces on the floater, generally both in terms of restoring forces, damping forces and possible excitation forces.

4.2 Structural models

When choosing how to model structural systems, it is important to consider the flexibility (stiffness), mass distribution and damping properties as well as the relevant eigenfrequencies of the structure. In general, relatively simple models may be applied for structures that have low flexibility and all important structural eigenfrequencies well away from wave and wind excitation frequencies, see [2.2.2]. An example of such a model is a rigid-body model where a part of the structure is restricted from deformation other than rigid body motions, generally in six degrees of freedom. A rigid body model is most relevant for the floater, and in certain cases the RNA could also be modelled as a rigid body. Tower flexibility is in most cases important in coupled wind turbine analysis, and should thus always be modelled as flexible.

**Guidance note:**

For modelling of TLPs it is particularly important to model the flexibility of the tower and tendons in a representative manner, as TLPs see significant changes in the natural periods in pitch and roll when the tower is modelled as flexible as compared to rigid.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

**Guidance note:**

For structures with high hydrostatic restoring forces it is required to account for hydrostatic stiffness related with hull shape to get the correct first tower mode frequency as it induces an offset toward higher frequencies.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

More sophisticated models should be selected to represent flexible parts of the structure, e.g. the turbine blades and the turbine tower, with a finite number of nodes. Each of these nodes is free to move in six degrees of freedom (or three if rotations are neglected), and the response of each node is determined from mass, stiffness and damping matrices.

Modal models, finite element models and multi-body models may be used for dynamic modelling of the FOWT unit. These three model types, and combinations of them, have been widely used in commercially available aeroelastic codes, providing reliable results. Most wind turbine models consist of a combination of these models, for example modal and multi-body models or FEM and multi-body models.

Modal structural models are finite element models applying a modal reduction scheme to reduce the number of degrees of freedom. Modal models are computationally efficient, but are not suited to handle effects such as nonlinearities occurring at large deflections within each body. However, modal reduction models of bodies (blades, tower, etc.) combined with a multi-body model, may handle non-linearities by subdividing flexible components into multiple bodies. Multi-body with modal reduction is a method used by many existing modal wind turbine codes. Also, corrections accounting for geometric stiffening in bodies modelled with modal reduction exist.

An alternative is to use a finite element (FE) formulation to model the structure. FE methods require higher computational effort than modal representations, but may, depending on the applied formulation, consider effects like large deformations and structural non-linearities, see /1/. A multi-body model may also give a good representation of non-linear deflections, provided that the structure is subdivided in a sufficient number of bodies. Increasing the number of bodies may lead to higher computational time.
A multibody formulation divides the model in different bodies, coupled using algebraic equations as constraints. Each of the bodies is modelled with a finite element model or a finite element with a modal reduction model. Large rotations and translations are accounted for the coupling interfaces, while small deflections are assumed within the objects, see /31/.

It is recommended that the dynamic structural model is tested and validated, before it is being applied in a coupled system analysis to simulate an FOWT. For example, structural frequencies and mode shapes of each component should be checked separately before being used in the coupled analysis. Care shall also be taken in choosing the correct model, considering the concept to be modelled. It shall be checked that the model can correctly handle the level of deflections, rotations and displacements.

Table 4-1 provides an overview of the structural model types that are applicable for different parts of the FOWT system. These are further detailed in the subsequent subsections.

### Table 4-1 Component modelling options in coupled analysis

<table>
<thead>
<tr>
<th>Structure</th>
<th>Modelling options</th>
<th>Reference</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floater</td>
<td>Rigid</td>
<td>[4.2.1.1]</td>
<td>For floaters or structural elements with small flexibility, e.g. barge.</td>
</tr>
<tr>
<td></td>
<td>Modal</td>
<td>[4.2.1.2]</td>
<td>Slender floaters.</td>
</tr>
<tr>
<td></td>
<td>FEM beam</td>
<td>[4.2.1.3]</td>
<td>Slender floaters.</td>
</tr>
<tr>
<td>WT tower</td>
<td>Rigid with mass/intertia and wind forces</td>
<td>[4.2.2.3]</td>
<td>For the purpose of floater motion analysis, where tower flexibility does not influence the floater and moorings (typically heavy floaters).</td>
</tr>
<tr>
<td></td>
<td>Modal</td>
<td>[4.2.2.4]</td>
<td>Slender towers.</td>
</tr>
<tr>
<td></td>
<td>FEM beam</td>
<td>[4.2.2.5]</td>
<td></td>
</tr>
<tr>
<td>WT blades</td>
<td>Point mass/intertia and wind forces</td>
<td>[4.2.2.3]</td>
<td>For the purpose of floater motion analysis, where blade flexibility does not influence the floater motions and moorings (typically heavy floaters).</td>
</tr>
<tr>
<td></td>
<td>Modal (single body per blade)</td>
<td>[4.2.2.4]</td>
<td>Small to moderate deflections (if geometric stiffening is applied). May include modal models with reduced DOF. May be suitable for floater response analysis.</td>
</tr>
<tr>
<td></td>
<td>Multibody/modal</td>
<td>[4.2.2.5]</td>
<td>May represent large deflections if enough bodies and modes are used.</td>
</tr>
<tr>
<td></td>
<td>Multibody/FEM beam</td>
<td>[4.2.2.5]</td>
<td>May represent large deflections if enough bodies are used.</td>
</tr>
<tr>
<td></td>
<td>Non-linear FEM</td>
<td>[4.2.2.5]</td>
<td>Large deflection.</td>
</tr>
<tr>
<td>WT drivetrain</td>
<td>Rigid with mass/intertia</td>
<td>[4.2.2.2]</td>
<td>Rigid rotating shaft. Suitable for the purpose of floater motion analysis if gear drivetrain rotation frequency is high enough not to interact with floater motion.</td>
</tr>
<tr>
<td></td>
<td>Rigid shaft, but with flexible torsional DOF</td>
<td>[4.2.2.2]</td>
<td>The torsional degree of freedom of the shaft should at least be accounted for if analysing the coupled dynamics/designing the controller.</td>
</tr>
<tr>
<td></td>
<td>FEM beam</td>
<td>[4.2.2.2]</td>
<td>Complex drive train design with significant bending portion.</td>
</tr>
</tbody>
</table>
### Structure

<table>
<thead>
<tr>
<th>Modelling options</th>
<th>Reference</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear spring</td>
<td>[4.3.2]</td>
<td>Taut mooring. May be suitable for floater motion analysis, but not for mooring design.</td>
</tr>
<tr>
<td>Non-linear spring</td>
<td>[4.3.3]</td>
<td>Catenary mooring. May be suitable for floater motion analysis, but not for mooring design.</td>
</tr>
<tr>
<td>Multibody/FEM bar</td>
<td>[4.3.3]</td>
<td>FEM bar with axial DOF only.</td>
</tr>
</tbody>
</table>

**Guidance note:**

The superelement approach, see /25/, is common for wind turbines with bottom-fixed structures. In this approach, the foundation designer delivers linearized stiffness, damping and mass matrices of the support structure together with the wave loads time series to the turbine manufacturer who performs coupled loads analysis. This assumes that the hydrodynamic loads are known at the start of the simulation i.e. these loads do not depend on the structural motions. This assumption is therefore not valid for FOWTs. It is not recommended to use the superelement approach for FOWTs.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

A summary of the common numerical tools may be found in the Table 4-2. The table is given as an example only. It does not relate to any recommendation, or validation of the tools.

**Table 4-2 Example of common numerical tools based on Lifes50+, D4.4 /27/**

<table>
<thead>
<tr>
<th>Software</th>
<th>Aerodynamics</th>
<th>Hydrodynamics</th>
<th>Structural dynamics</th>
<th>Mooring line dynamics</th>
<th>Controller modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAMIT</td>
<td>N/A</td>
<td>FD PT or TD CE</td>
<td>RB or Modal</td>
<td>GSM</td>
<td>N/A</td>
</tr>
<tr>
<td>AQWA</td>
<td>N/A</td>
<td>FD PT or TD CE+MD</td>
<td>RB or FEM (TD)</td>
<td>GSM or QSM or FEM</td>
<td>N/A</td>
</tr>
<tr>
<td>WINDOPT</td>
<td>N/A</td>
<td>FD PT</td>
<td>RB</td>
<td>QSM or FEM or FEM</td>
<td>N/A</td>
</tr>
<tr>
<td>FAST</td>
<td>(BEM or GDW) + DS or CFD</td>
<td>TD ME or CE + MD</td>
<td>Modal or MBS</td>
<td>GSM or QSM or FEM</td>
<td>DLL or UD or SM</td>
</tr>
<tr>
<td>BLADED</td>
<td>(BEM or GDW) + DS</td>
<td>TD ME or CE + MD</td>
<td>Modal or FEM</td>
<td>GSM or QSM or FEM or MBS</td>
<td>DLL</td>
</tr>
<tr>
<td>OrcaFlex</td>
<td>Coupled to FAST</td>
<td>TD ME or CE + MD</td>
<td>Coupled to FAST</td>
<td>GSM or QSM or FEM</td>
<td>Coupled to FAST</td>
</tr>
<tr>
<td>3DFloat</td>
<td>BEM</td>
<td>TD ME or CE + MD</td>
<td>FEM</td>
<td>GSM or FEM or FEM</td>
<td>DLL or UD</td>
</tr>
<tr>
<td>Flex5</td>
<td>BEM + DS</td>
<td>TD ME or CE + MB</td>
<td>FEM/modal</td>
<td>QSM</td>
<td>UD</td>
</tr>
<tr>
<td>HAWC2</td>
<td>(BEM or GDW) + DS</td>
<td>TD ME or CE + MD</td>
<td>MBS/FEM</td>
<td>GSM or QSM or FEM</td>
<td>DLL or UD</td>
</tr>
<tr>
<td>SIMA (SIMO/RIFLEX)</td>
<td>BEM + DS</td>
<td>TD ME or CE + MD</td>
<td>MBS/FEM</td>
<td>GSM or QSM or FEM</td>
<td>DLL or UD</td>
</tr>
<tr>
<td>Sesam/Wadam</td>
<td>N/A</td>
<td>FD PT + ME</td>
<td>RB</td>
<td>GSM</td>
<td>N/A</td>
</tr>
<tr>
<td>Simpack</td>
<td>(BEM or GDW) + DS or FVM or CFD</td>
<td>TD ME or CE + MD</td>
<td>MBS</td>
<td>GSM or QSM or MBS</td>
<td>DLL</td>
</tr>
<tr>
<td>SLOW</td>
<td>ACP</td>
<td>Reduced CE or ME</td>
<td>Modal or MBS</td>
<td>GSM or QSM or QSM</td>
<td>SM</td>
</tr>
</tbody>
</table>
4.2.1 Floater modelling

4.2.1.1 Rigid body models
In a concept phase it may be useful to assume parts of the structure, e.g. the floater, as rigid body. This is acceptable in case the structural deformations do not contribute significantly to global displacements of the entire FOWT. Rigid body models represent the floater as a six degrees of freedom system. In general, flexibility of the model may be important when performing second order wave force calculations, see [4.7.3] for more information. Particularly for TLPs, the rigid body assumption may not necessarily hold because of the influence of platform flexibility on the system natural frequencies and excitation of these from high-frequency wave loads on the floater.

Rigid body models may also be used to represent parts of the structure, e.g. the individual columns of a semi-submersible. This may be expedient if the flexibility of the bracings is important, or to extract resulting sectional forces in the bracings.

For the design analysis for the wind turbine, a rigid body model of the floater may be sufficient, if it may be shown that the flexibility of the floater does not have significant influence on the turbine response. This is in principle also true for the mooring design.

Note that in practice, in most platforms there is some effect of the platform flexibility on the coupled first natural frequency. It is very important that an assessment of this effect is performed and well understood between the platform designer and turbine manufacturer, as it may have important implications on the wind turbine control design adaptation in order to avoid potential resonances in the system. See [6.4.4] for more details.

4.2.1.2 Modal models
Modal models of the floater are normally used in combination with a multibody model. In this way, it is ensured that the contribution of mass, restoring and damping from hydroelastic effects are included in the analysis.

The principles concerning a sufficient number of mode shapes provided in [4.2.2.4] are also valid for the modelling of the floater.
4.2.1.3 Finite element and multibody models

Finite element or multibody representation of the floater, or parts of the floater, are recommended if elastic deformation of the floater is important. Typically, flexible models are important for slender structures, and beam elements are then the simplest elements that may be used.

Flexible models may also be applied with the purpose of extracting sectional forces for structural design.

Guidance note:

Beam models are often applied in combination with slender body wave force formulations, see [4.7.2.2]. Hybrid methods with beam elements connected to bodies with potential theory forces may also be applied to account for effects due to diffraction, hydrodynamic interaction and frequency dependent added mass and damping, see [4.7.2.4].

The element size used for the analysis should be checked with convergence tests. Models of individual structural parts may be convenient in their mesh convergence study.

4.2.2 Wind turbine tower, blade and rotor nacelle assembly modelling

4.2.2.1 General

Structural dynamics of the tower are a key design driver for the wind turbine controller and generally for ensuring a safe operation and avoiding structural resonances. Thus it is important that all these effects are accounted for, or at least understood during the design process. See [6.4.4] for more details.

Guidance note:

Typically, when comparing with bottom-fixed tower dynamics, the following changes are encountered in floating wind applications:

— analysis and simulation of the modes of vibration of the coupled system, ‘free-free’ modal analysis theory might be used. Following this, the floating support structure coupled modes (‘support structure’ including both substructure and tower, see Figure 1-2 for definition) are a combination of 6 rigid body motion modes at low frequency, followed by the elastic modes of vibration of the structure.

— for guidance, if exactly the same tower as in an offshore bottom fixed application is installed on top of a floating foundation, the resulting coupled support structure frequency may be higher for the floating case even when considering both foundations as infinitely rigid (i.e. an infinitely bottom fixed structure such as a jacket or monopile, and an infinitely rigid floating foundation). This may be explained by the fact that the resulting tower may be represented by a ‘fixed-free’ cantilever system for the bottom fixed case and a ‘free-free’ cantilever system for the floating case, see e.g. /26/.

— in practice, floating wind turbine towers are also typically stiffer than offshore bottom fixed towers due to strengthened designs to cope with increased loading experienced in the floating condition.

— platform flexibility might reduce the frequency of the fundamental support structure global mode, compared to the structural natural frequency of the tower alone.

4.2.2.2 Drive train modelling

In analysis of the rotor-nacelle assembly, all the sub components shall be modelled, resembling the correct mass distribution, stiffness and inertia. This approach is considered acceptable for standard wind turbines, see DNVGL-ST-0361 Sec.9. Modal, multibody or finite element models may be used. When the modal model is used, it shall be demonstrated that the system may be considered sufficiently rigid. The natural frequencies shall be correctly estimated.

In the analysis of the tower, floater or station keeping system, some detailed representation of the wind turbine sub-components may be omitted: the nacelle assembly may be simplified, using concentrated masses and inertial properties. However, the mass distribution and the inertia of the complete system shall resemble the real wind turbine.

A rigid rotating shaft may be suitable for floater motion analysis if gear drivetrain rotation frequency is high enough not to interact with floater motion. Flexibility in the torsional degree of freedom of the shaft should at least be accounted for if analysing the coupled dynamics/designing the controller. For direct drive generators, a rigid model may be sufficient.
4.2.2.3 Rigid body models for tower and WT
For simplified platform motion or mooring analysis, the tower and WT (including blades) may be modelled as rigid bodies. The rigid bodies shall represent the mass and rotational inertia of the tower including tower flanges, tower internals and WT along with the wind force experienced by both. In concepts with strong coupling between the mooring, tower and WT dynamics, for example a TLP, a rigid tower and WT model may not be used for these simplified analyses.
For detailed design analyses, both WT and tower shall be modelled as flexible (see [4.2.2.4] and [4.2.2.5]), as there is a non-negligible coupling between at least the floater modes, platform flexibility and tower dynamics for most concepts.

4.2.2.4 Modal models for tower and blades
Modal reduction models serve the purpose of reducing the problem size and computation time and build upon the principle of modal superposition. The number of mode shapes included shall be high enough to correctly represent the deflections of the structure.
Modal superposition builds on the assumption of small deflections. For large or soft turbines, this assumption may give incorrect loads, thus it shall be demonstrated that a modal model may be applied. It may, however, be sufficient with a modal model in the analysis of floater motions and station keeping system, even in the case of large, soft blades.

4.2.2.5 Finite element and multibody models for tower and blades
Non-linearity may be captured by applying a multibody assembled of linear finite elements with either a full model or a modal reduction model. For example, by modelling the blade as several separate bodies, a non-linear blade deflection model is achieved. The number of bodies shall then be high enough to represent the non-linear deflection.
Non-linear finite element methods are the best to represent very large deflections of blades. Large, soft blades typically show a strong coupling between edge, flap and twist deflections. However, multibody models have shown to give sufficient accuracy in typical non-linear benchmarking cases, see [16]. For analysis of other structural components of the FOWT, multibody models may sufficiently capture the load effects from the blades on the rest of the structure.
Modal models and linear finite element models may include options for first order non-linear corrections (called 'geometric stiffening' or 'stress stiffening') that may account for non-linearities for moderate def-stiffening of structural components. For wind turbine towers, this captures effects such as gravitational de-stiffening of towers due to the mass being offset from the undeflected position.

4.3 Mooring system modelling

4.3.1 General
In terms of modelling mooring lines in a numerical analysis two alternatives exist, commonly denoted quasi-static or dynamic modelling. In brief one may say that the mooring system in a quasi-static analysis is modelled as linear or nonlinear springs and hence does not include mass and drag forces acting along the length of the mooring lines. In a dynamic analysis, the mooring lines are modelled as slender elements so that mass and drag forces acting along the length of the line may be included.
In practice, a quasi-static mooring line model is often sufficient for global performance analysis and the design of the WT and tower, but tends to under predict mooring-line tensions. The mooring design should therefore be based on a dynamic mooring line model, unless it is demonstrated that effects from mooring line dynamics are negligible for the subjected structure. To investigate the importance of mooring line dynamics, floater motions from a quasi-static mooring analysis may be imposed on a local dynamic mooring model as an alternative to full system model. This approach may be used to design the mooring line or study local effects. The response predicted with the local and global model should be compared to ensure that the approach is valid for the selected mooring system.
For mooring systems with fibre ropes, special considerations related to visco-elastic behaviour shall be made, see the section on mooring system analysis in DNVGL-OS-E301.
4.3.2 Quasi-static mooring line modelling

Quasi-static analysis refers to a model where mooring line forces are modelled by a force-displacement relationship (a linear or non-linear spring). For a taut system, the restoring force from the line is related to elastic deformation of the tendon and exhibits an approximately linear behaviour. A catenary system gets restoring from the vertical lift-off of the mooring line from the seabed, and has by definition a non-linear relationship between top displacement and force.

4.3.3 Dynamic mooring line modelling

The need for a dynamic mooring line model depends on the importance of drag and inertia forces on the mooring lines. The magnitude of the dynamic effects increases with larger transverse velocities and accelerations of the mooring line integrated over the line length. Dynamic effects are typically more important for catenary systems in deep waters, but may also be relevant in shallower water for some systems.

Hydrodynamic excitation forces on mooring line components are normally negligible in comparison with the other forces, but may need consideration for buoyancy or weight modules.

In case the resonant responses of the mooring line eigenmodes occur, it is important that damping, in particular hydrodynamic damping, is correctly represented in the model. See [4.8] for more detailed guidance on damping.

4.3.4 Seabed modelling

Accurate bathymetry modelling is of special relevance in shallow water or when steep seabed slopes characterize the site. The interaction between a catenary system and the seabed may be modelled as vertical seabed stiffness and lateral friction. Only a non-linear analysis is able to represent the seabed interaction effect in a mooring line being cyclically lifted on and off the seabed. Friction coefficients and seabed stiffness properties should be based on the best available soil information.

