Guidance Notes On

Global Performance and Integrated Load Analysis for Offshore Wind Turbines

August 2023

GUIDANCE NOTES ON

GLOBAL PERFORMANCE AND INTEGRATED LOAD ANALYSIS FOR OFFSHORE WIND TURBINES
AUGUST 2023

American Bureau of Shipping
Incorporated by Act of Legislature of
the State of New York 1862

ABS Plaza
1701 City Plaza Drive
Spring, TX 77389 USA

Foreword *(1 August 2023)*

These Guidance Notes supersede the ABS *Guidance Notes on Global Performance Analysis for Floating Offshore Wind Turbines* (July 2020). This revision is effective 1 August 2023.

These Guidance Notes should be used in conjunction with the ABS *Guide for Building and Classing Bottom-Founded Offshore Wind Turbines (BOWT Guide)* and the ABS *Guide for Building and Classing Floating Offshore Wind Turbines (FOWT Guide)*.

These Guidance Notes provide guidance on the global performance analysis and integrated load analysis methodologies, modeling strategies, and numerical simulation approaches for bottom-founded and floating offshore wind turbines.

Since integrated load analysis (ILA) is required for certification by the IEC 61400 series standards and recommended for class, these Guidance Notes also provide guidance on the ILA procedures for bottom-founded and floating offshore wind turbines to comply with the following standards where applicable:

- ABS *Guide for Building and Classing Bottom-Founded Offshore Wind Turbines* (*BOWT Guide*)
- ABS *Guide for Building and Classing Floating Offshore Wind Turbines* (*FOWT Guide*)
- IEC 61400 series standards for offshore wind turbines
- Other referenced industry standards applicable to offshore wind turbines

These Guidance Notes do not set additional design requirements and criteria other than those specified in the *BOWT Guide*, *FOWT Guide*, and IEC 61400 series standards.

The July 2020 edition aligns these Guidance Notes with the latest edition of the *FOWT Guide*.

The August 2023 edition includes the integrated load analysis methodologies and procedures, expands the application to bottom-founded offshore wind turbines, and makes editorial changes.

These Guidance Notes become effective on the first day of the month of publication.

Users are advised to check periodically on the ABS website www.eagle.org to verify that this version of these Guidance Notes is the most current.

We welcome your feedback. Comments or suggestions can be sent electronically by email to rsd@eagle.org.

GUIDANCE NOTES ON

GLOBAL PERFORMANCE AND INTEGRATED LOAD ANALYSIS FOR OFFSHORE WIND TURBINES

CONTENTS

SECTION **1**

Introduction

1 General *(1 August 2023)*

Global performance analysis for an offshore wind turbine is conducted to calculate the global responses including displacements, motions, and loads that can be used for the design and design evaluation of the offshore wind turbine and its subsystems and components.

The subsystems of an offshore wind turbine typically include the rotor-nacelle assembly (RNA), support structure, and if deemed relevant, power cables. For a bottom-founded offshore wind turbine (BOWT), the support structure comprises the tower, substructure, and foundation. For a floating offshore wind turbine (FOWT), the support structure comprises the tower, floating substructure, and stationkeeping system. The complexity and fidelity of these subsystems in the global performance analysis model may vary at different design stages.

In the design process of an offshore wind turbine, wind turbine manufacturers design the wind turbine generator (WTG) including the RNA and the tower. Since the wind turbine generator is often type certified to the IEC standards, a site-specific design evaluation should be performed to verify the wind turbine generator's suitability for a wind farm project.

For the substructure and foundation or stationkeeping system of an offshore wind turbine, there are typically two design stages:

i) *Stage 1: Preliminary Design Phase.* Wind turbine manufacturers are often not directly involved. For the purposes of the design analysis, a generic wind turbine model or a simplified wind turbine model is normally used.

ii) *Stage 2: Detailed Design Phase*. Wind turbine manufacturers are involved. The design analysis is typically based on an integrated design approach using an integrated analysis model.

Each design stage may involve several design cycles in which analysis methodologies and modeling strategies of various fidelity levels are used for global performance analysis. These methodologies generally include the coupled and uncoupled time-domain analysis approaches as well as the frequency domain analysis approaches.

Integrated Load Analysis (ILA) as an integrated time domain analysis approach may be required by the regulators, ABS, or certification bodies. The terms "integrated load analysis" and "coupled analysis" are often used interchangeably in the literature. Although the integrated load analysis usually uses the coupled analysis approach, the integrated load analysis also refers to a specific design process for offshore wind turbines.