The horizontal friction model may influence the elasticity of the mooring line, and thus underestimating the friction may lead to an unrealistically soft behaviour and low line tensions. In addition, transverse friction loads may affect the horizontal projection of the mooring line.

The effect of the 3D seabed topography should be evaluated and considered in the numerical model if deemed important.

4.3.5 Anchor modelling

In a mooring analysis, it will most often be sufficient to consider the anchor points as being prescribed and fixed. In this case, no further geotechnical investigations than those carried out for the anchor design are required.

For a taut mooring system or a TLP the soil may contribute with significant damping. For these types of station keeping systems the soil damping may be assessed with an appropriate level of detail. If not, a conservative estimate shall be applied.

In the analysis of accidental limit states with failure of one mooring line in systems with drag embedded anchors, the validity of the assumption that the anchor is fixed should be assessed, since re-orientation of the loading direction of the anchor may change the anchor's holding capacity.

4.3.6 Shared anchor points

For anchors used as shared anchor points for mooring lines of two or more floating units, it may be important to consider the loading of all attached mooring lines. Special considerations on the correlation between the loads of the different attached mooring lines should be made.
4.4 Active ballast systems

In existing concepts, active ballast systems are used to counterbalance the overturning moment of the mean thrust of wind and hydrodynamic drift forces (mainly current). The response time of the ballast system is quite long, typically longer than 10 minutes.

Where applicable, the effect of active ballast systems shall be modelled in the analysis of FOWTs. It shall be considered if the response time for the active ballast system is in such a scale that it will influence the dynamic behaviour of the platform. If no dynamic effect is expected, ballast conditions may be assumed to be constant over a simulation period.

The ballast may be modelled by applying either mass or a constant overturning moment, or as missing buoyancy, depending on the design and analysis performed. The ballast varies with mean wind speed, wind direction as well as current speed and direction. However, it should be noted that the effect of internal free surfaces in the ballast tanks should be included in the global coupled model if deemed relevant (for example, reducing hydrostatic stiffness and metacentric height).

When defining design load conditions, specifying the characteristics of the ballast system is necessary, so that e.g. tolerances, response time and possible fault conditions are considered. Special consideration should be taken for sudden changes in thrust, such as gusts and emergency shutdown.

4.5 Mechanical systems

Floating wind turbines have typically the same internal architecture and use the same type of mechanical systems as in bottom-fixed wind turbines (with the exception of additional mechanical systems that might be present in the floating platform such as an active ballast system). Therefore, the requirements for modelling the mechanical systems present in the RNA for coupled analysis are the same as for bottom-fixed wind turbines. A key minimum requirement is to capture any effects that these systems might have in the global dynamics and loading on the system. These effects include but are not limited to:

- gearbox (if present): inertia and mechanical losses
- pitch actuator: overall system dynamics (including any delay from control output)
- dynamics in drive train as discussed in [4.2.2.2]
- generator torque: inertia, losses and overall system dynamics (including any delay from control output, which depends on power converter capabilities)
- mechanical braking torque, including application time along with upper and lower torque limits.

4.6 Aerodynamic model

4.6.1 Aerodynamic loads

4.6.1.1 Blade element momentum method

Most of the available commercial aero-elastic codes for wind turbines use the blade element momentum method (BEM) to calculate the loads on the rotor. The BEM combines the blade element and the momentum theories and it assumes that the rotor may be modelled as an actuator disc, while the flow is axisymmetric. The axisymmetric flow assumption is avoided by further extending BEM so that each blade is analysed separately.

The BEM is particularly suitable for aero-elastic implementations. This is due to the limited amount of computation time. Thus, even though more complex aerodynamic models are commercially available, the BEM is still widely used in the wind turbine industry for load calculations. This is also the case for FOWTs. However, some corrections and improvements shall be implemented in the BEM codes when these codes shall be applied to FOWTs:

- empirical correction of tip and hub losses
- dynamic inflow of the wind
— a dynamic stall model
— tower shadow effect.

For a description of the state of the art of BEM codes for FOWTs, see research project publication (UpWind).

For floater motion analysis and mooring analysis, it may be sufficient to use a simplified aerodynamic model e.g. a rigid RNA with optional point forces and moments on the tower top. Note that it is not only the horizontal thrust force that contributes to floater motion, but also lateral forces and moment forces from integrated aerodynamic forces over the rotor, the moment of the generator (which may contribute to roll motion), and gyroscopic moment of the rotating rotor. Also, the wind speed experienced by the rotor will be influenced by the floater motions, which in turn influences the wind force on the rotor. Thus, it is of utmost importance to account for the effects of the interaction between the floater motion and the turbine loads.

### 4.6.1.2 Other wind load models

Generalized dynamic wake (GDW) is an aerodynamic model, which implies a different solution method than BEM. The computational efficiency of GDW is similar to that of BEM, only GDW may exhibit convergence problems at large tip speed ratios.

Possible numerical methods that may be used to calculate the aerodynamic loads, including studying the effect of rotor motion, are:

— Vortex based methods, for example see /23/.
— Navier-Stokes solvers (computational fluid dynamics), see /15/.

Both methods have the disadvantage of relatively long computational times, but can be useful for analysing some aerodynamic aspects in more detail, such as blade-wake interaction. A comparison of the two methods is available in Sebastian and Lackner, see /20/. These numerical solvers are recommended only for a detailed study of the rotor.

Studies with numerical methods have been performed to confirm the validity of BEM for rotors with large imposed surge motions e.g. de Vaal et al., see /6/.

### 4.6.1.3 Wind loads on non-rotating components

Drag loads from wind on other structural parts than the rotor e.g. tower and nacelle may be significant, in particular at high wind speeds. Aerodrag is normally modelled as quadratic drag. For cylindrical shapes, typical drag coefficients may be found in DNVGL-RP-C205. This drag model may also be applied for the nacelle where the drag force is calculated based on the projected nacelle area perpendicular to the wind direction at any time. Since drag is both a force and damping, testing the sensitivity to drag coefficients is recommended.

### 4.7 Sea load models

#### 4.7.1 General

For modelling of sea loads, a general reference is made to DNVGL-RP-F205, DNVGL-RP-C205 and DNVGL-ST-0437. The following sections provide additional aspects with specific relevance for floating offshore wind.

#### 4.7.1.1 Hydrostatic loads

The structure weight and buoyancy force balance is the starting point for hydrodynamic analyses. Influences of power cables and mooring pretensions is part of this load balance. Usually this effort is trivial, but important for the success of subsequent hydrodynamic analyses. Buoyancy of large volume structures is calculated directly from the wetted surface geometry described by the radiation/diffraction model.

**Guidance note:**

Care should be taken for structures with a non-linear hydrostatic stiffness around the waterline (steep changes in waterline area, deck in water cases) and the challenges this presents in load modelling as potential flow software usually can only handle linear stiffness matrices, so some non-linear effects are missed.

---end of guidance note---
In cases where a dual model, including a strip method (e.g. Morison elements), is applied, this may also be handled automatically by the computer programme as long as the actual location and dimensions of the elements are implemented.

Applying the correct metacentric height (GML, GMT) in the analyses is just as important as the location of the centre of buoyancy. Influences of potential free surface effects shall be taken into account when determining the metacentric height.

Stiffness contributions of moorings lines shall be considered, either directly applying an FE or multibody mooring line model, or by applying mooring line forces in the floater analysis.

The mass distribution of the floater may either be entered as a global mass matrix, or from a detailed mass distribution (e.g. FE model). The input coordinate system varies depending on the software and may be referred to the vertical centre of gravity, or the water plane. Input of roll and pitch radii of gyration is very often a source of error in computer programmes. Applying the correct reference axis system is usually the challenge in this context.

4.7.1.2 Wave loads

Table 4-3 shows hydrodynamic effects that are known to be of importance for the different floater types. Only effects that are important for the floater motions are included.

The table is based on experience from oil and gas standards, in addition to effects that are found to be important during project and concept development for FOWTs. The table is given as guidance based on the typical natural periods for different concepts indicated in Table 1-9, and should be considered in light of these assumptions, not by concept type only.

Table 4-3 Hydrodynamic effects (effects of importance are marked "X")

<table>
<thead>
<tr>
<th>Effects</th>
<th>Reference</th>
<th>Spar</th>
<th>Semi-submersible</th>
<th>TLP</th>
<th>Barge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave frequency loads</td>
<td>[4.7.2]</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Radiation/diffraction</td>
<td>[4.7.2.4]</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Low frequency loads</td>
<td>[4.7.3.3]</td>
<td>X</td>
<td>X</td>
<td>2)</td>
<td>X</td>
</tr>
<tr>
<td>High frequency loads</td>
<td>[4.7.3.4]</td>
<td>X 1)</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ringing in steep waves</td>
<td>[4.7.4.2]</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viscous drag</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Mathieu instability 3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vortex induced motions</td>
<td>[4.7.7]</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>If strakes are applied: increased added mass and drag due to strakes.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical slamming loads</td>
<td>[4.7.4]</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Horizontal slamming loads</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
### 4.7.2 Wave frequency loads

#### 4.7.2.1 General

Hydrodynamic loads for offshore structures may be divided into a viscous part and a non-viscous part. For floating offshore wind turbines, the former is generally limited to drag while the latter comprises Froude-Krylov terms and diffraction terms. Several theories may be applied to model these hydrodynamic loads on wind turbine floating sub-structures. Strip theories or diffraction/radiation models are the most frequently applied.

Frequency domain analysis may be useful in the first stages of a project, but is limited in terms of accuracy when moving to more advanced stages of analysis. Time domain analysis enables to capture nonlinear hydrodynamic effects such as quadratic drag, and is suitable for coupling with aerodynamic codes.

In FOWT analysis, the floater may be modelled as a slender structure (strip theory model), a three-dimensional diffracting body or a combination of the two (dual model).

Modelling of the submerged part of the structure in the wave load analysis should consider the actual shape of this part, e.g. quasi-static list due to damaged compartment or static wind induced list in storm conditions. This applies to both first- and second-order wave load analysis.

Heave plates, added to provide viscous damping, should be adequately modelled in the radiation/diffraction analysis since they may give significant contributions to wave excitation and potential damping.

#### 4.7.2.2 Slender body load models (strip theory)

When the floater is modelled as a slender structure, wave radiation damping is neglected, and the wave loads on the body are calculated by means of strip theory (the semi-empirical Morison’s equation), which includes a drag term and an inertia term. Drag and added mass coefficients shall be chosen carefully, see DNVGL-RP-C205.

Slender body models inherently capture effects of nonlinear hydrostatics, nonlinear drag loads. Strip theory may also be used to represent wave loading in hydroelastic models.

Slender body load models may in principle be used for any sea state, provided a correct representation of kinematics is applied. DNVGL-RP-C20S [3.3.3] gives guidance on which stretching models may be applied to derive wave kinematics. The choice of a stretching model should be done carefully, where specific attention should be paid to extreme sea states. The stretching model is particularly important if a specific phenomenon, e.g. ringing, shall be studied.

The application of the strip theory has several limitations, as summarized in /3/, /10/ and /12/:

- wave radiation damping is not considered (which is acceptable for small volume or deeply submerged bodies)
- some of the terms of the added mass matrix are disregarded, which is valid for axially symmetric bodies
- the diffraction problem is simplified according to G.I. Taylors’ long wavelength approximation, which makes the theory valid only for slender bodies, see Figure 4-1. MacCamy-Fuchs correction provides one solution to analytically describe diffraction around circular cylinders.
- the method is mostly devoted to simple geometries (e.g. cylinders). For more complex shapes it requires calibration.

<table>
<thead>
<tr>
<th>Effects</th>
<th>Reference</th>
<th>Spar</th>
<th>Semi-submersible</th>
<th>TLP</th>
<th>Barge</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) For some large structures, e.g. semi-submersibles, higher order response has shown to be important in model tests, see /17/.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) May be relevant for TLP with low frequency. This depends on water depth.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) See DNVGL-ST-0119 [7.1.3.1]. Mathieu instabilities may occur as a result of variable hydrostatic stiffness (e.g. by strong variations in waterplane area in heave motion) of a semi-submersible or spar. This may be the result in coupling of heave and pitch motion. The relation between the heave eigenperiods and the roll/pitch eigenperiods should be checked to avoid Mathieu instability.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
— hydrodynamic interaction between bodies is neglected (except improved methods are used allowing for corrections).

In slender body load models, it shall be ensured that the buoyancy, hydrodynamic pressure and drag on end nodes of slender elements are included. Also, the influence of hydrodynamic pressure on conical sections may give a significant load effect, particularly in the heave response, and shall be considered.

Hydrodynamic drag and lift forces on plates and appurtenances should be taken into account. Drag and lift coefficients considering the type of flow should be considered.

When applying strip theory care shall be taken to consider axial forces on the elements in a correct way. Depending of the size of the structure, axial forces on vertical elements may need to be corrected to consider Froude-Krylov forces.

### 4.7.2.3 Calibration and fidelity of slender body load models

Strip theory requires a discretisation of the structure. The level of discretisation (i.e. number of elements) depends on the spatial integration method used and its order. It shall be verified that the typical wave profile is well represented by the discretisation applied, and that the intersection with the free surface and splash zone is refined enough to capture free surface variations.

Strip theory needs a proper calibration to produce reasonable results. Variation of drag and added mass coefficient with Reynolds (Re) and Keulegan-Carpenter (KC) numbers shall be determined for every location in the floating structure and for every sea state. Taking the floater motion into account in the KC evaluation can be challenging. Navier-Stokes models (CFD) or model tests may be applied for model calibration. CFD, although connected with significant modelling effort, may also be useful to capture the effects of the free surface, multiple members, Reynolds effects etc. on drag coefficients.

### 4.7.2.4 Large volume load models (potential theory)

An alternative to the Morison’s formulation is to model the floater as a three-dimensional diffracting body. The wave loads on the body are calculated in frequency domain by means of potential theory, typically by a panel method.

Potential theory may capture frequency dependency in the wave loads and hydrodynamic interaction between bodies. The wave loads may be solved either linearly or non-linearly. However, hydrostatic restoring is assumed linear and viscous effects are not accounted for.

The computations may be performed directly in the time domain, or they may provide frequency-domain transfer functions to be used in another time domain simulation code using the Cummins equation. For simulations in time domain, the frequency dependency of damping and added mass shall be accounted for in the simulation, e.g. by retardation functions or equivalent state-space formulations.

Diffraction/radiation models may be built for any kind of geometry, but attention to which simplifications that have been made by the models should be paid. For example, the models may be limited to moderate sea states and subjected to limitations in terms of floater motions and wave steepness. Corrections may be applied to overcome those limitations, with different levels of empirical or theoretical validation.

In the calculation of potential wave theory, the mean position of the body is also to be considered.

Regardless of whether Morison’s formulation or potential theory is used, the wave loads will not be fully correct. Using Morison’s formulation, the wave radiation effect is disregarded, and using potential theory the viscous drag is missing. Therefore, a combination of the methods is sometimes used: potential theory plus viscous effects from Morison’s formulation. Often a slender model is used together with a panel method to introduce the effect of viscosity by drag forces on the Morison elements, see /10/.

### 4.7.2.5 Calibration and fidelity of large volume load models

To solve the diffraction-radiation problem, the floating body is discretised into panels. The level of discretization depends on the integration scheme. A general rule is, that the refinement should provide correct representation of the vertical wave kinematics over the structure, and at least 7 to 10 panels per wavelength should be used. This may be quite demanding for short wave cases. For parts of the mesh where two surfaces are in close proximity of each other, a mesh refinement is normally required.

A general recommendation is, to perform grid convergence for a representative range of sea states, using at least 3 grids to find a balance between accuracy and computational cost.
4.7.2.6 Validity of load models

A guideline for when the various theories are valid is offered in Figure 4-1. This figure strictly holds for a vertical, circular cylinder with diameter D in waves having wave length L and height H, but is also applicable as guidance for a floating structure with circular-like cross-section. In general, wave loads on large volume structures may be based on radiation/diffraction theory. Frame or slender floaters may be modelled using strip theory members. As noted above, it is also possible to establish numerical models combining both strip theory elements and large floater loading (dual model) when both drag and diffraction loads are important.

![Figure 4-1 Regions of validity of different wave force formulas for a fixed circular cylinder with diameter D in waves with wavelength L, height H and period T](image_url)

It has become increasingly common to apply computational fluid dynamics (CFD) when solving strongly nonlinear fluid-structure interaction problems. Examples of such problems are wave impact (slamming) and ringing loads in steep waves. CFD methods solve the Navier-Stokes equations in time domain by various numerical schemes, offering a more correct way to compute strongly nonlinear wave loads as well as dealing more properly with viscosity than other methods. CFD is also the most appropriate tool if one is to study vortex induced motions (VIM) numerically.

For detailed design phases, where for example loads on the tower structure during wave impact in steep waves may be needed, it is recommended to use sophisticated methods such as CFD, see /30/. However, other means to deal with this type of problems exist, applying analytic models for studying effects of wave impact and ringing loads. In either way, the results of numerical computations should be duly verified, especially in severe sea states and steep waves.
4.7.3 Second order loads

4.7.3.1 General
Second order loads are proportional to the square of the wave amplitude. The forces are generally smaller than the first order wave excitation, thus the excitation is typically observed as resonant response below and above the wave frequency range. For moderate sea states, the second order wave forces may be expressed by the sum of wave components for the frequency pairs $\omega_i \pm \omega_j$, where $i, j = 1, N$. $a_i, a_j$ are the corresponding wave amplitudes and $H^{(2)}(\omega_i, \omega_j)$ is the quadratic transfer function (QTF) expressed as a complex quantity.

$$F(t) = Re \sum_{i,j} a_i a_j H^{(2)}(\omega_i, \omega_j) e^{i(\omega_i \pm \omega_j)}$$

Second order loads may be divided into low-frequency loads ($\omega_i - \omega_j$ and $\omega_j - \omega_i$ terms) and high-frequency loads ($\omega_i + \omega_j$ and $\omega_j + \omega_i$ terms).

Guidance specifically relevant for FOWT analysis is given in this section. More details may be found in DNVGL-RP-F205.

4.7.3.2 Quadratic transfer functions
Second order loads on a large volume body may be found using quadratic transfer functions (QTFs), which express the relationship between the wave forces and wave frequencies (see equation in [4.7.3.1]).

There are commercial diffraction codes that calculate QTFs in the frequency domain based on discretization of the floater body surface and the free surface. This is normally done as pre-processing to a coupled time-domain analysis. Since QTFs depend on the first order motions it is important that the first order motions are represented correctly in the diffraction code model. A challenge for current diffraction codes is that wind induced motions are not accounted for. The effect of wind induced motions on the QTF may be neglected if the wind force spectrum is small compared to the wave force spectrum at frequencies of first order motions. If this is not the case, the QTF should be verified against model tests.

Second order load calculations may require specific meshing of the structure, in particular near the free surface intersection, the free surface itself should be meshed to address certain second order wave load contributions. Sensitivity to grid refinement and to the size of the meshed domain shall be performed. The pitch degree of freedom is normally a good variable to monitor during the mesh sensitivity study, but convergence for the rest of the variables should also be assessed at the end of the sensitivity study.

4.7.3.3 Low-frequency loads (difference-frequency)
Low frequency loads (difference-frequency loads) may be an important source of excitation in low-frequency modes, such as surge/sway and pitch/roll of catenary moored floaters.

The mean drift force is obtained by keeping only diagonal terms in the difference frequency. The vertical mean drift force is usually only of interest for structures with small water plane area and catenary mooring. The low frequency wave loads (either the mean drift force or the full QTF matrix) is usually calculated by means of a 3D radiation/diffraction code. For slender structures in high sea states, where diffraction effects are small, the low frequency loads can be correctly reproduced by a slender body approximation accounting for both potential flow effects and viscous drag due to relative motion.

Newman's approximation states that the off-diagonal elements in the full QTF matrix may be approximated by the diagonal elements, thus slow drift forces may be calculated efficiently. Newman's approximation usually gives satisfactory results for slow-drift motions in the horizontal plane if the natural period is much larger than the wave period. For slow-drift motions in the vertical plane, e.g. the heave/pitch motions of a spar, Newman's approximation may underestimate the slow drift forces and in such case the solution of a full QTF matrix is required. These recommendations are taken from DNVGL-RP-F205 which is based on experience from offshore oil and gas platforms. For FOWT concepts, caution should be exercised.
when applying Newman’s approximation. It is recommended that the full QTF matrix is computed. This is particularly important for floaters with relatively large and shallow pontoons/bases in relation to the columns. Current leads to changes in second order wave loads, due to a modification of the wave field close to the floater. For wave induced drift loads in particular, contributions due to intersection with the free surface are affected by current. Use of diffraction-radiation codes to address this issue require to mesh the free surface, but the accuracy of these codes tend to decrease with increasing frequency of encounter. Another option is to apply simplified approaches, as proposed by Aranha, see /2/, or Clark et al., see /5/. In addition to this inviscid effect, viscous drag induced by current results in another force responsible for additional offset of the floater. Drag and inertia coefficients under wave and current conditions may be significantly different from those under wave only or current only conditions. Some experimental values may be found in Moe et al., see /24/, for example. The viscous contribution to the wave drift force, due to waves in the splash zone and current below the MWL, is more significant than the potential flow contribution in long waves. Semi-empirical formulas accounting for this for a semi-submersible may be found in e.g. see /21/.

The wave drift damping force is defined as the increase in the second-order difference frequency force experienced by a structure moving with a small forward speed in waves. When the slow-drift frequency is much smaller than the wave frequency, the slow-drift velocity varies little over a few wave periods and may be interpreted as an apparent forward speed. By expanding the difference frequency force in a Taylor series in terms of the forward velocity, and retaining the linear term only, the wave drift damping is proportional to the forward velocity. The wave drift therefore behaves like a linear damping, provided that the increase with forward speed is positive. This is usually the case. However, in some special cases the wave drift damping may be negative. Wave drift damping may also be applied to quantify the effect of current on wave drift forces. Further guidance on the calculation of wave drift damping loads may be found in DNVGL-RP-C205. Viscous effects should also be included in wave drift damping, see /9/. This effect may be estimated in decay tests in wave tanks.

4.7.3.4 High frequency loads (sum-frequency)

Detailed recommendations on high frequency loads may be found in DNVGL-RP-F205. For FOWTs, high-frequency loads are generally expected to be more important for TLPs than for other FOWTs because of the low pitch, roll and heave periods (in the range 1 s -5 s, see Table 1-9). However, the possibility of excitation of structural modes (in particular tower bending) due to high-frequency loads of any FOWT should be considered.

Springing may give significant fatigue damage, since it may occur in wave conditions that are associated with FLS load cases. Also, the relative importance of resonant excitation compared to first order wave response may be larger in smaller waves compared to extreme conditions.

At least the following aspects should be considered for springing analyses (see DNVGL-RP-F205):

— discretization (mesh) of wetted floater surface geometry
— discretization of free surface and its extension
— number of frequency pairs in the QTF matrix
— damping level for the tendon axial response.

At resonance of the first tower bending mode, aerodynamic damping is important. Hence, an idling turbine could experience a larger second order response than a turbine in operation.

Guidance note:

For TLPs, floater pitch and roll modes may be influenced by the first bending mode of the tower (and even flexibility of the hull). Gueydon and Jonkman, drr /7/, showed that the importance of this in estimation of QTFs were negligible. Nevertheless, it is important to include structural flexibility in the coupled analyses to get excitation of the correct modes. Figure 4-3 illustrates the shift of pitch frequency from a fully rigid TLP model to a model with flexible tower, see /7/.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---
Figure 4-3 Non-dimensional amplitude of a pitch sum-frequency QTF, showing the shift of pitch frequency from a fully rigid TLP model to a model with flexible tower according to /7/

4.7.4 Extreme wave loads (slamming or ringing)

4.7.4.1 General
Extreme wave loads due to for example slamming or ringing shall be analysed in the time domain. When very refined analysis methods are required, such as CFD, the associated analysis cost may be large. In such cases, it is standard practice to only analyse critical events, e.g. analyse a specified wave cycle that is found to generate critical slamming loads. The critical events may be indicated by simpler models where full short-term sea states may be analysed at reasonable computation cost.

Several approaches exist for estimating wave loads due to slamming/wave impact, see DNVGL-RP-C205. Wave impact loads may also be estimated by means of classical methods due to Von Karman or Wagner, Faltinsen, see /3/, or by applying potential theory through a boundary element method. However, due to increased computational capacity it becomes more and more common to analyse wave impact problems with CFD methods. Depending on the method, this offers the most detailed modelling of the physical effects involved, and it also in general allows modelling of the steep waves that may be relevant. However, as for any advanced method, the results shall be properly verified. This may be done e.g. by comparison with model tests.

4.7.4.2 Ringing
Deepwater TLPs may experience large resonant high frequency transient response, called ringing. Waves exciting ringing have a wavelength considerably longer than a characteristic cross-section of the structure (e.g. diameter of column). Therefore, ringing loads are normally most relevant for extreme wave conditions (e.g. DLC 6.1 as defined by DNVGL-ST-0437).

Ringing loads may be analysed by means of CFD. However, alternative methods that are less computationally demanding exist. One of these is the so-called FNV (Faltinsen, Newman and Vinje) method, see /8/. Rainey
equations are based on energy considerations and provide a generalisation of the Morison equation, including nonlinear terms. Since ringing is a transient phenomenon, the response shall be solved in time domain. However, a linear structural model may be applied.

### 4.7.4.3 Water entry and wave-in-deck loads

For an FOWT with a deck or platform, it may be important to analyse the loads associated with wave impact on the deck structure, tower and other equipment located on the deck/platform. Wave-in-deck forces are horizontal and vertical forces due to slamming, inertia and drag from a wave crest hitting a deck structure. In extreme seastates, it shall be considered if wave impact loads may introduce significant floater motions. Guidance on calculation of wave impact loads may be found in DNVGL-RP-C205. For loads associated with water entry on the deck, it may be necessary to consider hydroelastic effects. This may for example be relevant for stiffened plates. Hydroelasticity implies that the structural deformation following an impact influences the hydrodynamic pressure. However, it is generally conservative to neglect hydroelastic effects, see DNVGL-RP-C205. The prediction of water entry or green water involves strongly nonlinear problems. Standard analysis tools are semi-empirical based on linear or second-order hydrodynamics, and model testing calibration is needed in the design process.

### 4.7.5 Current loads

An accurate modelling of the current conditions is important for determining offset and forces on mooring lines. For structures with large drafts the current forces acting on the hull structure itself may also be significant and in some cases dominant over other environmental loads. Current loads should be determined from tank tests. Alternatively, current loads may be estimated from model basin tests or calculations according to recognised theories, e.g. as described in DNVGL-RP-C205 Sec.6. If numerical flow analysis is applied to establish current coefficients, calibration towards wind tunnel or model basin tests is necessary. Both for wind tunnel tests and numerical flow analysis it is important that a representative model of the units under the water hull is applied. Drag forces induced by current are generally described using drag coefficients based on experimental data, see /19/. Viscous drag coefficients depend on the nature of flow (oscillating or steady flow). It is therefore of importance to apply the correct drag coefficients with due attention to the excitation as well as the damping contribution. Guidance for selection is given in DNVGL-RP-C205 and DNVGL-RP-F105, under consideration of KC-number (Keulegan-Carpenter number) describing the relative importance of drag in oscillating flows. Sensitivity checks with different sets of drag coefficients are therefore recommended. Hydrodynamic drag and lift forces on plates and appurtenances should be taken into account. Drag and lift coefficients considering the type of flow should be considered.

### 4.7.6 Moonpool effects

The analysis of moonpool effects is described in DNVGL-RP-C205 and DNVGL-RP-N103.

### 4.7.7 Vortex induced oscillations (vortex induced vibrations and vortex induced motions)

Water or air flow over a structural member due to towing of the floater, wind, wave and sea currents may cause unsteady flow patterns due to vortex shedding. Vortex shedding cause a dynamic load that may cause resonant response in the structure, both in-line and normal to the flow direction (cross-flow). Due to the unsteady flow regime, vortex induced response is not covered by standard load models for wind and current, and therefore shall be considered separately. It is convenient to differentiate this response in two categories:

- vortex induced excitation of floater rigid body motions (vortex induced motions - VIM)
- vortex induced structural vibrations (vortex induced vibrations - VIV).
Since VIM may cause additional excitation of the rigid body modes, it shall be considered in the evaluation of floater motions. The effect causes cyclic loading on the mooring lines, and shall therefore be included in evaluation of the mooring line fatigue design.

VIM may be disregarded if it is demonstrated that onset of VIM is unlikely to happen, considering the site specific current velocities and geometry of the structure.

It shall also be evaluated if onset of VIV is possible for the slender members of the platform, e.g. tendons of a TLP or braces of a semi-submersible. Tower VIV in parked conditions shall be evaluated.

More details of VIM and VIV may be found in DNVGL-RP-C205.

## 4.8 Damping

### 4.8.1 General

The damping of a floating offshore wind turbine significantly influences the system’s reaction to actions like wind, waves and currents and the dynamic loading (action effects). Damping may be added to the model in different ways. However, the correct value of damping shall be reproduced and particular accuracy shall be applied with the components subjected to vibrations and potential instabilities, such as blades and tower.

Within the classical analysis of dynamic response, damping is given as damping ratio $\zeta$ or logarithmic decrement $\delta$. In the following the formulations are given for a single degree of freedom system:

$$
\zeta = \frac{d}{d_{\text{crit}}} = \frac{d}{2\sqrt{cm}}
$$

$$
\delta = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}} \approx 2\pi\zeta
$$

where:

- $\zeta$ = damping ratio
- $\delta$ = logarithmic decrement, defined as the natural log of the ratio of the amplitudes of any two successive peaks
- $d$ = damping
- $d_{\text{crit}}$ = critical damping
- $c$ = stiffness
- $m$ = mass.

All relevant effects as structural, aerodynamic, hydrodynamic, soil and mooring damping should normally be considered in the analysis. The total damping is then assumed to be the sum of the individual components.

$$
\zeta = \zeta_{\text{struct}} + \zeta_{\text{aero}} + \zeta_{\text{hydro}} + \zeta_{\text{mooring}} + \zeta_{\text{soil}}
$$

**Guidance note:**

The damping is described in previous equations with a linear damping formulation. This is inconvenient for nonlinear damping effects like drag loads e.g. for slender structures. However, in many cases these non-linearities may be satisfactorily linearized e.g. by linear superposition. Alternatively, hybrid methods using e.g. Morison drag term may be used, but care should be taken selecting drag coefficients and the flow velocity components to be applied. For damping analysis of different floating structure types, including non-linear damping, see DNVGL-RP-C205 Sec.7.
Damping gets importance for floating wind turbines especially for cross-wind fatigue loading especially in cases where the load is excited by waves with a high wind-wave misalignment.

The importance of the different damping sources varies with the location where the damping force is generated and the deflection of the system. As a consequence, it may be expected, that aerodynamic and hydrodynamic damping are of primary importance while soil damping for a floating wind turbine may have only minor influence. In addition the application of active or passive damping devices shall be taken into account.

Damping may be applied in the dynamic model in various ways. Typical models that may provide damping in a FOWT model are:

- global structural damping
- local structural damping
- seabed friction or soil damping
- hydrodynamic damping (linear and quadratic drag) on submerged parts of the floater or mooring lines
- aerodynamic damping
- controller-floater motion interaction.

Time domain solvers may, depending on the solver time integration method, introduce numerical damping in a model. Sensitivity to time integration parameters in the solver algorithms and time steps should be performed. A decay test with zero damping may be used to reveal numerical damping.

The overall global damping in the model shall be verified by decay-simulations determining the logarithmic decrement for all relevant eigenmodes. Guidance on how to perform such analysis for wind turbines (not floating) may be found in Koster, see /28/. Structural decay test should be performed separately for blades, tower and floater, to more accurately match specified damping values.

It should be noted that yaw excitation may be significant for FOWTs, and that yaw damping should be carefully determined.

Unless damping levels can be demonstrated through e.g. model tests, CFD or full scale measurements, the damping ratios assumed for coupled analysis should be at the lower end of the ranges given in literature.

4.8.2 Structural damping

Structural damping is due to internal friction forces of the member material and depends on the strain level and associated deflection. For most structural materials, structural damping is independent of the frequency and the damping force linear with the vibration velocity. Structural damping may be either applied as modal damping or Rayleigh type damping with mass dependent and stiffness proportional terms.

Modal damping models set a specific level of critical damping on each of the modes included in the model. For the wind turbine, these levels are normally specified by the turbine manufacturer.

In some cases, it may be necessary to evaluate the damping matrix individually or damping of higher modes shall be established. When the damping ratio of the two modes is known Rayleigh damping may be assumed as a function of mass and stiffness matrix, see /34/. Rayleigh damping is normally set to fit a certain level of critical damping at two specified frequencies of the structure. Damping for the remaining frequencies follow from the chosen Rayleigh parameters. Caution is advised as the model inherently overpredicts damping at high frequencies, thus it is recommended to plot damping ratio as a function of frequency to make sure all the relevant eigenfrequencies of the structure have a reasonable damping level.

For wind exposed steel members, according to DNVGL-RP-C205, the structural damping ratio \( \zeta_s = \delta_s / 2\pi \) may be taken as 0.15%, if no other information is available. In /29/ the authors derive the damping ratio for the first modal form of a steel caisson structure as \( f_n \approx 0.32 \) Hz to \( \zeta_s = 0.24\% \).

Grouted connections will in general have a higher damping ratio than welded steel structures. Consequently, using the value for steel is thus conservative for grouted connections, too.
For slender elements in water (pipes), the structural damping ratio at moderate deflection is typically ranging from 0.5% for pure steel pipes to 3% to 4% for flexible pipes.

For mechanical elements of the RNA or blades special assumptions shall be taken into account.

4.8.3 Hydrodynamic damping

Hydrodynamic damping on the floater has high influence on its behaviour and shall be documented by relevant model tests, CFD analysis or full scale measurements. In absence of measurements or analysis, at an early stage of design, values from literature or similar designs may be acceptable.

Contribution to hydrodynamic damping of floater motion may come from:

- quadratic damping due to viscous loads on the hull (skin friction and form drag)
- linear and/or quadratic drag on mooring lines (viscous damping)
- radiation damping
- wave drift damping.

On slender bodies wave radiation damping may be neglected and Morison formula may be used to analyse damping forces normal to the structure directly by using the motion of the structure relative to the flow.

On Morison elements, drag should be applied in both transverse and longitudinal directions. For simple geometries and initial studies, drag coefficients may be found in DNVGL-RP-C205 [6.6] and DNVGL-RP-N103 App.B. The application of Morison’s equation has several limitations, as summarized in Jonkman, see /10/, Newman, see /12/, and Faltinsen, see /3/, especially regarding radiation damping, see [4.7.2.2].

In terms of damping ratio the viscous hydrodynamic damping for vertical cylinders in deep water based on CFD may be assumed to be in the region of $\zeta_{\text{hyd},v} \approx 0.1\%$ /29/

For large volume structures damping due to wave radiation, hull skin friction, hull eddy making damping, viscous damping from bilge keels and other appendices shall be considered.

If the structure may be considered a large volume the motions may be categorized in three frequency bands:

- wave frequency (WF) motions: the motion is in the area of typical wave periods between 4 s and 25 s
- low frequency (LF) motions: slow varying response with periods higher than those of the waves
- high frequency (HF) motions: periods below the typical wave periods e.g. ringing and springing of TLP’s.

The damping of these motions is usually of different nature and is considered separately, using different models. Wave radiation damping is calculated from potential theory. Viscous damping effects are usually estimated by simplified hydrodynamic models or from experiments. For simple geometries, computational fluid dynamics (CFD) may be used to assess viscous damping.

The hydrodynamic damping might be adjusted with the results obtained by model tests.

The primary wave damping (other than roll/pitch damping for some barge shaped structures) is related to radiation damping. Radiation of energy in form of waves is occurring if the structure is forced to oscillate with the wave frequency in a rigid body motion mode with no incident waves. Panel methods are usually used to solve the diffraction and radiation problems. The generated wave loads are usually described with added mass, damping and restoring loads and analysed in the frequency domain.

It shall be noted, that due to the relation between wave damping (generating waves) and excitation (loading due to incoming waves), measures to increase wave radiation damping will increase diffraction loads on the structure.

Wave diffraction solutions do not include viscous effects (vortex, pressure drag). If body members are relatively slender or have sharp edges, viscous effects may be important and viscous effects should be added to the diffraction forces. For slender bodies or sharp edged barges viscous damping in roll and pitch should be included.

For large volume floater types, for e.g. semi-submersibles with shapes which may lead to flow separation introducing considerable viscous damping, a dual hydrodynamic model may be applied, adding the relative velocity component of the Morison equation to consider quadratic viscous damping to the radiation/diffraction loads on the same element.
In addition, viscous effects should be considered for the heave motion of semi-submersibles or spars, depending on the design, e.g. when heave plates are used. To derive heave motion damping model tests should be performed.

For barge shaped structures high damping values have been observed for roll and pitch viscous damping. Koster, see /28/, states up to $\zeta_{\text{hyd},\nu} \approx 20\%$ of critical damping. Further information on estimation of roll damping is given in /29/. The bilge keel roll and pitch motion damping coefficients are nonlinear and approximately proportional to wave height and period.

Moonpools provide additional damping to floating structures, especially for the heave motion. Neglecting viscous damping of the water motion in the moonpool will result in unrealistic large motions and free surface elevation in the moonpool close to resonance. Details about moonpool analysis are given in DNVGL-RP-C205 [7.3] and DNVGL-RP-N103 [3.5].

Regarding damping of slow frequency motions see DNVGL-RP-C205 [7.4.5].

### 4.8.4 Aerodynamic damping

The aerodynamics damping is stronger in operation conditions than in parked or idling conditions. Since the aerodynamic damping during operation is acting only towards direction of the rotor axis, wind-wave misalignment has strong impact on FLS loads.

### 4.8.5 Damping effects from controller

Controller-floater motion interaction may result in what is commonly termed 'negative damping', as active control may excite resonant floater motions. More on this effect may be found in the DNVGL-RP-C205 Sec.6. Input of floater or tower top motion signals to the controller can be used to actively damp undesired motions.

### 4.8.6 Mooring damping

Additional damping may be introduced in the floating wind turbine by the station keeping system due to:

— damping from mooring due to its motions (transverse in particular), current, etc.
— damping due to possible contact friction between hull (spar) and lines
— seafloor friction, if the mooring system has sea-bottom contact.

Friction forces from contact of a line or cable with the structure are very difficult to predict and thus ignored. Synthetic ropes are sometimes used, e.g. in a taut mooring system to provide elasticity and low weight. Compared to steel, synthetic ropes exhibit more complex stiffness characteristics (e.g. hysteresis), resulting in the need to derive damping behaviour from tests.

Quadratic viscous damping due to current and the motion of the line is taken into account as a result of drag coefficients specified for the moorings. Drag coefficients for mooring components without marine growth may be found in DNVGL-OS-E301.

### 4.9 References


Nielsen, F. G. (no date), *Some Hydrodynamic issues related to offshore wind turbines*.


/27/ Lifes50+, D4.4 (2015), Deliverable D4.4 – *Overview of the numerical models used in the 1928 consortium and their qualification*.


SECTION 5 LOAD CASES SET-UP AND DATA ANALYSIS

5.1 Introduction

It is acknowledged that coupled simulation codes applicable for FOWTs require considerable computational effort. Typical dimensions of a full load case set up vary from $10^2$ to $10^4$ different load cases resulting in a data volume of several gigabytes up to terabytes in terms of stored time series. Possible reduction of computational effort without giving up required accuracy of the final results can be done by careful consideration of the variations and combinations of environmental input parameters, suitable adjustment of calculation parameters of the specific simulation code applied and finally in the consideration of the peculiarities of the floating support structure and rotor nacelle assembly (RNA) design. A common tolerance applied for the accuracy of a reduced load simulation compared to a complete load set up is $\pm 5\%$, corresponding to a 95th percentile of a quasi-infinite number of load cases.