In the context of offshore wind turbine design standards such as IEC 61400-3-1 and IEC 61400-3-2, an integrated load analysis refers to the design analysis method and procedure for load and load effect calculations for the entire offshore wind turbine comprising the RNA and the support structure. The design evaluation of the RNA components and the support structure is performed using the results from the integrated load analysis.

3 Application *(1 August 2023)*

These Guidance Notes provide guidance on global performance analysis and integrated load analysis (ILA) methodologies, modeling strategies, and suggestions for numerical simulations for BOWTs and FOWTs.

Since integrated load analysis (ILA) is required for certification by the IEC 61400 series standards and recommended for class, these Guidance Notes also provide guidance on the integrated load analysis procedures for bottom-founded and floating offshore wind turbines to comply with the following standards where applicable:

- ABS *Guide for Building and Classing Bottom-Founded Offshore Wind Turbines* (*BOWT Guide*)
- ABS *Guide for Building and Classing Floating Offshore Wind Turbines* (*FOWT Guide*)
- IEC 61400 series standards for offshore wind turbines
- Other referenced industry standards applicable to offshore wind turbines

These Guidance Notes do not set additional design requirements and criteria other than those specified in the *BOWT Guide*, *FOWT Guide*, and IEC 61400 series standards.

5 Analysis Methodologies *(1 August 2023)*

5.1 General *(1 August 2023)*

Global performance analysis for offshore wind turbines in these Guidance Notes refers to:

i) Global load analysis for bottom-founded offshore wind turbines (BOWTs), or

ii) Global performance analysis for floating offshore wind turbines (FOWTs).

Different analysis methodologies may be used in a global performance analysis as summarized below in this Subsection.

5.3 Frequency-Domain and Time-Domain Analysis for Offshore Wind Turbine *(1 August 2023)*

5.3.1 Frequency-Domain Analysis *(1 August 2023)*

Frequency-domain analysis refers to calculation of loads and responses in the frequency domain by solving the equations of motion using methods of harmonic analysis or methods of Laplace and Fourier transformations.

5.3.1(a) Frequency-Domain Analysis for BOWTs *(1 August 2023)*

For BOWTs, the frequency-domain analysis approach may be used for the fatigue analysis of the substructure subject to wave loads. The equations of motion are linearized in the frequency-domain analysis. The wind and wave load effects are decoupled. The dynamic interaction between the RNA and the support structure caused by combined wind and wave excitations is not accurately modeled. The critical dynamic interaction is aerodynamic damping. The frequency-domain approach is thus less accurate than the time-domain approach.

In the frequency-domain analysis, the support structure is modeled with a finite element (FE) model, and structural dynamics equations are solved in the frequency domain. The RNA is typically modeled as an equivalent concentrated mass on top of the tower. Aerodynamic damping as a function of wind speed and wind-wave misalignment should be separately evaluated and applied in the analysis. The frequency-domain approach can reduce simulation time significantly compared to the time-domain approach. Due to accuracy limitations, the frequency-domain method is usually used in the preliminary design phase.

5.3.1(b) Frequency-Domain Analysis for FOWTs (1 August 2023)

For FOWTs, the frequency-domain analysis generally includes the following types of analysis in the frequency domain for the floating substructure and stationkeeping system:

- Wave load calculation
- Motion analysis
- Air gap analysis
- Mooring analysis

In the calculation of FOWT wave frequency responses, linear wave theory is usually employed, while more sophisticated methods may be employed to model finite amplitude waves. The low frequency motion analysis should be carried out to evaluate the responses to wind dynamics and wave drift forces. The damping levels used in such analyses should be properly determined and documented. For the Tension Leg Platform (TLP)-type floating support structure, where second-order sum-frequency effects are deemed significant, the high frequency springing responses of the floating substructure and tendons should be evaluated.

Frequency-domain analyses for evaluating aerodynamic responses of the RNA and effects of turbine control systems should be properly formulated. Preferably, combined aerodynamic, hydrodynamic, and control system actions in the frequency domain are used in the calculation of FOWT dynamic responses.

Frequency-domain analyses cannot capture nonlinear dynamic interactions among the components and subsystems of the FOWT. Methods of approximating nonlinearity in the frequency domain, and their limitations, should be investigated to show they can provide acceptable solutions for the intended application. Frequency-domain analyses are also unable to account for transient responses as well as nonlinear aerodynamic and hydrodynamic load effects. Because of these limitations, most currently available simulation software for FOWTs is based on the time-domain analysis approach as described in 1/5.3.2. Frequency-domain analyses are normally performed to calculate the hydrodynamic coefficients which are used as input to time-domain analyses.

5.3.2 Time-Domain Analysis *(1 August 2023)*

Time-domain analysis refers to calculation of the loads and responses in the time domain.