Therefore, in order to reduce the number of simulations required to determine the design driving loads, the following approaches are typically applied:

— clustering of an offshore wind farm (OWF) into reduced number of representative design positions
— during conceptual design phase, focusing on reduced set of critical load cases
— for final design loads and for certification, all design load cases (DLCs) of the applied standard should be considered, with an appropriate selection of simulation lengths (including length of initial transient phase), number of seeds, directionality and misalignments, based on the conceptual design analysis and additional sensitivity analyses.

Guidance on clustering concepts may be found in [2.2].

A reduced DLC set may be based on studies such as:

— sensitivity analyses
— brute force methods
— experience from previous analysis of the same concept
— pre-screening of critical DLCs with reduced simulation models, see /3/
— response surface methods, e.g. design of experiment (DoE) approach using latin hypercube sampling (LHS), see /1/
— bin reduction methods /4/
— probability based sampling /6/
— genetic programming /5/

In the following sections guidance is given for the load case set up for the different limit states of a floating offshore wind turbine (FOWT). Mentioned load cases references as DLC X.x referring to the load case definition of DNVGL-ST-0437, Table 4-3 and DNVGL-ST-0119 (floater specific load cases). The offshore load cases of DNVGL-ST-0437 correspond widely with IEC 61400-3-1. The load cases from DNVGL-ST-0437 and DNVGL-ST-0119 shall be considered in the final design.

5.2 Extreme loads – ultimate limit states

Extreme loads are generated primarily by extreme environmental impacts e.g. storm events with a recurrence period of 50 years, see Sec.3. Furthermore, system failures such as loss of power or braking failures (e.g. due to rotor overspeed) typically generate extreme loads similar to bottom fixed wind turbines. For FOWT unfavourable combinations of wind and wave (wind-wave misalignment) and oscillation effects enabled by the additional dynamics of the station keeping system (e.g. ringing) are additionally critical. Floater and mooring damages and instability due to leakage as described in DNVGL-ST-0119 for floater specific load cases may cause extreme loading to the structural components of a FOWT. In the next section the important environmental conditions for ULS analysis of a FOWT are described followed by recommendation for simulation tool settings and typical design driving load cases.
5.2.1 Converting site conditions to load cases

It is important to implement the ULS site conditions approved in the design basis stage (which is based on the met-ocean data analysis) for the detailed design. See DNVGL-ST-0437 for the aspects not listed here below.

5.2.1.1 Normal sea state

The normal sea state is described in DNVGL-ST-0437 where pairs of wave height and wind speed are associated along with the potential full range of wave spectral periods. This range of periods may lead to many simulations. By assuming platform and mooring extreme loading not be driven by NSS DLCs, some assumptions may be made to reduce the possible combinations. RAOs of the nacelle accelerations and displacements may be used to place the peak spectral period over the frequencies with the largest responses as long as they are within the 90th percentile of possible wave periods. These peaks are likely to be situated at rigid body natural periods and splitting frequencies.

There is a range of possible wave periods associated with a pre-defined wave height. For bottom fixed structures, it might be acceptable, for a given wind speed and wave height, to use a single value of wave periods. For FOWT, the response might be sensitive to wave periods. Therefore, a range of wave periods derived from the scatter diagram shall be considered. Any peak period, which is close to an eigenfrequency of the system shall also be considered. For the current, a conservative value of a constant current speed may be assumed.

5.2.1.2 Extreme sea state and severe sea state

For extreme and severe sea states (ESS and SSS), all the points on the environmental contour of (wave height, wave period) shall be considered and not just the largest wave heights and associated wave periods. A possibility to limit the number of combinations is to consider the whole wave period range and apply for each period a wave height higher than the ones of the contour.

For SSS, the sea state is conditioned on an operational wind speed. If sufficient information is not available, ESS parameters may be used as a guidance.

50 year return current speed and wind speed may be assumed as initial conservative assumptions however a lower current speed may also result in larger dynamic responses due to reduced hydrodynamic damping and hence should be considered.

Guidance note:

For extreme and severe sea states (ESS and SSS) of bottom fixed wind turbines, it is possible to apply an embedded wave approach in order to reduce the long simulations. In this approach, a non-linear single design wave is modelled by a stream function wave and is embedded into an irregular time series. This approach is however not applicable for FOWT where natural periods are expected to be larger than the wave period and the dynamic memory effects are important. It is therefore not possible to use the embedded wave approach to reduce the simulation time of FOWTs.

---end---of---guidance---note---

5.2.2 Adjustment of simulation parameters for ultimate limit states

Available simulation tools offer a large number of simulation parameter settings which help to find a suitable balance between computational effort and reliable load results. This recommended practice cannot go into the details of the various numerical tools. The recommendations given herein deal with the most common and most effective parameters valid for most of the available numerical tools. These adjustment parameters are the simulation length of specific load cases, the selection of an appropriate number of seeds for the generation of stochastic wind and wave inputs and the applied initialisation period to exclude unrealistic transients at the beginning of the simulations.

5.2.2.1 Simulation length

If RNA or tower loads during stationary load cases are expected to be dominated by wind loading (DLC1.3 and DLC1.1), a 10 minute simulation length is expected to be appropriate. However, the applicability of the selected duration should be documented by sensitivity studies.
For floater, tower and mooring system design, a minimum duration of 3 hours is recommended for load cases expected to be dominated by wave loading (DLCs using the ESS and SSS), see DNVGL-ST-0119. However, shorter durations, e.g. 1 hour, may be applied for conceptual design studies or if this may be documented to be sufficient by sensitivity studies. This may be the case where the wave frequency response is dominant over low frequency response.

For transient cases (emergency shutdowns, etc.) sufficient simulation length should be given to allow for a full decay of the triggered motions. The duration is strongly dependent on natural periods and the damping of the floater. For catenary and rope mooring systems, it is recommended to apply at least a 600 second simulation time for transient load cases.

5.2.2.2 Seed sensitivity
In the standards the calculation of a number of independent turbulent wind files within a certain wind bin is required in order to achieve a full representation of a turbulent wind spectrum. Typically, the different wind files are generated by a random variation of the turbulence spectrum start parameter (seed). The number of seeds for ULS cases should be high enough to sufficiently well estimate the sought characteristic values. This depends on the sensitivity to the random variables that are varying with each seed, as well as the simulation length. The number of seeds may therefore be set based on a sensitivity study in which the relevant characteristic values are estimated based on an increasing number of seeds.

Guidance note:
An example of the sensitivity study could be to use the minimum number of seeds as suggested by DNVGL-ST-0437 load standard [4.4] and then compare the results with those obtained using double number of seeds. In DNVGL-ST-0437 for instance it is requested to apply a minimum of 6 seed for fatigue simulations. If there is no significant difference in the estimated characteristic values due to the increased seed numbers, then it may be assumed that 6 seeds are sufficient.

5.2.2.3 Initialisation period
The initialisation periods at the beginning of each simulation are significantly longer for FOWT simulations compared to bottom fixed structures. During the initialisation period the software code is determining the equilibrium for the operational parameters (rotor speed, blade pitch angle) and the deflections of the coupled system. This simulation period should be excluded from ULS post-processing tools since in this simulation window unrealistic deflections and excitations are present. A sensitivity study with constant wind and a stationary irregular sea state may reveal the duration of initialisation period for the floater type in question. The initialisation period is also strongly dependent on the applied simulation code and on the wind turbine control algorithm. In general, an initialisation period of at least 600 seconds is recommended. Pre-setting of operational parameters (rotor speed and blade pitch angle as function of the average wind speed) and the setting of initial deflections as a function of environmental parameters may reduce the initial period significantly and may be automated in some codes.

5.2.3 Floating support structure characteristics for ultimate limit states
In the following, typical design driving situations (as given in DNVGL-ST-0119 and DNVGL-ST-0437) are discussed. The recommendations below do not ensure that all design driving situations have been considered, otherwise industry standards would not recommend running the full set of design load cases. The actual driving cases should be dependent on site conditions and the FOWT design. Nevertheless, the following sections may provide some general guidance for initial sizing or conceptual designs.

In particular, there are several situations from which loading may vary considerably between designs. These are fault load cases, maintenance load cases and severe sea state (SSS) load cases. These load cases are only mentioned herein if there is a floating specific comment to be made. Redundancies in control and mechanical systems should dictate what fault cases should be modelled along with historical information if available. Maintenance cases are typically a trade-off between length of possible maintenance windows and loading, it is assumed at early stages that it may be possible to later come up with a strategy that did not drive turbine loading, however, this is not guaranteed or necessarily economical.

Load levels during operation in severe sea state (as defined in DLC 1.6) depends heavily on the simulation approach taken. Typically the protection system (either dedicated, based on sea state, and/or standard
turbine protection systems such as overspeed alarms) refuse the turbine operating during the 50 year sea state, particularly close to cut out wind speed. Conservative approaches of disabling the protection systems are sometimes used in simulations however lead to unrealistic operating conditions. Herein it is assumed that the protection system is able to keep the turbine operating only in non-design driving situations unless mentioned otherwise.

Many cases that typically drive the design of FOWT systems are shared over all types of floater as discussed in [5.2.3.1]. However, where floater specific comments are appropriate these are provided in [5.2.3.2] to [5.2.3.5].

5.2.3.1 General ultimate limit states design drivers
The following load cases derived from DNVGL-ST-0437 may drive the design of the components stated. However, note that the design driving load cases largely vary depending on the site conditions, concept design, controller behaviour etc., and hence taken only as a guidance. Further, it shall be noted that the conventional design load cases shall be adapted to the site/and concept-specific cases such as varying gust period etc.

— RNA

The main load components of the RNA is generally driven by design load cases 1.3, 1.4 and 6.1.

— DLC 1.3

This load case may be linked to the extrapolation load case 1.1 depending on the approach taken. The level of turbulence, defined by parameter 'c', may therefore depend on the outcome of 1.1, see IEC 61400-3-1, ed. 4. Because of this, a conservative value of 'c' should be chosen initially if extrapolation shall not be performed for all load components. Guidance on a suitable value should be sought from the wind turbine OEM. However, a conservative 'c' value e.g. 2.5 may be appropriate in the absence of further information.

— DLC 1.4

A load case that often drives many load components within the RNA, most commonly the yaw bearing overturning moments, hub out of plane moments and blade flapwise loads. The wind conditions for DLC 1.4 are entirely independent of the site, with only the normal sea state environmental conditions affected. This has little impact on the RNA loading, making for a straightforward set up. This observation may lend itself to exclusion from the early stages of site specific assessments of existing RNA designs if already proven on a floating support structure.

— DLC 6.1

For wind turbines in general the high wind speeds associated with 50 year storm load case along with the feathered pitch angle often drive the in-plane blade pitch bearing extreme loads (i.e. loading acting to provide torque about the rotor axis). Compared to a fixed configuration, the floating environment is not expected to greatly influence this load component. However, the large rigid body floating motions are expected to cause large global forces in the nacelle structure.

— Miscellaneous

Blade torsional loads may typically be dependent on DLC 6.2 due to the high wind speeds and large angles of attack experienced. Although, as with the in-plane blade pitch bearing loads, this is not expected to be influenced by the floating condition itself. The hub thrust load may be driven by DLC 1.6 due to high sea state in combination with high accelerations/pitch angles and high aerodynamic thrust. However, this is generally not the case for the yaw bearing thrust, which is more dependent on DLC 6.1.

— Tower

The tower top is expected to be driven by the same load cases as the RNA and gradually, moving towards the bottom, be dominated by the high wind speed and sea state, non-operational storm load cases, primarily DLC 6.1.

— DLC 6.1

As the wave induced motions generally dominate towards the tower base, this leads to DLC 6.1 being the driving case due to 50 year waves (causing large inertial/gravity loads) associated with high wind speeds (applying large aerodynamic loading to the rotor) combined with a normal safety factor. The
extreme current may also lead to high heel angles adding additional gravitational components into the
tower loading.

— Miscellaneous
Load cases considering the failure of the active ballast systems, if present, damaged stability from
leakage during storm conditions or shutdown cases may lead to significant additional gravity loads
from the overhanging nacelle and so drive extreme loading towards the tower base. This may depend
on redundancy of the ballast system. Also, DLC 6.2 may be design driving. However, in general it
results in similar load levels as DLC 6.1 and so at a very early stage may be ignored.

— Floater
For the floater again DLC 6.1 is the main driving load case and at least near the tower to floater
connection all points discussed regarding the tower base are relevant.

— DLC 6.1
In this case the wave and current loads coming directly from the hydrodynamics are the cause of the
loading, with some contribution coming from the tower base aerodynamics and inertial/gravity loads.

— Moorings
Tension leg mooring systems are discussed in [5.2.3.3]. For design of catenary mooring systems, it is
expected that DLC 1.6, DLC 6.1 and DLC 6.2 are the most significant cases to consider. Depending on site
conditions, they may all be design driving.

— DLC 6.1
The large sea state and associated normal safety factors are expected to cause the largest dynamic
mooring line tensions and in general be the main contributor to the mooring design.

— Miscellaneous
Load case DLC 1.6 is expected to yield the largest mean line tensions around rated wind speed as a
result of the combined current and aerodynamic thrust loading. Given the combination with a large
sea state this may lead to driving mooring loads at sites with significant swell. Also, floater specific
load cases of DNVGL-ST-0119 related to mooring loss may be critical for the design depending on the
mooring arrangement.

5.2.3.2 Ultimate limit states design drivers for semi-submersibles
For semi-submersibles, wave periods that have particular relationships with the distance between the
columns are important. For example, if the wave length is twice that of the distance between columns both,
large platform pitching and large forces acting between columns will result. The associated wave periods are
generally termed splitting periods and are likely to be design driving even if the associated extreme wave
height is much smaller than the absolute 50 year wave height. Further, the torsional load on the structure by
diagonal or near-diagonal seas shall be investigated.

5.2.3.3 Ultimate limit states design drivers for tension leg platforms
In the case of TLPs, it is expected that the RNA is not heavily affected by the platform support structure
as the tower top movements are expected to be minimal (in a similar order as those of the bottom fixed
offshore wind turbine). For TLP designs which tend to larger yaw motions the combination of power
production and sea state driven yaw motions may cause unfavourable gyroscopic effects for the rotor and the
drive train in addition to increased load due to oblique inflow.

In the floater, towards the fair-lead points of the tendons, additional important floater specific load cases of
DNVGL-ST-0119 may be important.

For the tendons, it is important not to lose tension (tendon slack). Hence, the six platform rigid body motions
may be used as a constraint as TLPs have a limited number of possible motions for which tendon slack is
avoided, motions potentially caused by set down effects. Lower water levels may make tendon slack more
likely and should be considered in DLC 6.1.

Load cases with extreme current conditions may be driving the design of the tendons and shall be
considered. Further, the load cases with leakage, mooring failures etc. (DNVGL-ST-0119, DLC 2.6-2.8 and
DLC 7.3-7.5) are relevant for tendon dimensioning. Finally, the ULS load cases which may cause ringing and springing shall be considered, see [4.7.3.4] and [4.7.4.2].

5.2.3.4 Ultimate limit states design drivers for barges
The suitable load cases to cover for initial barge design may be taken from [5.2.3.1]. Given their large wetted area near the water surface, barges are particularly exposed to wave and current loading with larger loads being associated with larger pitch angles of the platform. Moreover, in barge simulations it is likely that critical loads occur because of rotor shut down following alarm thresholds exceedances (such as rotor overspeeds, acceleration sensors, etc.).

5.2.3.5 Design drivers for spar ultimate limit states
The maximum static pitch angle of the support structure may be expected in load cases with opposite direction of wind and current. However, severe wave conditions or shut-down of the turbine may lead to larger dynamic pitch values.
For spar structures with low yaw stiffness, special considerations should also be made to load cases with excitation in yaw. Load cases having high turbulence or high aerodynamic imbalance may be important for the yaw moment.

5.3 Fatigue loads – fatigue limit states

5.3.1 Converting site conditions to load cases
The environmental conditions at offshore sites that may have a significant effect on FOWT fatigue loading are generally wind, waves, current and water level. The combinations of variables such as directions and magnitudes will lead to an large number of simulations to consider and so it is expected that the data is reduced in some way, ideally backed up by sensitivity studies.
Environmental conditions at the site are complex and the inputs are discussed in detail in Sec. 3. The major environmental conditions which are expected to contribute to fatigue load cases are:

Wind [5.3.1.2]:
— wind speed
— wind direction
— turbulence intensity.

Waves [5.3.1.1]:
— significant wave height
— peak period
— wave direction
— wave spectral shape - usually characterized by peak enhancement factor.

Current (for both wind driven and tidal) [5.3.1.5] and [5.3.1.6]:
— current velocity
— current direction
— current profile.

Miscellaneous [5.3.1.3] and [5.3.1.4]:
— water level
— water depth variations or sea bed changes
— yaw error
— control modes (e.g. active ballast on/off).

The following sections look at each parameter group individually and subsequently how they may all be combined. Please also see DNVGL-ST-0119 [3.2].
5.3.1.1 Wave conditions
While setting up the design load case table, it is important to cover the finalized met-ocean conditions. However, often it is nearly impossible to consider all the wave conditions for the given mean wind speed. Hence, binning and lumping become necessary. While doing binning and lumping, it is important to include the sensitive wave parameters such as the peak period close to any structural or rigid body motion eigenfrequency, which might drive the design. Apart from the resonance aspect, it may also be important to consider the wave length of the considered sea state, as the loading is sensitive to the wave length. If the wave length becomes comparable to the structural dimensions such as the spacing between the columns in the case of semi-submersible platforms etc., this may eventually result in splitting forces (see DNVGL-ST-0119 [7.1.5.2]). The selection of these wave parameters and the binning and lumping procedure should be documented, which may be carried out by means of sensitivity studies or by means of the experience from previous projects, see further details in [2.2].

It should be noted that for the fatigue limit state of some materials, the damage equivalent load approach is not applicable and the whole wave scatter table may need to be modelled. In this case an appropriate resolution of significant wave height would be 0.5 m unless conservative assumptions are made such as using at least the 90\textsuperscript{th} quantile value, in which case any bin size may be considered if justified.

As the motion of the platform is very sensitive to the wave period it is recommended to keep a fine resolution (maximum of 2s bin sizes) in this dimension when analysing all parts of the floating offshore wind turbine. Around resonant or frequencies with high response a finer binning is recommended. If some of the system natural frequencies are within the wave frequencies these should be accounted for in the fatigue calculation. If data is available, a finer discretization near the system natural periods is also recommended.

**Guidance note:**
An example lumping procedure is given below, which may be applicable for the FOWTs:
For the bottom fixed structures, it is typical that the $H_s$ and $T_p$ are lumped based on the wind speed.
The formulae for the lumping of $H_s$ and $T_z$ (or $T_p$) may be found in Kühn, see /7/.
However, for FOWT, some of the assumptions considered for this methodology may be not be valid. This depends on the type of structure and the site. During the conceptual design phase and with regards to RNA loads, it is considered acceptable to use co-direction of wind and waves and to consider the lumping method suggested by Kühn, see /7/, for $H_s$ and $T_p$.
Where the analysis of the fatigue limit state should be performed using damage equivalent loads, for the given mean wind speed the significant wave height environmental dimension may be removed using the relationship below, if applicable, where 'm' is the inverse slope of the S-N curve of the material.

$$\text{Damage} \propto S^m \propto H_s^m$$

Where many values of 'm' should be considered, the most conservative (highest) number should be used although it is standard practice not to consider those applicable to the blades and hub. In this case loading is generally dominated by wind conditions and including it may lead to overly conservative results for other structures.
A linear relationship between loading and wave height is assumed in the above. Where loading is dominated by second order or higher order wave loading, this relationship is no longer applicable. In those cases, the nonlinearity should be taken into account, which will usually result in a larger damage equivalent loads and responses.

---end---of---guidance---note---

5.3.1.2 Wind
Standard approaches for the inclusion of the ambient distribution of the turbulence intensity are recommended, resulting in the use of the 90\textsuperscript{th} percentile level of turbulence intensity.

For a wind farm, wake effects of neighbouring wind turbines shall be considered. DNVGL-ST-0437 App.H gives recommended models to use for including this effect which is significant for fatigue loading on the RNA and tower. Simplified methods are suggested in /8/ for reference.

**Guidance note:**
Wake meandering and partial wake loading may be important for platform yaw. These effects are not yet studied thoroughly and are not considered in today’s industrial practice.

---end---of---guidance---note---

For the RNA and the tower wind speed bin sizes no larger than 2 m/s are recommended, when only considering the mooring system and the floater coarser bins may be appropriate if justified. If it is found that
wave loads are design drivers for fatigue damage of the floater or mooring system, it may be necessary to lump the wind speeds based on the waves.

5.3.1.3 Yaw error
For the loading of the RNA and the tower the tolerance of the yaw system to track the wind should be captured. Industry practice suggests maximum values of ±8 degrees are appropriate unless other values are supported by measurements. Considering the tolerances may lead to a trebling of wind speeds if taken as a separate variable. However, the approaches below may be applied to prevent this:

— a variation in wind direction over the length of the simulation may be applied
— share the potential tolerances over simulations to ensure the overall time at each yaw error is modelled.

5.3.1.4 Water level
It is expected that for deep water the sensitivity of fatigue to tidal level is small and a conservative value may be applied for all simulations.

5.3.1.5 Wind-induced current
Relationships given in DNVGL-ST-0437 may be used to map wind induced currents directly to wind speed and direction assuming a fully developed current profile. This negates the need for another environmental dimension as it is mapped directly to wind speed.

5.3.1.6 Tidal currents
Generally tidal currents provide a mean load and offset on the floater, in a limited number of circumstances this may be ignored but where the following effects are important currents should be considered:

— nonlinearities such as to mooring response
— large heel angles leading to effective up/downflow through rotor
— fatigue cycle means used in structural design, e.g. concrete or cast structures.

If the current shall be included in fatigue its properties generally lend itself to only a smaller number of extra environmental dimensions compared to other environmental variables as there are often only 2 prominent directions. Conservative assumptions may be used to prevent adding another environmental dimension depending on what the focus of the load analysis is:

— Current direction and speed leading to the largest expected heel angle in a simulation.
— Current direction and speed leading to the largest mooring line fatigue e.g. for catenary line increasing the tension of the tautest line.

5.3.1.7 Combinations of environmental conditions
The environmental variables may be discretised into bin sizes appropriate to all aspects of the FOWT, in which case a single load analysis may be performed, the results of which may be used for the design of all subcomponents (moorings, floater, tower and RNA). Alternatively, a coarser resolution may be used for some environmental conditions in which case the results of the analysis may only be appropriate to a limited number of subcomponents.

If the environmental conditions may be described through probability distributions, appropriately dependent on each other, then the fatigue analyses may be performed by a Monte Carlo type approach. The number of environmental condition samples may be chosen based on convergence of a fatigue metric such as lifetime weighted damage equivalent load.
Guidance note:

For most of the numerical tools available the sea state realisation is a summation of \( N \) different frequency components \( f \).
The discretisation of the wave spectra may be carried out in different ways:

- constant frequency increment \( \Delta f = f_{i+1} - f_i \), defined by the duration of the simulation \( T \), \( \Delta f = \frac{1}{T} \).

- variable frequency increments, e.g.variants of the equal energy method, random frequency with \( N > 1000 \). A good frequency discretization should to be defined for the regions near system's natural frequencies.

For model validation/verification exercises, it is recommended to use the same free surface elevation in the verification/validation runs that may be recreated using a fast fourier transformation.

Wind-wave direction misalignment should be investigated as aerodynamic damping may have an impact on the loading for the aligned simulations. For conceptual design, larger wind wave misalignment angles than 90 degrees may be considered. However, correct allocation of time for each condition is required.

5.3.2 Adjustment of simulation parameters for fatigue limit state

5.3.2.1 Simulation length

As for ULS, a sensitivity study to determine the sufficient simulation length is recommended. For global loads (e.g. floater, tower, RNA components), a duration as low as 10 minutes may be sufficient as long as enough seeds or number of environmental condition bins are considered. For sub-structure components such as platform components, mooring lines, etc., a simulation duration of three hours may potentially be necessary because the large surge motions are quite slow.

Depending on the rainflow counting algorithm, it might be that there are unclosed cycles (half cycles) in the counting results. The unclosed cycles may influence the preliminary analysis such as simulation time, see /2/. This is because the ratio of unclosed cycles to closed cycles is higher for shorter simulations (e.g. 10 minutes) than for longer simulations (e.g. one hour). The influence of unclosed cycles strongly depend on the weighting factor applied. Therefore, it is recommended that unclosed cycles are avoided by adapting appropriate algorithm.

5.3.2.2 Seed sensitivity fatigue limit state

To select an appropriate number of seeds for FLS load cases, a convergence study is recommended.

Guidance note:

In a convergence study, an increasing number of seeds are added to each environmental combination and resulting fatigue metrics are assessed (e.g. lifetime weighted damage equivalent loads). When adding seeds has little effect on the fatigue metrics, the required number of seeds has been established.

Alternatively, for fatigue, this problem may be thought of in terms of environmental condition bin size and a convergence study performed using a fixed number of seeds per bin but with reducing bin size.

Guidance note:

Due to practical limitations in terms of computational capacities, only a limited number of FLS simulations is possible. Therefore, it is recommended to increase the number of environmental bins (reducing bin sizes) to a sufficient level before increasing the number of seeds per bin.

5.3.2.3 Initialisation period

The duration of the intialisation period (run-in-time) of fatigue simulation follows the same approach as for the set up of extreme load cases, see [5.2.2.3].
5.3.3 Floating support structure characteristics for fatigue limit state

Wave loading is important for the tower, floater, and mooring line fatigue design. In addition, the mooring lines are sensitive to current loading. The RNA is expected to be driven by the same conditions as that of the bottom fixed offshore turbines as often the RNA designs are generic (applicable for both bottom-fixed and floating offshore wind turbines), dimensioned by the design load envelope. DLC 1.2 may be the major contributor to fatigue and wind/wave misalignment may be important as well especially 90 degree wind/wave misalignment due to the missing aerodynamic damping. Based on the site conditions, the importance of DLC 7.2 shall be assessed. Current in line and opposing the wind may be considered in early phase, as this may give large pitching moments.

For conceptual design, a smaller number of directional combinations may be considered. For DLC 6.4 and DLC 7.2 aerodynamic damping effect is small. So, collinear wave and wind seas may be considered for concept design.

5.4 Accidental limit states

5.4.1 Accidental limit states load cases

Characteristic accidental loads for FOWT shall be taken as 1000-year loads i.e. loads with an annual probability of exceedance of $10^{-3}$, see DNVGL-ST-0119.

As per DNVGL-ST-0119, accidental loads are foreseen to be loads due to:

- impacts from unintended collisions by drifting service vessels
- unintended change in ballast distribution (e.g. failure of active ballast system)
- change of intended pressure difference
- loss of mooring line or tendon
- dropped objects
- fire and explosions
- accidental flooding
- fare tropical storms (if applicable).

The load cases related to accidental loads are given in DNVGL-ST-0119. The redundancy condition and the transient condition between intact and redundancy condition are considered as ALS load cases. It is ALS design criteria that loads occurring at the time of the accidental event and thereafter do not cause complete structural collapse. Therefore, loads at both states shall be evaluated.

During the ship collision, there may be a redistribution of the loads due to the non-linearity of the material or due to the collapse of certain components. This shall be considered in the coupled analysis. The lateral drifting speed of the vessel may be found in DNVGL-ST-0119.

In case any compartment is flooded as a result of damages, the shift of the centre of gravity shall be considered. The assumption made is dependent on the ballast system capability as well as the power supply availability of the grid or the power back-up in such condition.

5.4.2 Redundancy analysis

If one mooring line in a mooring system is lost and the remaining part of the FOWT meets the ALS criterion, which is survival for at least a one year return period load effect, then the initial undamaged mooring system is said to be redundant.

Guidance note:
The dynamic behaviour of the FOWT in the case of a lost mooring line should be carefully assessed. Depending on the type of mooring system and the number of mooring lines, the line tension may increase or decrease in such a situation.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---
In case the station keeping is not redundant, higher consequence class (class 2) is required. This leads to higher load safety factors as required in DNVGL-ST-0119. Note that since the system is not redundant, it is not necessary to consider the above-mentioned ALS load cases.

For a TLP, the minimum tension in at least three corners shall remain non-negative in the required accidental environment which is one year return environmental loads. This is a requirement of DNVGL-OS-C105.

In case it is not obvious to conclude whether a station keeping system is redundant or not, it may be necessary to carry out a qualification of the redundancy. It shall be demonstrated that the system is capable of withstanding one year return period load effects in the damaged condition after an incident.

### 5.5 Serviceability limit state

#### 5.5.1 Serviceability limit state load cases considered

**Serviceability limit state**

For the RNA, it is acknowledged that the most proper way to verify SLS criteria is to compare project loads and design loads of the components. However, a full load simulation is usually not possible at the conceptual design phase. During this development phase, it may be acceptable to assume some limit values which are subjected to further adjustments at later stage.

SLS limit values correspond to project-defined criteria, see DNVGL-ST-0119. Therefore, below mentioned values are given only for indication.

- max. tilt at tower top during operational load cases e.g. DLC 1.2, 1.6:
  - permanent value: 0.5 degrees
  - mean value in the time series: 5 degrees
  - max. value in the time series: 10 degrees
- max. tilt at tower top during non-operational load cases e.g. DLC 6.1, 6.2: 15 degrees
- max. acceleration at tower top during operational load cases e.g. DLC 1.2, 1.6: 0.3g
- max. acceleration at tower top during non-operational load cases e.g. DLC 6.1, 6.2: 0.6g.

**Guidance note:**

Typically, the model in the load simulation considers an ideal vertical tower. For the bottom fixed structure, the permanent tilt angle is due to installation and fabrication tolerances. It is usually assumed acceptable to limit the out of vertical distance to a certain value such as 8 mm per 1 m length which is approximately 0.5° and add a constant bending moment in the resulting bending moment at tower bottom. It is assumed that the out of plane verticality does not lead to non-linearities in the loads at the tower bottom. For the FOWT, if the tower is modelled as vertical in the load simulation, the permanent tilt angle should be limited so that it does not lead to significant non-linear effect.

---end---of---g-u-i-d-a-n-c-e---n-o-t-e---

#### 5.5.2 Consequence of serviceability limit state cases

The potential consequences of SLS cases on the RNA, but not limited to, may be as follows:

- One scenario of the implementation of SLS cases is that, if the RNA loads exceed the design loads, then the designer may decide that the turbine shall be stopped in such circumstances, which may result in an increased number of shut downs and start-ups. This shall be taken into account for the FLS. In addition, the final consequence may be on the loss of electrical power due to the increased shut downs, which may also need to be addressed.
- The second scenario may be that the loads due to SLS conditions are still within the design envelope. In this case, it may be necessary to redefine certain protection system limiting values such as tower top acceleration. In such conditions, the functionality of the updated protection system shall be documented and probably demonstrated by means of in-situ tests.
5.6 Data analysis

5.6.1 Computation of characteristic loads

Characteristic loads are loads and structural responses without safety factors. The reference period of the extreme values used to derive the characteristic loads should equal the largest time period of stationarity assumed in the environmental conditions.

**Guidance note:**
As an example, it is typical to assume stationarity over a period of 3 hours for waves and 10 minutes for wind. According to the above, the reference period of the extreme values used to derive characteristic loads should then be 3 hours. However, it should be noted that the wind time series may be modified in accordance with [3.1.4] to avoid unrealistic extreme wind speeds.

---end-of-guidance-note---

For bottom fixed wind turbines, the statistical methods used to derive characteristic loads based on the extreme values (such as mean of maxima, absolute maxima, mean of top half maxima etc.,) are well established in IEC 61400-1 and IEC 61400-3-1. The same methods are also applicable for most parts of the FOWTs. However, for the mooring system, the required extreme value shall be estimated as the most probable max of the time series of the line tension, see DNVGL-OS-E301.

5.6.2 Partial load factors
Partial load factors as detailed in DNVGL-ST-0119 shall be applied.

5.6.3 Design loads
Design loads are characteristic loads multiplied by partial load factors.
Guidance on the documentation of ULS loads may be found in DNVGL-ST-0437 App.C.
During conceptual design, it is possible to include some contingency factors to derive design loads wherever uncertainties (such as finalization of soil conditions, etc.) are present.

5.6.4 Computation of 1 Hz damage equivalent load
As an intermediate check, it is useful to evaluate the plausibility of loads based on the 1 Hz DEL, see App.B for further information. The 1 Hz DELs may provide valuable insights into the load variations in the time series signals. This may provide indications on which environmental combinations result in worst loading (or consume larger fatigue life).

5.6.5 Computation of life time damage equivalent loads and Markov matrices
The life time fatigue damage is expressed by means of life time loads by taking the wind distribution into account.
Usually, the project is designed for a specific site and the site wind distribution is usually derived and approved, a priori. For calculating the damage equivalent loads for a specific project, the actual site Weibull distribution is used.

Please note that the damage equivalent loads are relevant for the material such as steel, composite, etc. However, for concrete, as the mean load is important, the fatigue is usually expressed by means of Markov matrices. A typical format of the Markov matrices is providing the number of cycles for a load range for the given mean load. For details regarding Markov matrices for concrete, see DNVGL-ST-0126.
5.7 References


/6/ Abdallah, I., Natarajan, A., & Sørensen, J. D. (2015), Assessment of extreme design loads for modern wind turbines using the probabilistic approach. DTU Wind Energy.


SECTION 6 CONTROLLER

6.1 Introduction
The controller for the floating system (wind turbine and platform) is used to operate the system in such a way that it achieves its objectives of safe operation and energy capture. The controller typically has the ability to manipulate the blade pitch angle, the generator torque, shaft brakes, nacelle orientation and possibly ballast levels to achieve these objectives. The controller manipulates these actuators as a function of measured turbine states, and has in-turn an impact in those same turbine states, resulting in a tight coupling between the dynamics of the system and the dynamics of the controller. The coupled system is illustrated in Figure 6-1.

![Coupled system of control system and floating system](image)

Figure 6-1 Coupled system of control system and floating system

6.2 Energy capture objective
The foremost objective of the turbine is to collect energy. A typical variable-speed, pitch-controlled, horizontal-axis wind turbine functions in four major regions of operation when producing power. The regions are illustrated in Figure 6-2 with typical steady state trajectories of control variables, and are also described below. Note that specific implementations and naming conventions may differ.

6.2.1 Cut-in
At very low wind speeds the turbine is activated and the rotor is controlled to operate at its minimum speed. The blade pitch angle is held constant and the generator torque is allowed to vary in order to keep the speed constant.

6.2.2 Variable speed
As the wind speed increases, the rotor speed is allowed to vary in order to maximise energy production and reduce loads. The rotor speed is controlled by allowing the generator torque to vary while the blade pitch angle is kept constant.

6.2.3 Region transition
As the wind speed increases further, the rotor will reach its maximum speed. The controller will vary the generator torque to keep the rotor speed from exceeding the maximum speed.

6.2.4 Above rated
The wind is now above its rated value for the turbine and the turbine has reached its rated power. The generator torque alone is no longer capable of keeping the rotor from exceeding the maximum speed and is kept at its maximum level. The blade pitch angle is now used to shed additional aerodynamic torque by altering the aerodynamic performance of the rotor thereby keeping the rotor speed approximately constant.
6.3 Safe operation objective

The wind turbine operates in turbulent wind, and when coupled with a floating platform, any motion of the platform also introduces an apparent wind on the rotor. Therefore, depending on the region of operation, the blade pitch angle and/or the generator torque will continuously be adjusted by the controller to reject wind disturbances, keeping the turbine as close to its steady state trajectory as possible as seen in Figure 6-2, see /1/. In designing the controller, care should be taken that the system aero-hydro-elastic natural frequencies are not excited by the controller.

The controller may also be designed to actively damp specific system resonances through the intelligent use of actuators. For example, the generator torque demand may be used to dampen drivetrain oscillations, the collective blade pitch angle may be used to stabilise the platform in pitch and surge motions and the individual blade pitch angle may be used to reduce asymmetric loading on the rotor, see /2/.

The complete power production turbine controller, with power control and load reduction control loops, shall operate in a stable manner over the entire operational envelope of conditions expected for the turbine. This includes (but is not limited to) during the entire range of operational:

— turbine states (start-up, shut-down and normal operation)
— sea states
— wind conditions and
— platform motions.

The controller is also required to implement safety related actions on the floating system. For example, emergency shut-downs may be initiated based on the environmental conditions and/or system faults. The specific logic behind the safety related actions may have a substantial impact on the resulting dynamics and
loading on the entire system. Therefore, the various safety related actions also should be carefully designed taking into account knowledge of the entire system.

6.4 Challenges for floating wind

The methods for achieving the objectives described in the previous sections are relatively mature for bottom-fixed wind turbines. However, the addition of a floating platform introduces several challenges that require careful consideration when designing and implementing controllers. In general, it should not be assumed that an existing controller for a bottom-fixed turbine will meet the required objectives if applied to a floating system. In this section a series of challenges have been identified with potential solutions offered, however, it should still be expected that speed/power variations as well as loading variations will increase when moving from a fixed foundation to a floating platform. All solutions presented should be tested in suitable higher-fidelity 'coupled' simulation and during prototype commissioning.

6.4.1 Coupling of platform surge/pitch motions with pitch-speed control

Controlling the rotor speed with blade pitch control may prove to be de-stabilising for platform motions in the surge and/or pitch directions. This is because feathering of the blade leads to a decrease in both aerodynamic torque and aerodynamic thrust and vice versa when pitching the blades to fine. A reduction in torque will decelerate the rotor, but also reduce thrust loading on the rotor, causing the turbine and platform to pitch/translate forward. The forward motion of the turbine will result in an increase in apparent wind speed through the rotor, requiring the blades to pitch further to feather to maintain the rotor speed. This cycle may result in an unstable positive feedback loop. This effect is well documented in literature, see e.g. /3/ and /4/.

The implications for control design may be illustrated well using a pole-zero plot, or a root locus plot as shown in Figure 6-3. The figure shows the platform modes (poles) and zeros resulting from a linearization of the OC4 turbine at an above rated wind speed, from collective pitch angle to generator speed, see /5/. The zero associated with the platform pitch is clearly non-minimum phase (NMP) and limits the gain crossover frequency to below 0.03 Hz, which is extremely slow. If onshore performance was required for this turbine, we may expect the gain crossover frequency to be ~0.15 Hz, but directly applying the onshore controller may destabilise the platform pitching motions.

Figure 6-3 Root locus of the pitch-speed control loop with a PID controller on the OC4 turbine. Open loop poles (x), open loop zeros (o), root locus (-), lines of constant damping/frequency (-)
Many methods have been presented to decouple the rotor speed control loop from the platform motions, these may largely be separated into three groups described in [6.4.1.1], [6.4.1.2] and [6.4.1.3].

6.4.1.1 Reduce bandwidth of the speed control loop
The speed control loop may be stabilised by detuning the controller (reducing overall loop gain) until the controller bandwidth is below that of the platform natural frequencies. This method results in the rotor speed control being decoupled from platform motions by frequency separation. It is suitable for systems with large rotor inertia and frequencies below platform natural frequencies. The weakness of this method is that rotor speed variations (and consequently power and thrust variations) may be become very large. In the example shown in Figure 6-3, this may require the controller gain crossover frequency being reduced to below 0.03 Hz. See /6/ for an analysis of this method.