5.3.2(a) Time-Domain Analysis for BOWTs (1 August 2023)

Two time-domain approaches may be utilized for the global load analysis for BOWTs. One is the integrated load analysis, which usually uses a coupled time-domain analysis approach. Another is the sequential analysis approach, which is a semi-coupled time-domain analysis approach. The descriptions of coupled analysis and sequential analysis are provided in 1/5.7.1 and 1/5.7.2, respectively.

5.3.2(b) Time-Domain Analysis for FOWTs (1 August 2023)

Time-domain analysis for FOWTs generally includes the following types of analysis in the time domain:

- Integrated load analysis
- Motion analysis
- Air gap analysis
- Mooring analysis

Time-domain analyses consist of numerically solving the equations of motion in the time domain for the FOWT subjected to environmental conditions and the RNA operational loads. As the input to time-domain analyses, time series of wind and wave conditions are generated to simulate turbulent wind conditions and stochastic wave elevations and kinematics.

Time-domain analyses are the preferable approach for FOWT global performance analyses, primarily because they can provide a rational means of modeling the nonlinear and transient effects in FOWT global responses. These nonlinear effects include, but are not limited to, hydrodynamic drag forces, finite wave amplitude effects, nonlinear restoring forces from moorings as described in 3/5.7.2, and effects of motion suppression devices or components (e.g., heave plates). Time-domain analyses also allow modeling of the coupling effects among responses of the turbine RNA, the tower, the floating substructure, the stationkeeping system, and if needed, the power cable.

Time-domain analyses should be carried out for a sufficient period to achieve stationary statistics, particularly for low frequency responses. Multiple realizations of an individual set of stochastic site conditions may be necessary to generate adequate data for statistical analysis and to verify the consistency of the simulation. The most probable maximum responses should be predicted using appropriate distribution curve fitting or other recognized statistical techniques.

For the TLP-type floating substructure, the ringing (the high frequency vertical vibration excited by impulsive loading) and the springing (the high frequency vertical vibration excited by cyclic loading at or near the resonant periods) responses of the TLP hull and the tendon should be considered as appropriate. Further guidance on high frequency ringing and spring analyses can be found in API RP 2T.

The effect of Vortex-Induced Motions (VIM, see 3/7.7.5) for the floating substructure in the form of Spar, single column TLP, or other types of deep-draft hull structure should be taken into account as appropriate.

5.3.3 Combined Time-Domain and Frequency-Domain Analysis *(1 August 2023)*

Combined time-domain and frequency-domain analysis refers to the approach where first-order wave frequency responses are computed in the frequency domain while other dynamic responses are computed in the time domain. Total dynamic responses are the combination of relevant responses obtained from frequency-domain and time-domain analyses.

5.3.3(a) Combined Time-Domain and Frequency-Domain Analysis for BOWTs (1 August 2023)

Combined time-domain and frequency-domain analysis may be used in fatigue analysis for the substructure in the preliminary design stage. In this approach, the wave and wind load effects are decoupled. The fatigue analysis is performed through a combination of the time domain analysis of aerodynamic responses and the frequency domain analysis of hydrodynamic responses of the substructure. The contribution of wind to the combined responses can be approximately simulated for a wind turbine in a calm sea, considering the added mass as the only hydrodynamic effect. The wave responses can be determined in the frequency-domain as described in 1/5.3.1(a). Aerodynamic damping should be separately evaluated and applied in the analysis. The equivalent stress range of the combined fatigue for each load case can be obtained by combining the equivalent stress range of fatigue induced by wind and wave responses using direct quadratic superposition or the weighted quadratic superposition.

5.3.3(b) Combined Time-Domain and Frequency-Domain Analysis for FOWTs (1 August 2023)

This approach can be used in the following analysis for the floating substructure and stationkeeping system of FOWTs:

- Motion analysis
- Air gap analysis

- Mooring analysis

To reduce the complexity and computational effort associated with full time-domain simulations, combined time-domain and frequency-domain analyses are often employed. Typically, the mean and low frequency responses (hull displacements, mooring line tensions, anchor loads, etc.) are computed in the time domain while the wave frequency responses are solved separately in the frequency domain. The frequency-domain solution of wave frequency responses is normally processed to obtain either statistical peak values or time series, which are then superimposed on the mean and low frequency responses.

5.5 Quasi-Static and Dynamic Analysis for Foundation and Stationkeeping System *(1 August 2023)*

5.5.1 Quasi-Static Analysis *(1 August 2023)*

The quasi-static analysis approach refers to the analysis method where the foundation of BOWTs or the stationkeeping system of FOWTs is modeled quasi-statically.