6.4.1.2 Explicitly remove pitch actuation at platform frequencies
Several methods involving the reduction of the pitch activity at the platform frequencies, whilst maintaining the pitch actuation outside these frequencies have been investigated. These methods make use of auxiliary feedback loops which can augment the speed controller inputs and/or outputs to mask activity that is occurring in response to the platform motion. The result is that any blade pitch activity will only react to rotor speed changes outside (above and below) the frequency of platform motions, preventing destabilising positive feedback. The strength of this method is that the existing speed controller may be used with little modification, as long as the auxiliary control loops are well designed. The controller should be faster than a reduced bandwidth controller. See /7/, /8/ and /9/ for implementations of these methods.

6.4.1.3 Introduce explicit platform stabilisation loops
It is also possible to actively stabilise platform motions using a variety of methods. These techniques measure platform motions in some way (e.g. nacelle acceleration) and apply corrective blade pitch commands to stabilise the motions whilst still maintaining adequate power capture. However, additional corrective pitch activities can increase pitch actuator loading and drive train loads. Synthesis techniques for this method range from multi-input multi-output (MIMO) optimal designs such as linear quadratic gaussian (LQG), model predictive control (MPC) and H∞; to multiple classically tuned single-input single-output (SISO) designs.

If the design is constrained by using collective blade pitch angle control for speed control and platform stabilisation, the position of the NMP zero in the speed control loop may not change. However, by utilising additional sensors for the platform stabilisation loop, it is possible to reshape the root locus for the speed control loop. An example of this is shown in Figure 6-4 which shows the system first introduced in Figure 6-3, but with the addition of a platform stabilisation loop from nacelle acceleration to collective blade pitch angle. The figure shows a clear shift in the locus shape, allowing a larger range of gains before stability is breached. The astute reader may notice the gain crossover frequency is not increased sufficiently, however, the overall loop gain is much higher, so the response away from the pitch frequency is greater. The net result is similar to that of blade pitch activity removal at platform frequencies, but is also coupled with active platform damping from the stabilisation loop at those frequencies, so we may expect improved performance.
Figure 6-4 Root locus of the pitch-speed control loop with a PID controller on the OC4 turbine including a blade pitch platform stabilisation loop. Open loop poles (x), open loop zeros (o), root locus (-), lines of constant damping/frequency (-).

We may also make use of additional actuators to change the response. For example, if there is spare capacity in the generator/power converter, it may be possible to introduce generator torque actuation to assist the pitch actuators. Using generator torque actuation allows speed control of the rotor without impacting platform surge/pitch motion (low aerodynamic influence) and having only a minor impact on roll/sway motion. Like the blade pitch controller, this loop may take a range of inputs to achieve its objectives, for example rotor speed and/or nacelle acceleration. Utilising the additional actuator may also shift the zeros of the blade pitch-speed control loop, see /10/, allowing a further increase in bandwidth of the pitch-speed loop. This phenomenon is illustrated in Figure 6-5 which shows the speed controller root locus with the addition of both blade pitch and generator torque platform stabilization loops that use nacelle acceleration feedback. We may see that the zero caused by platform pitch motions is no longer NMP. Other actuators may include, using individual blade pitch control, to introduce asymmetric rotor tilt loading to assist in stabilising the platform.
Figure 6-5 Root locus of the pitch-speed control loop with a PID controller on the OC4 turbine including blade pitch and generator torque platform stabilisation loops. Open loop poles (x), open loop zeros (o), root locus (-), lines of constant damping/frequency (-).

Using MIMO optimal design techniques does not usually require looking into the root locus of each individual loop, however linear analysis of the results will reveal the same resulting characteristics. See /9/, /10/, /11/, /12/, /13/, /14/ and /15/ for various implementations of these techniques.

There is no requirement that these techniques shall be used in isolation and we may expect that a combination of techniques may result in the best performance.

6.4.2 Non-linearity due to large system motions

The stability of control designs is usually demonstrated with high-order linearized models of the floating system with the controller in closed loop. For fixed-base turbines a range of linear models are defined across multiple operating points that may be parameterised by wind speed. At each of these operating points, classical stability margins may be used to infer robustness of the system to errors in modelling. These errors in modelling may be greater for floating turbines as the turbine may undergo larger motions. It is recommended that the controller is demonstrated to be robust across the full range of operation, preferably by suitable higher-fidelity simulations in a full range of conditions. For measurable/predictable low frequency events such as tidal height changes, it may be advantageous to gain schedule the controllers to avoid sacrificing performance for robustness.

6.4.3 Lightly damped yaw motion

Some floating turbine designs may have relatively lightly damped yaw degrees-of-freedom. Making use of individual blade pitch control (IPC) to reduce asymmetric loading in the yaw direction may reduce excitation in this degree-of-freedom. See /16/ for guidance on designing IPC controllers. If given a yaw reference, the IPC may also be used to actively damp yaw platform motion in a lightly damped system.
6.4.4 Rotor harmonic clashes with structural frequencies

It is not uncommon to see the tower of a floating turbine have a significantly higher dominant natural frequency than fixed base machines as explained in [4.2.2.3]. This may be for a number of reasons including the use of wider and/or shorter towers. The increase in frequency may result in a clash with the blade passing frequency (3P) within the operational range of the turbine. This clash may induce significant fatigue damage on the tower. Possible solutions to avoid this problem are:

— change the operational rotor speed range to be outside the clash
— implement a speed exclusion zone within the controller which prevents the turbine operating at specific speeds and
— implement IPC to reduce 3P excitations of the structure.

6.4.5 Monitoring

Additional monitoring requirements have been identified for FOWTs in DNVGL-ST-0438. It is important that alarms and safety actions are designs to protect the turbine during the full range of motions of the turbine.

6.4.6 Fidelity

As the control behaviour has a strong impact on the overall system dynamics, it is important that any floating system model used for dynamic analysis includes a suitable representation of the control system. The following recommendations are made for the requirements of the control system model:

— the control system update rate (both measurements and demands) should mirror that of the system in the field
— the controller tuning should mirror that of the system in the field
— the controller logic should mirror that of the system in the field
— the sensor characteristics (noise and dynamics) should mirror that of the system in the field, including any impact due to large platform motions, i.e. the impact on nacelle acceleration measurements
— input and output signal delays should mirror that of the system in the field
— the dynamics of any actuators should mirror that of the system in the field.

6.4.7 Active ballast system

6.4.7.1 Active ballast system description

Active ballast system concepts are being taken up by some floating platform designers to benefit power capture and reduce structural loading by maintaining a desired heel angle. Typically, they counter mean overturning moments arising from the environmental effects of current loading and wind turbine thrust, or drag depending on the operational state. A measurement of the inclination of the platform is fed into a control system which acts to move ballast in the floater to maintain a preferred heel angle.

The trade off in the control design may be to reduce the activity of the system, which may use power unnecessarily and wear out components, while tracking as closely as possible the desired inclination, to maximise power and reduce loading. Generally, filters may be used to avoid acting on high frequency inclination deviations, due to effects such as waves, while hysteresis may be present in the system to prevent unnecessary usage and mean tolerances may be present on the mean heel angle.

6.4.7.2 Integration with the wind turbine controller

As the environmental conditions that the controller counters vary slowly over time, it is common for the control systems that move ballast in the platform to also act over long time scales and so, from a frequency perspective, are quite isolated from the wind turbine controller dynamics. If this is the case, then the two control systems may be designed separately which might be more practical. However, if this may not be
proven then the two systems shall be designed together to ensure a robust and stable control of the overall FOWT system.

Regardless of which design philosophy is followed and by whom, the effects of the active ballast system shall to be taken into account when performing the coupled analysis exercise as described in [4.4].

6.4.7.3 Fault analysis

Including active ballast control in the FOWT system adds an extra degree of complexity and with it the potential for malfunction. The floater designer shall study this potential through a failure modes and effects analysis and include faults that affect wind turbine loading within the load calculations, as stated in [4.4]. The extent to which malfunctions may occur will depend on both physical redundancy and redundancy in the control system, both of which should be considered.

6.5 References


SECTION 7 MODEL TESTING AND VALIDATION

7.1 Introduction

7.1.1 General
In this chapter recommendations are given for physical model testing of floating offshore wind turbines (FOWTs). The recommendations shall be read in conjunction with the general recommendations for hydrodynamic model testing provided in DNVGL-RP-C205 Sec.10. While DNVGL-RP-C205 focuses on applications in the oil and gas and maritime industries, the present RP is focussed specifically on model testing of FOWT substructures.

7.1.2 The purpose of model testing

7.1.2.1 General
Compared to full scale tests at sea, model tests require less time and resources, may be carried out with less risks and more flexibility. A good control of the loading conditions makes it possible to investigate rare but critical conditions. Also, control of the relative importance of different environmental loadings is a desirable benefit provided in a model basin. Model tests may be carried out to assess a wide range of issues. The items listed in DNVGL-RP-C205 [10.2] are also relevant for FOWTs:

— hydrodynamic load characteristics
— global system concept and design verification
— individual structure component testing
— marine operations, demonstration of functionality
— validation of numerical models
— estimation of extreme loads and response.

In addition to these, model tests of FOWTs are carried out to understand the loading mechanisms and relative importance of, and coupling between different environmental loads.

Model tests are often performed during the development of new concepts. Such tests may serve both for validation (or calibration) of numerical models, and to identify unexpected phenomena. The goal of the model tests should be to explore effects that are known to either be very important (i.e. confirm their importance) or that may be inadequately modelled in the numerical model.

7.1.2.2 Validation of numerical models
For development of new FOWT concepts, it is recommended to base the design on analytical or numerical models. The most important purpose of model tests in this context is therefore to validate the numerical model that is being used. It is expected that some simplifications shall be applied in all model test campaigns, and some phenomena are expected to be represented inaccurately in the model tests. It is therefore recommended to take a risk-based approach in selecting the focus for the model test campaign and subsequent validation of the numerical model. This means that uncertain and/or important aspects identified by the numerical analyses prior to tests shall be the focus for validation by the model test. In this way, the model test may be designed to emulate the desired effects as accurately as possible. Through this, uncertainties in the numerical model are reduced. Phenomena identification ranking tables may assist the assessment of aspects that should be the focus of the experimental validation, see /15/.

Further recommendations on validation of numerical models based on the results of model tests are given in [7.5].

7.1.2.3 Unforeseen phenomena
Model tests are often the first and last opportunity to carry out a global check of the global behaviour before it is built at full scale. Unforeseen phenomena may be revealed and explored in a controlled setting. It should
be noted that undiscovered phenomena are not guaranteed to be discovered even in model tests, because the physical models contain simplifications and are ‘only’ models of the full scale reality.

7.1.3 Basin model tests versus wind tunnel tests

The focus of this RP is on wave basin tests, even though equivalent wind tunnel tests may also be important for model validation, in particular of aerodynamic rotor models for FOWTs. Model tests of FOWTs in wind tunnels may be performed to evaluate aerodynamic and coupling effects. In these tests, the scaled down tower and RNA is placed on a robot base, at which loads and bending moments are measured and transferred through a virtual model of the floater. Floater motions and hydrodynamic loads are calculated in real time and the motions are applied at the tower base of the physical model. See /5/ for information on this approach.

Wind tunnel tests of FOWTs are more suitable for assessments of wind turbine performance and validation of aerodynamic load models than tests performed in model basins. As stated in [7.1.2.2], uncertain or important aspects to investigate in the model tests should be identified by numerical analyses and expert assessment prior to the tests. Depending on which aspects shall be studied, model tests either in a basin and/or in a wind tunnel may be recommended.

**Guidance note:**
In addition to the possibility of performing coupled tests in wind tunnels, wind tunnels are commonly applied to determine hull wind forces and current force coefficients.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

7.2 Challenges and limitations of model testing of floating offshore wind turbines

7.2.1 Scaling effects

**7.2.1.1 General**
Scaling effects are described in DNVGL-RP-C205 [10.9]. This is a particular issue for floating offshore wind turbines (FOWTs) due to the often equivalent importance of both aerodynamic and hydrodynamic loads. The fact that aerodynamic loads on the turbine scale differently than the wave loads is a significant challenge for model scale tests of FOWTs, and should be addressed in the design of the tests. The table below shows common dimensionless numbers used for defining the scaling laws.

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Froude</td>
<td>( Fr = \frac{U}{\sqrt{gL}} )</td>
<td>Ratio inertia force to gravity force.</td>
</tr>
<tr>
<td>Reynolds</td>
<td>( Re = \frac{UL}{v} )</td>
<td>Ratio inertia force to viscous force.</td>
</tr>
<tr>
<td>Keulegan-Carpenter number (KC)</td>
<td>( Ke = \frac{vT}{mD} )</td>
<td>Relative excursion of a water particle in oscillating flow relative to the size of a structural element.</td>
</tr>
<tr>
<td>Tip speed ratio (TSR)</td>
<td>( TSR = \frac{\omega R}{U} )</td>
<td>Ratio between the tangential speed of the blade tip and the actual wind speed.</td>
</tr>
</tbody>
</table>
### Strouhal number (St)

$$St = \frac{f L}{U}$$

Ratio between vortex shedding frequency times a characteristic length and flow velocity.

### Euler

$$Eu = \frac{pU^2}{F}$$

Ratio inertia force to pressure force.

### Weber

$$We = \frac{U}{\sqrt{\rho / \rho L}}$$

Ratio inertia force to surface tension force.

Froude, Reynolds, KC and TSR are particularly important for global behaviour of FOWTs. It is not possible to fulfill all model scale laws when doing model tests, as usually only one of the above dimensionless numbers may be fulfilled at the same time. This results in differences in forces between the model and the full scale prototype due to different flow conditions. These differences are referred to as scale effects, and appear mainly due to flow separation, surface friction and roughness, water spray effects, turbulence and cavitation.

Froude scaling is often applied in basin tests. Force components which then are affected by scaling effects include current forces, viscous wave forces, viscous drift forces, drag forces on mooring lines and power cables, and aerodynamic forces. Viscous scaling effects may be reduced if the surfaces are defined with sharp edges as this generates well defined shedding.

**Guidance note:**

A possible way to assess the scaling effects may be to do repeated tests with different model scales. However, this is not typically done for economic reasons. It may also be possible to do sensitivity studies to assess whether the viscous forces observed in the model basin are transferrable to full scale.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

If a FOWT is comprised of small elements relative to typical ocean wave lengths, drag loads caused by waves on these elements may be important. Use of appendages like strakes and heave plates increase the importance of viscous loads. However, scaling effects for these types of appendages are not necessarily large.

#### 7.2.1.2 Froude scaling law

For FOWTs, Froude’s scaling law is recommended when wave loads are important, because inertia and gravity loads are the main drivers for the behaviour of surface waves. When the model is geometrically similar to the full scale structure, the geometrical scale factor is defined as $\lambda = \frac{l_s}{l_m}$ where $l_s$ is a full scale length and $l_m$ is the same distance in model scale. The most common scaling factors when applying Froude scaling law are summarized in the table below.

**Table 7-2 Froude’s scaling law. $\rho_s/\rho_m$ is the ratio between water density in full scale to water density in model scale**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scaling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>$\lambda$</td>
</tr>
<tr>
<td>Angle</td>
<td>$\lambda^0$</td>
</tr>
<tr>
<td>Time</td>
<td>$\lambda^{1/2}$</td>
</tr>
<tr>
<td>Mass</td>
<td>$\lambda^3$</td>
</tr>
<tr>
<td>Velocity</td>
<td>$\lambda^{1/2}$</td>
</tr>
</tbody>
</table>

**Froude’s scaling law**

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Velocity</td>
<td>$\lambda^{1/2}$</td>
</tr>
</tbody>
</table>
Froude's scaling law

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scaling factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear acceleration</td>
<td>$\lambda^0$</td>
</tr>
<tr>
<td>Angular acceleration</td>
<td>$\lambda^{-1}$</td>
</tr>
<tr>
<td>Force</td>
<td>$(p_s/p_m)\lambda^3$</td>
</tr>
<tr>
<td>Moment</td>
<td>$(p_s/p_m)\lambda^4$</td>
</tr>
<tr>
<td>Frequency</td>
<td>$\lambda^{-1/2}$</td>
</tr>
<tr>
<td>Power</td>
<td>$(p_s/p_m)\lambda^4$</td>
</tr>
<tr>
<td>Flexural rigidity (EI)</td>
<td>$\lambda^5$</td>
</tr>
</tbody>
</table>

One important consequence of following Froude's scaling law is that the Reynolds number is not maintained, which implies that drag and lift loads may not scale properly. For FOWTs, this is particularly important because the aerodynamic loads acting on the tower and most importantly the RNA are dominated by lift and drag loads. Consequently, when following Froude's scaling law, the aerodynamic loads on the FOWT will not be correct for geometrically similar physical models of the wind turbine, see /25/. Possible modelling strategies to avoid this error are listed in Table 7-3 (see also [7.3]). There exists no perfect work-around for this problem, and specific scaling issues with each method should be considered. See also /19/.

Table 7-3 Strategies to mitigate Froude/Reynolds scaling issues, depending on the method to model aerodynamic loads in the model test

<table>
<thead>
<tr>
<th>Method</th>
<th>Strategy to mitigate Froude/Reynolds scaling issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive obstructing disc</td>
<td>Calibrate thrust force, see [7.3.5.2].</td>
</tr>
<tr>
<td>Passive fan/jet</td>
<td>Calibrate thrust force, see [7.3.5.2].</td>
</tr>
<tr>
<td>Hybrid method with fan/jet</td>
<td>Aerodynamic loads are calculated in software, and fan/jet is adjusted to give desired loads, see [7.3.5.4].</td>
</tr>
<tr>
<td>Hybrid method with cable-driven robots</td>
<td>Aerodynamic loads are calculated in software at full scale, and the resulting loads are applied by a cable-driven robot at model scale, see [7.3.5.4].</td>
</tr>
<tr>
<td>Physical wind turbine model (with blades rotating in the wind)</td>
<td>Redesign blades to achieve desired thrust, see [7.3.5.3].</td>
</tr>
</tbody>
</table>

Guidance note:

Drag and lift loads are preserved better when Reynold's scaling law is applied, but Reynold's scaling is usually not desirable in hydrodynamic model testing due to the importance of balancing inertia and gravity forces. Furthermore, keeping Reynold's number constant for a reduced geometrical scale would require wind velocities that are unrealistically large (which also potentially may influence the generated waves)

---end---of---guidance---note---
7.2.2 Wind generation

Floating offshore wind turbines are more sensitive to temporal and spatial variations in the wind field than oil and gas structures. Perfect wind tunnel conditions in a typical model basin may not be expected. In particular, generating a Froude scaled wind field at low wind speed in a basin is not straightforward. The swirl and turbulence intensity of fan generated wind may be dissipated by a dedicated wind generator, see /24/. Other techniques with which creation of swirls may be reduced are given in Courbois, see /19/. The way the air flow circulates in the room and how this affects the wind field should also be considered.

In general, the generated wind field should be validated by measurements of the wind prior to the tests. Limitations of wind measurement devices, e.g. the ability (or lack thereof) to measure the high frequencies of the wind spectrum, should be noted.

7.2.3 Laboratory size limitations

For FOWTs, the space available above and around the model basin may put constraints on the modelling of the wind turbine loads (cf. [7.3.5] for modelling of wind turbine loads). When a physical rotor model is used in the tests, care should be taken that uncontrolled wind turbulence does not result in thrust variations affecting the targeted dynamics of the system. Then, the size of the rotor in relation to the volume through which the wind is generated may become the most limiting parameter which then determines the scale of the test.

7.2.4 Rotor nacelle assembly weight limitations

If a fully instrumented physical rotor model is used in the tests, it may be difficult to avoid that the mass of the rotor-nacelle assembly (RNA) with instrumentation is heavier than the desired scaled-down mass, see /12/. The challenge increases with decreasing model scale. It is possible to account for this by shifting masses in the support structure to maintain the global moments of inertia and COG, but the mass distribution will not be maintained. This may be of importance for the structural modes and force measurements of the tower if an elastic model of the tower is applied. If mass deviations cannot be avoided, one possible way to address the mass deviation is the 'model of the model' approach, see [7.5.1].

Mass deviations may also be addressed by investigating numerically which results of the model test are inaccurate due to the mass deviation. The consequence for all relevant responses should be addressed in such a numerical investigation, and validation should only be carried out for the responses that are not affected by the deviation in mass.

7.2.5 Influence from instrumentation cables and actuators

7.2.5.1 Instrumentation cables

Measurement and power cables may influence the motion. This should be evaluated in every model set-up, for example by comparing free decay tests with and without as many of the cables connected as possible.

7.2.5.2 Actuators

When actuators are used to apply the wind loads, the actuators may influence the motion due to their own dynamic response. This should be evaluated in every model set-up, for example by comparing free decay tests with/without the actuators connected.

7.2.6 Wind turbine performance

Modelling of wind turbines in basins are in general not detailed enough to provide reliable data on power production.
7.2.7 Wind turbine controller
Building a fully functional FOWT with a physical rotor model which includes a wind turbine controller, requires simplifications. It is recommended to test the controller separately before including it in such model tests, cf. [7.3.5.3].

7.2.8 Floater and moorings
DNVGL-RP-C205 [10.4] describes some restrictions and simplifications encountered in hydrodynamic basin tests. Most notably, the basin size required to model catenary lines properly may limit the possible scale of the test unless truncation is applied.

7.2.9 Validity of tests
If a concept that has been model tested is altered, a new model test is recommended unless a numerical model calibrated by the model test results exists, is proven to remain valid, and simulations with the numerical model do not show large changes in the response of the system. Nonlinear hydrodynamic effects may alter significantly if geometrical changes to the model are significant or the water depth changes.

Guidance note:
When considering re-use of old model tests, it is difficult to quantify how large deviations are acceptable. In general, this is more a qualitative task than a quantitative. In other words, if all the same effects are seen in the old and new responses (calculated by the numerical model), the numerical model of the updated design may be argued to be validated. However, if hydrodynamic coefficients for the numerical model of the old design were calibrated based on the model test of the old design, new hydrodynamic coefficients should be established for the new design before the numerical comparison is carried out.

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7.3 Coupled aerodynamic and hydrodynamic model testing

7.3.1 Introduction
This section considers methods for the modelling of FOWTs in hydrodynamic testing facilities. The recommendations given by DNVGL-RP-C205 are applicable also for FOWTs. In addition, the relatively complex loading induced by the wind should be included. This is addressed in [7.3.5] below.

7.3.2 Selection of model scale
The choice of the model scale is depending on several parameters, and it is typically governed by the following factors (see also DNVGL-RP-C205 [10.9]):

— Limitations of model basin, e.g. tank size (area and water depth) and ceiling height, and its capability of generating the environmental conditions. This constraint usually puts an upper limit on the size of the model.

— The size of the chosen system for modelling of the aerodynamic loads: depending on the modelling method applied to model aerodynamic loads on the turbine and tower (cf. [7.3.5]), the fine mechanics and mass distribution of the RNA may put a lower limit on the size of the model, or require simplifications of the model.

— The minimum load magnitude and load variation that the actuator(s) may accurately apply on the model.

— The minimum load magnitude and load variation, that may be accurately applied on the physical wind turbine model.

— Possibility to properly model (at chosen scale, and with the required accuracy) hydrodynamic forces and phenomena, that are important for the results with the available wave maker and current generation facilities.
— Whether scaling of results may be performed based on proven model laws and empirical corrections.
— Whether acceptable measuring accuracies may be obtained.
— For tests with a full operating turbine model, scale may be dictated by the size of the already existing turbine model.

Large scales are often limited by the laboratory size, its capabilities to generate the environmental conditions, and practical/economic considerations. If physical wind is included, the size of the rotor may also be limited by the area spanned by the wind generator in the laboratory. Smaller scales are often limited by the ability to reproduce the right mass and structural stiffness of components, the increased uncertainties and less repeatability in the modelling, as well as larger scaling effects. In general, it is recommended to use as large scale as possible. For the validation of numerical models used in design, a scale larger than 1:50 is recommended. However, the recommended scale depends on the characteristic size of the structure and environmental conditions to be simulated.

7.3.3 Modelling of floating substructures

The floater model should be shaped as a geometrically scaled-down version of the hull of the floater. At model scale, the inertia properties should also be kept when Froude scaling is applied so that natural periods of the system and the wave response are properly represented. Depending on the modelling method applied to model aerodynamic loads on the turbine and tower (cf. [7.3.5]), it may be challenging to get the correct scaled-down mass of the fully instrumented RNA. In such cases, the mass of the floater model may be shifted to maintain inertia properties of the whole system. The error introduced by this approach shall be considered in the analyses of the test results, see [7.2.4].

Rigid floater models are usually sufficient for validation and global response evaluations. The possible influence of floater flexibility on model test results should be considered.

7.3.4 Modelling of the mooring system

For modelling of the mooring system, it is recommended to follow the guidance provided in DNVGL-RP-C205.

7.3.5 Modelling of the wind turbine

7.3.5.1 General

There are different ways to model the wind turbine in coupled tests performed in basins. The methods described herein uses different approaches to ensure that some of the aerodynamic load components are correct. However, these methods differ in the level of complexity and accuracy. When selecting a method for testing, it is important to be aware of the limitations of the method.

Guidance note:

For floating structures, the mean offset and the low frequent response to wind are the main targets of wind load modelling. Because of its slowly varying speed, the wind is likely to excite low frequent motions of a moored system. For an operating FOWT, the wind loads may be the dominant cause of the mean horizontal offset and the tilt angle of the structure.

In general, the methods may be arranged in three groups:

— passive methods
— physical rotor models
— real-time hybrid model testing.

Regardless of the method used for including aerodynamic loads, it may be important to model the mass and stiffness characteristics of the tower and turbine as accurately as possible. The stiffness characteristics may be important for the response of TLPs.

Physical rotor models and some passive methods require physical wind fields generated by fans. If the wind is generated by axial fans, it tends to be very turbulent due to the swirl of the fans (see also [7.2.2]). Further, the wind (which is created locally) may change quickly in space as it circulates in the model basin.
Shear with the water surface, walls and the ceiling of the basin may alter the uniformity of the wind. These effects should be sought minimised and the wind field should be documented before tests are initiated.

**Guidance note:**
Common ways to improve a wind generator is to diffuse the turbulence with screens or nozzles, see /9/. For the recirculation of the flow, larger basins (with more open space) are advantageous.

---end---of---guidance---note---

### 7.3.5.2 Passive methods
Passive methods are defined as fixed solutions that account for the steady mean thrust on the turbine from the wind. Methods that account for time-varying thrust forces only are also considered passive methods if they are included in a passive way, i.e. no possibility to include blade-pitch or torque controller. Examples of passive methods are:

- A wire applying a constant horizontal force to simulate a steady wind force is the simplest example of a passive method. This method will only account for steady thrust force on the turbine. Since this does not account for the coupling between floater motion and thrust, the aerodynamic damping is not correct, which again implies that pitch and surge amplitudes are incorrect. All other aerodynamic and wind turbine effects are also neglected.

- One or more wires mounted on winches applying time varying loads to simulate the wind load is a more sophisticated example of a passive method. This method accounts for the variation of the wind loads caused by the variation of the wind velocities, but it will ignore the coupling effect between floater motions and wind loads, which e.g. results in an incorrect thrust and aerodynamic damping.

- A solid or perforated disc combined with wind generated by fans may be used to represent the thrust force on the turbine. The disc should be sized to provide the correct mean force and RNA weight. The model wind speed may also be adjusted to give the correct mean force for various wind speeds.

General limitations with the passive methods are that they do not account for aerodynamic torque and other aerodynamic loads, as well as the effect of blade-tower aerodynamic interactions. The control systems present in the full scale system for blade-pitch or torque regulation cannot be modelled, and these methods may not be able to capture the correct derivative of the thrust with respect to TSR, which is important for the aerodynamic damping. Gyroscopic effects are also not captured by these methods, unless e.g. a rotating disc with tuned rotational velocity is attached on the tower to account for this. A passive method does not represent a very realistic condition and should not be used for final verification studies, if the aim of those are to verify the responses for wind velocities above rated and below cut-out. However, for extreme load cases where the turbine is idling, passive methods like the solid or perforated disc approach may be valuable. Furthermore, simple passive methods such as a wire applying a constant force may very well be used in tests where the aim is to calibrate hydrodynamic coefficients.

### 7.3.5.3 Physical wind turbine models
Physical wind turbine models are actual scaled down functional rotors with blades rotating in a wind field generated by a battery of fans. In this method, both the wind and the waves are modelled physically to deliver aerodynamic and hydrodynamic loads on the FOWT. The effect of the rotating inertia of the rotor and the drivetrain are physically modelled.

The physical model of the wind turbine may be scaled down by geometric scaling. This means that the wind field and the rotor blades are scaled according to the Froude scaling law. The geometric relations of the blades are preserved, but Reynolds similitude is not conserved. This means that the flow around the blades of the turbine cannot be replicated at the model scale, see /20/. Therefore, it is recommended to apply performance scaling of the rotor blades, see /21/. This means that the blades of the scaled down turbine model are redesigned to match the thrust force and power performance of the full scale wind turbine, see e.g. /14/ and /24/. An alternative approach, where the blade twist was modified instead of the airfoil was taken by Courbois, see /9/. A wind turbine model based on performance scaling may be combined with a Froude scaled wind field and floating substructure in the model basin, see /11/.

Because performance scaling first and foremost aims at reproducing the thrust force in some conditions, emulation of other aerodynamic effects may be less accurate, and the validity outside the range of the
calibrated wind velocities is not guaranteed. The importance of effects that may not have been emulated accurately should be assessed on a case to case basis.

It is challenging to preserve the mass distribution in physical wind turbine models, due to the weight of the scaled down wind turbine. The effect of this should be evaluated when considering results from model tests, see [7.2.4]. Further, see [7.2.2] regarding the generation of a Froude scaled wind field.

In principle, scaled down wind turbine models may be equipped with a pitch control simulating the full scale control mechanism. Before tests with controller are executed in the model basin, knowledge of the system’s response is required. The response time of the thrust variation is critical for the stability of the controller, which should operate at the Froude scaled time. It is recommended to test the FOWT without the controller prior to the tests with an active controller. Such tests serve to understand the floater's behaviour without the pitch controller.

7.3.5.4 Real-time hybrid model tests

Real-time hybrid model tests combine the physical experiment in model scale with numerical simulation in real time. The test object is divided into two parts: the floating substructure is tested physically in the laboratory at model scale and a virtual model of the wind turbine is simulated at full scale on a computer. The two models are connected and interact in real-time through a network of sensors and actuators, see /28/. The aerodynamic loads are calculated in full scale on the computer taking into account the real-time measured floater motions and are then scaled down using Froude scaling, avoiding the Froude-Reynolds scaling conflict. The numerical simulation inherently captures the aerodynamic damping. In addition to operational and survival conditions, the hybrid approach may model fault conditions such as blade seize or transient responses in emergency shutdown of the generator. In this method, the applied wind field and aerodynamic loads in the tests are known. The uncertainties related to physical modelling of the wind and the turbine loads are eliminated.

The forces simulated by the software may be applied by a different type of actuators. A ducted fan mounted on top of the turbine tower may be used to generate a force representing the turbine thrust force, see /1/. This method focuses on the application of the thrust force only. Recent developments include the use of several small electrical fans mounted in a matrix layout. In that case, the system of fans may in principle be calibrated to include the effect of other aerodynamic loads than thrust, see /4/. Cable-driven robots may be used to apply complex aerodynamic and inertial loads on the structure. This approach allows for applying multiple load components by connecting the structure to several land-based winches, see /3/, and /28/. The effect of wind shear, wind gust, tower shadow, blade size, possibly wind-waves interaction may for example be included, provided that they are described by the numerical simulation.

Numerical analysis should be performed prior to the test, on the one hand to allow selecting suitable actuators, and on the other hand to identify possible aerodynamic load components that have an insignificant effect on the quantities of interest, see /2/ and /13/. The complexity of the hybrid setup may be reduced by removing load components that induce insignificant responses.

The frequency at which the motions are measured is dictated by the sampling rate of the measurement acquisition system. The time and the motions are scaled up using Froude scaling as they are provided to the software. Therefore, it is recommended to check the stability of the software results at this time step.

A challenge with real-time hybrid testing relates to the complexity of the control system used to connect the physical model with the numerical simulation. Time delays may for example cause additional damping or may put spurious energy into the system. Actuators may also have a physical limitation to emulate high frequency loads that may be important for some types of structures (e.g. TLP’s). The capacity of the actuators to produce load variations at frequencies and in the range of amplitude that are important for the behaviour of the considered floater should be verified.

**Guidance note:**

The complementary alternative to the real-time hybrid tests described above, are hybrid tests that are performed in wind tunnels. In these tests, a wind turbine aero-elastic model (with individual pitch control, IPC) is placed on a moving base in a wind tunnel, while hydrodynamic loads and floater motions are simulated in real time on a computer.

See /5/ for more information.
7.3.5.5 Effects that may be investigated in tests
As stated in [7.1.2], the model test should be designed to emulate accurately the effects that should be investigated. This implies for example if the main concern of a specific concept is the behaviour in conditions where the turbine is idling or parked, the passive method with a disc representing the wind turbine may be fully applicable.

7.3.6 Simplifications at conceptual design phase
Simplified hydrodynamic model tests of an FOWT at an early phase of the development may be advantageous. Such tests may identify risks and reduce uncertainties at an early stage. While seeking simplified approaches, effects that are important for the design should be sought modelled as correctly as possible. The following list of simplifications may be relevant for early concept evaluations:
— Wind load modelled passively by a single winch (to assess mean offset and tilt). Since this does not account for the coupling between the floater’s motion and the rotor’s thrust, the induced aerodynamic damping is ignored and the amplitudes of pitch and surge are wrong.
— Smaller scales than the recommended minimum 1:50 may be applied.

The effects of any simplification in the model to be tested should be assessed. In many cases, numerical simulations may have a higher value at the conceptual design phase than experiments with too many simplifications. For final verification studies, or validation/calibration tests, the identified important effects, see [7.1.2.2], should be sought modelled as correctly as possible, i.e. the simplifications above may not be applied.

7.3.7 Measurements of physical parameters
7.3.7.1 General
Parameters to be measured during the model experiment depend on the purpose and type of tests carried out. Some quantities may be measured directly in the experiments, and other quantities may be derived from the measurements. DNVGL-RP-C205 [10.6] describes some quantities that may be derived from the measurements.

Physical quantities that should be measured in model tests of FOWTs are similar to those measured when testing other types of floating structures. Acceleration and loads at the RNA are essential parameters for FOWTs in operation, and should be included in the measurements. Furthermore, the wind turbine rotor is spanning a large area of the test section. Therefore, in the case physical wind is used in the experiments, it is important to also measure the spatial variations of the wind field.

Such measurements shall be performed as part of the documentation of the wind generator while no turbine interferes with the flow. The wind velocities may also be measured during tests in presence of the wind turbine. However, wind measurements during the test shall be made in a way that minimizes the alteration of the wind flow to the turbine.

7.3.7.2 Instrumentation and measurements
In the following, physical parameters that should be measured are given. Note that some of these quantities (marked with *) in the following list) shall be recorded directly by the software simulations in the case of real-time hybrid model testing. The list of parameters is as follows:
— Environment:
  — wave elevation
  — wind speed *
  — current speed.
— Model:
  — 6 DOF position
  — platform acceleration/platform displacement
  — mooring line/tether tension. May be measured at multiple locations along the line
— power cable tension if the power cable is modelled. However, this is not necessary, if the focus of the
test is the FOWT rather than the cable, as the influence of the cable on the FOWT may be neglected.
— internal moments and shear forces, e.g. at tower base and hub. However, reliable results rely on a
realistic elastic scaling, in particular of the tower:
— shear forces at the nacelle
— acceleration at the nacelle (for rigid models, this may also be derived from floater motions)
— rotor speed *)
— blade pitch angle *).

In addition, it may be relevant to measure (see DNVGL-RP-C205):
— Relative waves: air-gap and green water.
— Local slamming/impact loads.
— Video: it is recommended to record all model tests on video. It serves primarily as a visual support to
the measurements, but may for some cases be used for quantitative information. Underwater video
recordings may also be used to study the behaviour of underwater lines and their interaction with the
floater.

7.3.7.3 Data acquisition, analysis and interpretation
Data acquisition, analysis and interpretation of the measured data is common for all model experiments, see
DNVGL-RP-C205 [10.8].

7.3.8 Overall level of confidence and uncertainties
ITTC, see /17/ and /18/, provides extensive description of the uncertainty analysis of measurements in
hydrodynamic experiments. Uncertainties particularly related to testing of FOWTs in model basins includes
(see also /19/):
— the accuracy of the RNA modelling (geometry, elasticity, mass distribution)
— sensitivity to the dynamic response of the instrument cables
— sensitivity to additional loading on instrument cables (wind, current and waves if submerged)
— the accuracy of the spatial and temporal variations of the wind field generated. To reduce uncertainties,
the applied time series of the wind field should be repeatable.
— the accuracy of the actual installation of the FOWTs including the mooring and anchor system
— the accuracy of the model used for redesigning the scaled rotor blades (performance scaling) if a physical
wind turbine model is applied
— the decreased accuracy caused by large horizontal motions (including yaw rotation)
— for hybrid model testing the results are sensitive to time delays and the limited frequency range of the
actuating system, as well as the accuracy and correctness of the simulation models applied for real-time
aerodynamic load calculations
— the dynamic response of the actuators applying the wind loads (e.g. eigenfrequencies of cables,
bandwidth of winches, fans or propeller engines if these are used in hybrid models)
— the accuracy of actuators (e.g. rotational speed of fans, if these are used in hybrid methods)
— possible inaccuracies for low wind velocities (i.e. loads with small magnitude).

See also /27/ for a description of measurement, model and environmental uncertainties in model tests of
FOWTs.

In general, it is recommended to assess the uncertainties by performing repetitive tests of the individual
subsystems. By doing this, the possible bias and/or uncontrolled variability in the model setup is
documented. In particular, for FOWTs, the wind turbine loads should be assessed by repetitive tests with the
turbine fixed (i.e. not floating). See also [7.4.2] for recommended documentation tests.
7.4 Test program and documentation

7.4.1 General

This chapter provides an overview of the different types of tests that are recommended to be included in model experiments. It is advisable to do the experiments in a step-wise approach, with increasing complexity of the physics and test set-up. Typically, the programme consists of the following main test categories:

— documentation tests
— tests in single environment
— tests in combined environment.

Note that not all the tests described below are required. The type of tests depends on the purpose of the model experiments and the characteristics of the floater.

Table 7-4 Recommended tests for different purposes. See more details in [7.4.2] to [7.4.7]

<table>
<thead>
<tr>
<th>Type of test/purpose</th>
<th>Calibration of added mass and radiation damping, see also [7.5.1]</th>
<th>Calibration of hydrodynamic drag loads (i.e. damping and excitation due to drag), see also [7.5.1]</th>
<th>Concept demonstrations</th>
<th>Validation of numerical models, see also [7.5]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Documentation tests</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration of the environment</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Documentation of the model characteristics</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Calibration and documentation of aerodynamic loads</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Documentation of instrumentation</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Hammer tests</td>
<td></td>
<td>X (If flexible model)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclination tests</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Static pull-out tests</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Decay tests</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Single environment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave only</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Wind only</td>
<td></td>
<td>(Irregular sea)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current only</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Combined environment</td>
<td>Wind wave + swell wave</td>
<td>X</td>
<td>If relevant</td>
<td></td>
</tr>
</tbody>
</table>


### Type of test/purpose

<table>
<thead>
<tr>
<th>Type of test/purpose</th>
<th>Calibration of added mass and radiation damping, see also [7.5.1]</th>
<th>Calibration of hydrodynamic drag loads (i.e. damping and excitation due to drag), see also [7.5.1]</th>
<th>Concept demonstrations</th>
<th>Validation of numerical models, see also [7.5]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave + current</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave + wind</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave + wind + current</td>
<td>X ¹)</td>
<td></td>
<td>X ¹)</td>
<td></td>
</tr>
<tr>
<td>All (wind wave + swell wave + current + wind)</td>
<td></td>
<td></td>
<td>X ¹)</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>Fixed hull tests</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Forced oscillation tests</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹) The most important design load cases according to numerical analyses carried out prior to the model tests should be tested.

### 7.4.2 Documentation tests

The experimental setup should be checked and documented prior to the tests. This is to ensure that the actual model basin experiment represents satisfactorily the conditions that the experiments are set up to simulate.

#### 7.4.2.1 Calibration of the environment

It is recommended to pre-calibrate the environment before the tests, without the model present, to document the actual conditions in the model basin. The calibration of the environment should be carried out without the model present. This procedure requires a minimum level of repeatability of the environment in the tank facility. Low levels of repeatability contribute to the uncertainty of the final test results. See DNVGL-RP-C205 [10.3] for a detailed description on modelling and calibration of waves, currents and wind conditions in test facilities. Calibration of wind conditions are only relevant for approaches where the wind field is modelled physically (see [7.3.5]). For these approaches, the coherence, turbulence and wind gradients of the generated wind field over the entire rotor span should be measured and documented. The importance of discrepancies between the generated environment and the model should be assessed by a numerical model.

#### 7.4.2.2 Documentation of model characteristics

Model geometry, mass, mass distribution, metacentric height, waterline, bending stiffness of flexible tower models and other structural properties (e.g. the first global structural natural frequencies) should be checked and documented. Depending on the modelling method, it may be difficult achieve the correct mass distribution and stiffness properties. For some structures, in particular light structures such as TLPs, tower mass and stiffness characteristics should be modelled as correctly as possible to get the correct coupled roll and pitch modes. The influence of deviations in model characteristics should be evaluated and documented. This evaluation should be carried out applying a numerical model.
Guidance note:
The result of an evaluation of the influence of deviations in model characteristics may be that some responses are wrong. This information is crucial to be aware of when applying model test results for any purpose.

---end---of---guidance---note---

7.4.2.3 Calibration and documentation of aerodynamic loads
The wind turbine model should be calibrated and documented against expected load characteristics prior to the tests, regardless of the turbine modelling approach (see [7.3.5]). The range of wind velocities for which the model is valid should be established during these tests. When evaluating what test conditions the model is valid for, relative wind velocities due to floater motions should be considered. The influence on results due to deviations from desired load characteristics should be evaluated and documented.

Guidance note:
For methods requiring a physical wind field, the tests should be carried out with a fixed model and a wind generator in the model basin. For hybrid methods, the tests should be carried out on the floater model, to ensure the ability to apply the correct loads on a moving structure.

---end---of---guidance---note---

For passive methods (see [7.3.5.2]), wind load calibration is done by adjusting the passive device. As an example, the 'thrust' in a set-up with a drag disc may be calibrated by adjusting the size of the disc.

For methods with a physical wind turbine rotor, wind loads are calibrated during the design of the rotor model. The load characteristics of the rotor should be documented during the documentation tests. If an active rotor control system is used, it should also be checked and documented against expected behaviour prior to the test.

If hybrid methods are applied, it should be tested that the control system connecting the numerical model and the physical model achieves satisfactory reference tracking and disturbance rejection. By reference tracking it is meant the ability to apply a given load time series on the physical structure. By disturbance rejection, it is meant the capability to apply a given reference on a moving object. These tests may be performed the following way:

— decay tests with no actuation
— decay tests with actuation on but zero force applied (follow model)
— decay tests with constant wind applied by actuators (i.e. representing an operating wind turbine)
— application of a chirp force at a fixed model.

These tests shall be adapted depending on the technology used in the hybrid tests. Cable robots and fan-based actuation systems require different types of validation tests.

7.4.2.4 Documentation of instrumentation
Requirements on the type of instrumentation are given in [7.3.7]. Sensor characteristics (e.g. sampling rate) and accuracy levels of instrumentation shall be checked and documented.

7.4.2.5 Hammer tests
It is recommended to carry out hammer tests at relevant locations of the substructure to document structural eigenfrequencies. In particular, the first bending mode of the tower in both fixed and floating condition should be tested, if the tower model is flexible. Even if the model is considered rigid, hammer tests may be used to detect or identify the source of spurious vibrations in the measurements.

7.4.2.6 Inclination tests
Inclination tests should be performed to check the static stiffness in pitch and roll.

7.4.2.7 Static pull-out tests
Static pull-out tests (excursion tests in surge, sway and yaw) shall be carried out to document the static restoring stiffness of the mooring lines and possibly the power cable (if included in the model).
7.4.2.8 Decay tests
Natural periods in actual degrees of freedom shall be checked by performing decay tests. It is recommended that all degrees of freedom are checked in moored or tethered configuration, and additional decay tests in free-floating configuration (e.g. heave, roll and pitch) should be performed whenever possible. The tests should be carried out both with and without instrumentation and actuation cables, to document the possible influence of these. Hydrodynamic damping coefficients, valid for mild weather conditions, may be obtained from the decay tests, but to be applicable in design conditions they should be obtained from tests in irregular seas.

The following decay tests are recommended:
- tests in still water for all 6 DOFs
- pitch, surge and yaw tests in constant wind (to assess aerodynamic damping and control behaviour of controller if applied):
  - below rated speed
  - at rated speed
  - above rated speed if pitch or torque controller are available
- tests in current (if relevant).

Guidance note:
If obtaining hydrodynamic coefficients, possible scaling effects should be kept in mind. Most notably, the damping may be overpredicted due to the low Reynolds regime.

---end of guidance note---

7.4.3 Fixed hull tests
These tests may be used to obtain the environmental loads on the platform. The hull is fixed and loads of the environment are measured separately. For non-symmetric geometries, it is recommended to test in different headings.

If wave diffraction loads are of interest, then fixed hull tests with waves may be performed. Different wave periods of regular waves should be measured.

Steady currents should be used for measuring current loads. One option is to tow the model in calm water and measure the drag resistance.

7.4.4 Forced oscillation tests
Forced oscillation tests may be used to obtain hydrodynamic added mass and radiation damping coefficients. The model should then be oscillated at different frequencies. Forced oscillation tests may also be carried out on distinct appendages of the hull, which are expected to be drag dominated (like truss elements and heave plates) to determine drag and inertia coefficients, see e.g. /22/. However, the applicability of these coefficients if the rest of the floater is present may be limited because the presence of the floater changes the flow. Forced oscillations may also be carried out with waves present.

7.4.5 Tests in single environment
It is recommended to perform tests in a single environment to document effects of waves, current and wind separately. These tests should be carried out with the model in moored or tethered configuration.

7.4.5.1 Current only tests
Guidance note:
VIM and VIV can also be assessed by towing tests, see DNVGL-RP-C205.

---end of guidance note---
These tests may be used to establish current loads in steady current (uncoupled from waves) through measurement of the platform offset with a given restoring stiffness, see DNVGL-RP-C205 [10.6.5] for more information.

The tests may also be used to study vortex induced motions (VIM), typically for column shaped structures such as semi and spar-type platforms. Vortex induced vibrations (VIV) on cables or mooring lines, may also be studied. See DNVGL-RP-C205 [10.6.6] for more information.

**7.4.5.2 Wind only tests**

The programme should include tests with constant wind and turbulent wind. The tests should span over a range of wind speeds including below rated, rated and above rated wind speeds. Tests with wind speeds above cut-out should also be performed. The wind only tests may be carried out as part of the wind load calibration, see [7.4.2.3].

**7.4.5.3 Wave only tests**

These tests are important to establish the wave-induced motion response characteristics and the wave-induced slow-drift responses. Other strongly nonlinear effects, such as wave run-up, wave slamming, air-gap and green water effects, may also be relevant to investigate in these tests. See DNVGL-RP-C205 for more information.

The undisturbed wave elevation, measured during the wave calibration, is normally used as the reference for these experiments.

The following wave states may be relevant, depending on the goal of the model tests:

— Regular wave tests may be carried out to obtain linear motion transfer functions (RAOs) in the wave-frequency range. Tests in regular waves can also be used to estimate the mean wave drift excitation force at selected wave periods by measuring the mean offset. A range of wave periods and wave amplitudes (to quantify non-linear effects) should be tested.

— Broad-banded wave spectra with low energy can also be used to establish the linear RAOs. Ideally, these broad-banded spectra shall have constant energy across a range of frequencies. Using steeper sea states gives linearized RAOs where nonlinear effects may be included. Different wave steepness may be needed to quantify nonlinear effects.

— Bi-chromatic wave tests may be carried out to estimate off-diagonal terms of the quadratic transfer function (QTF) matrix. A large number of such tests are required if a full QTF is required, see e.g. /8/. See also DNVGL-RP-C205 for more information.

— Irregular wave tests to obtain e.g. RAOs, QTFs, or extreme values, see DNVGL-RP-C205 [10.8.3]. The hydrodynamic damping should be obtained or at least checked with irregular wave tests. For FOWTs it may be valuable to investigate the sensitivity of aerodynamic damping by testing the same sea states as the one tested with wind included. It may also be valuable to vary H_s (while keeping T_s constant) to check for non-linear effects.

**7.4.6 Tests with combined environmental conditions**

Waves, currents and wind normally occur in combination in real conditions. The global system behaviour in combined environmental conditions should therefore be verified experimentally. This is to verify the overall behaviour, but also because the interaction between waves, currents and wind may introduce other nonlinear effects that are not captured by testing in single environmental conditions only. Collinear conditions are often run in model tests, often because of limitations in the laboratory facilities but also because collinear conditions are considered conservative. Non-collinear conditions are also recommended, particularly to study the effect of non-symmetrical aerodynamic damping. Further, it is recommended to consider both unidirectional and multidirectional waves, as it has been shown that unidirectional waves are not necessarily more critical for FOWTs than multidirectional waves, see /10/.

Wave-current tests are important to capture nonlinear wave-current interaction effects such as increased wave drift forces and damping as well as viscous effects.

Wave-wind tests are particularly important for FOWTs, e.g. to study the dynamic effect of aerodynamic damping and responses due to the rotor control system. The tests should be carried out with irregular waves.
and turbulent wind. The same sea states as during the wave only tests should be tested to investigate the effect of aerodynamic damping. Both aligned and misaligned wind-wave conditions should be studied, with the wind speeds below rated, at rated and above rated wind speed.

Wind-wave and swell tests are important if the FOWT is meant to operate in an area which is exposed to swell, that have developed far away as well as to shorter waves arisen more locally by the wind. For these conditions, the direction of the wind-waves and swell won’t necessarily coincide exposing the FOWT to potentially more complex motions. These tests should also be carried out including wind and current. Misaligned environmental loads should be considered.

7.4.7 Design load conditions

The limit states considered for design of floating offshore wind turbines include fatigue limit states (FLS), ultimate limit states (ULS), accidental limit states (ALS) and serviceability limit states (SLS). Model tests in ‘real’ sea conditions with realistic combinations of environmental conditions are needed to confirm the design loads. Design load cases for FOWTs may be found in DNVGL-ST-0119, DNVGL-ST-0437 and IEC 61400-3-2, see /16/. However, it is expected that only a small number of these are tested in the basin. The selected test cases should reflect the purpose of the test, as described in [7.1.2]. Nevertheless, it is recommended to include a few of the driving ULS and ALS load cases in the model tests. For extensive studies of nonlinear extreme wave and response statistics it is recommended to repeat the tests with several different random seed numbers for the environmental spectra, to obtain different realizations. A selection of FLS and SLS conditions may also be of relevance to check the validity of the numerical model applied in fatigue life calculations also in milder conditions.

7.4.8 Reporting

The characteristics of the model setup, as well as the results of the test campaign should be documented and reported in a standard format. See ITTC guidelines /19/ for a suggested report structure.

7.5 Calibration and validation of numerical models

7.5.1 'Model of the model'

Due to scaling effects and other inevitable differences between the scaled model and the full scale FOWT, it is recommended to base the model validation on consideration of two separate numerical models: one representing the desired design at full scale ('design model'), the other representing the experimental model at full scale ('model of the model'). Comparisons between the experiment and numerical model should be done with the 'model of the model'. When validating numerical models with this approach, conclusions for the 'design model' should be drawn with caution based on the conclusions valid for the 'model of the model'.

7.5.2 Validation of coupled numerical model

The following tests are recommended to validate numerical models:

— Documentation tests:
   — calibration of the environment
   — documentation of model characteristics
   — calibration and documentation of aerodynamic loads
   — documentation of the instrumentation
   — hammer test (only if an elastic model is used)
   — inclination test
   — static pull-out tests
   — decay tests in still water with and without instrumentation cables, and in wind at relevant wind speeds.
— Tests in single environment:
  — current only tests
  — wind only tests at rated wind and above rated
  — wave only tests in irregular sea states.
— Tests in combined environment:
  — as a minimum, combined wind and wave environment to check coupling effects. Preferably, tests with simultaneous wind, wave and current. The load cases that prior to the model tests have been identified as design driving should be tested in the model tests. As a minimum, it is recommended to test DLCs 1.2, 1.6, 5.1 and 6.1 (see DNVGL-ST-0437) as part of the numerical model validation.

The validation of the numerical model should be based on comparisons between results of the model tests and the numerical model, for tests in single environment and in combined environment. The following responses should be verified by considering both time series and frequency spectra:
— thrust (alternatively, shear force at top of tower)
— bending moments at the top or at the bottom of the tower
— motions in 6 degrees of freedom, i.e. surge, sway, pitch, roll, yaw and heave
— mooring line tension.

If deviations are identified, these should be investigated and explained. The random and systematic uncertainties in the quantities of interest should be assessed and quantified, according to [7.3.8].

7.5.3 Calibration of hydrodynamic coefficients

Hydrodynamic coefficients may be calibrated based on model tests in basins. It is recommended to calibrate the coefficients based on tests in irregular sea states. It is not necessary to include aerodynamic loads in the model, unless the geometry of the floater changes significantly (due to heeling) when subjected to wind loads.

An example of the calibration of hydrodynamic coefficients based on model tests is given in /6/ and /7/.

The following tests should be carried out to calibrate hydrodynamic coefficients:
— Documentation tests:
  — calibration of the environment
  — documentation of the model characteristics
  — documentation of the instrumentation
  — inclination test
  — decay tests in still water and in irregular waves, with and without instrumentation cables.
— Forced oscillation tests.
— Wave-only tests (sea state depending on purpose).

7.6 References


/16/ IEC 61400-3-2 Design requirements for floating offshore wind turbines.


/18/ ITTC 2014b, Recommended Procedures and Guidelines 7.5-02-07-02.1 Seakeeping Experiments, Rev. 5.

/19/ ITTC 2014c, Recommended Guidelines 7.5-02-07-03.8 Model Tests for Offshore Wind Turbine, rev. 0.


APPENDIX A GENERAL ENVIRONMENTAL CONDITIONS

For definition of environmental classes, key environmental wave parameters for various regions in the world are given in DNVGL-RP-C205 App.C. The significant wave heights tabulated in DNVGL-RP-C205 refer to three hour stationary sea states. For stationary sea states with durations other than three hours, the significant wave height data in DNVGL-RP-C205 shall be suitably converted to properly refer to the actual sea state duration. The data in DNVGL-RP-C205 App.C include Weibull scale and shape parameters for regional long-term distributions of significant wave heights.

For the USA, the database of meteorological and ocean conditions of NREL may be used for the conceptual design, see /1/. The following conditionalities are used:

— wind speed was considered as an independent parameter
— wind/wave misalignment was conditioned by wind speed
— significant wave height was conditioned by wind speed and wind/wave misalignment
— peak spectral period was conditioned by wind speed and significant wave height.

![Figure A-1 Locations of the data buoys used in Stewart et al. (/1/)](https://nwtc.nrel.gov/metocean)

The distribution parameters of the full joint probability functions as well as the buoy data may be found at https://nwtc.nrel.gov/metocean.

Furthermore, the research project LIFES50+ specifies environmental conditions for three locations:

— moderate environmental conditions at Golfe de Fos-France
— medium environmental conditions at Gulf of Maine-USA
— severe environmental conditions at West of Barra-Scotland.

See report D1.1 (2015) of LIFES50+ project.

A.1 References

APPENDIX B DAMAGE EQUIVALENT LOADS

B.1 1 Hz damage equivalent loads

Using 1 Hz damage equivalent loads (DEL) is a convenient way of representing the fatigue damage of the given load component. Unlike the lifetime damage equivalent load, a Weibull scaling is not needed for 1 Hz DELs. Comparing 1 Hz DELs is therefore a method to check the plausibility of the loads.

![Figure B-1 Example of comparing 1 Hz DEL](image1)

For 1 Hz DELs, a constant amplitude load cycle is assumed which may give rise to same fatigue damage if a rainflow counting is done on a varying amplitude time series signal. Since, a typical fatigue load simulation lasts for 600 s duration, see IEC 61400-13, 600 constant amplitude load cycles would result in the 1 Hz DEL.

![Figure B-2 Illustration of 1 Hz DEL](image2)
For the given 10 minute (600 cycles) time series and material slope (m), the formula of 1 Hz DEL is given below, see IEC 61400-13.

\[
L_{eq} = \left( \frac{\sum_{i} L_i^m n_i}{600} \right)^{1/m}
\]

where:

- \( L_{eq} \) = 1 Hz DEL
- \( L_i \) = load range of the \( i^{th} \) bin of the fatigue load spectrum
- \( n_i \) = number of cycles in the \( i^{th} \) bin of the fatigue load spectrum
- \( m \) = inverse slope of the S-N curve for the given material.

A schematic of the process is given in Figure B-2. It may be seen that the typical 10 minutes time series load is converted to 1 Hz DEL for the required material slope which shall be the applied basis to evaluate the fatigue loads. The physical meaning of this approach is that if the damage equivalent load corresponding to this constant amplitude time varying load signal gives rise to the same fatigue damage corresponding to the varying amplitude time series. This means that one 10 minute time series load results in a unique value of the 1 Hz load value. When plotting these values against the mean wind speed variable, it is helpful to identify the resulting scatter due to different effects such as seed-sensitivity, influence of resonance etc. Further, if necessary it is also convenient to scale it to the required level if the Palmgren-Miner summation is followed. Another measure of the damage equivalent load is the standard deviation of the load signal. The 1 Hz DEL gives indication about to the standard deviation of the signal.

**B.2 Damage equivalent loads**

Damage equivalent loads (DEL) are used to compare different load spectra. The calculation is only based on equivalent load ranges and a predefined inverse slope of the S-N curve.

\[
L_{eq} = \left( \frac{\sum_{i} L_i^m n_i}{N_{ref}} \right)^{1/m}
\]

where:

- \( L_{eq} \) = DEL
- \( L_i \) = load range of the \( i^{th} \) bin of the fatigue load spectrum
- \( n_i \) = number of cycles in the \( i^{th} \) bin of the fatigue load spectrum
- \( m \) = inverse slope of the S-N curve for the given material
- \( N_{ref} \) = reference number of cycles, typically taken as \( 10^7 - 10^8 \) for wind turbines.

Comparing DELs might be useful to predict the damage or to validate 2 different models but some considerations should be taken into account:

- Each material is characterised by a different inverse slope (m). Therefore, selection of representative inverse slope is important.
- Furthermore, the mean level of the load spectrum is not considered in the comparison of DELs. Comparing DELs be not sufficient for materials which damage depends on mean level such as concrete or composite materials.
— By definition, DEL is always associated with a load component e.g. bending moment. Comparing DELs assumes that the damage is mainly driven by one load component. This is acceptable for tubular towers but might not be true for structures having complex form.

It is mathematically possible to convert the DEL of different number of cycles.

\[
\frac{L_{eq,N_{ref1}}}{L_{eq,N_{ref2}}} = \left(\frac{N_{ref2}}{N_{ref1}}\right)^{\frac{1}{m}}
\]

It is however not possible to convert DEL of different inverse slopes.
CHANGES – HISTORIC

There are currently no historical changes for this document.
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