5.5.1(a) Quasi-Static Analysis for the Foundation of BOWTs (1 August 2023)

The soil-structure interaction (SSI) effects are modeled as linear or nonlinear elastic springs. Soil damping effects may be added separately.

5.5.1(b) Quasi-Static Analysis for the Stationkeeping System of FOWTs (1 August 2023)

In quasi-static analyses, the mooring system is modeled quasi-statically and wave actions are accounted for by statically offsetting the hull using wave-induced hull motions. Dynamic actions on the mooring lines associated with mass, damping and fluid accelerations are neglected. Experience has shown that the reliability of mooring system designs based on quasi-static analyses can vary widely depending on the hull type, water depth and mooring line configuration.

5.5.2 Dynamic Analysis *(1 August 2023)*

Dynamic analysis refers to the analysis method where the foundation of BOWTs or the stationkeeping system of FOWTs is modeled dynamically.

5.5.2(a) Dynamic Analysis for the Foundation of BOWTs (1 August 2023)

The dynamic analysis approach considers the dynamics of the soil-structure interaction (SSI) through the modeling of the effects of damping, nonlinear stiffness, and effects of added-mass from the soil.

5.5.2(b) Dynamic Analysis for the Stationkeeping System of FOWTs (1 August 2023)

Dynamic analysis of the mooring system accounts for the time-varying effects due to mass, damping, and fluid accelerations. Time-varying fairlead motions are calculated from the hull structure's surge, sway, heave, roll, pitch, and yaw motions. Dynamic models are used to predict the mooring line responses to fairlead motions. Either frequency-domain or time-domain analyses can be used to predict dynamic responses of the mooring system.

5.7 Coupled, Semi-Coupled, and Uncoupled Analysis

5.7.1 Coupled Analysis *(1 August 2023)*

A coupled analysis takes into account the interactions or coupling effects between subsystems of an offshore wind turbine.

5.7.1(a) Coupled Analysis for BOWTs (1 August 2023)

There are various types of interactions, also known as coupling, among subsystems of a BOWT. A coupled analysis implements the time-domain approach. More specifically, the complete system of equations accounting for the structural model of the substructure, elastic models of the tower and the RNA, the foundation model, as well as the control system, are solved simultaneously using a nonlinear time-domain dynamic analysis. The foundation can be modeled using either the quasi-static or dynamic analysis method (see 1/5.5).

When a coupled model is used for global performance analyses, coupling effects among responses of the turbine RNA, the tower, the substructure, and the foundation can be considered at each incremental analysis time step. A more accurate simulation of the effects of the turbine control system and the turbine's operating conditions can also be achieved using this approach.

5.7.1(b) Coupled Analysis for FOWTs *(1 August 2023)*

There are various types of interactions, also known as coupling, among subsystems of the FOWT as described in 4/3.9. A coupled analysis implements the time-domain analysis approach. More specifically, the complete system of equations accounting for the rigid body model of the hull structure, elastic models of tower and turbine RNA, the slender body model for the cables and mooring lines, as well as the control system are solved simultaneously using a nonlinear time-domain approach for dynamic analysis. In a coupled analysis, the mooring system is modeled using the dynamic analysis method (see 1/5.5.2(b)).

When a coupled model is used for global performance analyses, coupling effects among responses of the turbine RNA, the tower, the floating substructure, the stationkeeping system, and the subsea power cable can be considered at each incremental analysis time step. A more accurate simulation of the effects of the turbine control system and turbine's operating conditions can also be achieved using this approach.

5.7.2 Semi-Coupled Analysis *(1 August 2023)*

A semi-coupled analysis takes into account part of the interactions or coupling effects between subsystems of an offshore wind turbine.

5.7.2(a) Semi-Coupled Analysis for BOWTs *(1 August 2023)*

The sequential analysis approach for BOWTs is a semi-coupled analysis in the time domain. The finite element model of the substructure is reduced to a super element connected to the tower supporting the RNA model. Through the coupled aero-servo-elastic simulation, the interface loads at the tower base can be obtained. The obtained interface loads together with the wave loads on the substructure are used as the input for further dynamic structural analysis. Aerodynamic damping is not simulated consistently and simultaneously along with the wind and wave loads. The aerodynamic damping should be evaluated separately and applied in the analysis.

5.7.2(b) Semi-Coupled Analysis for FOWTs *(1 August 2023)*

In a semi-coupled analysis for an FOWT, the coupling effects between aero-elastic and aero-control (servo) are neglected. The tower and the RNA are modeled as part of the hull as a rigid body. The aerodynamic loads are modeled by the wind forces applied at the top of the tower. Effects of the control system should be suitably considered in deriving the aerodynamic loads on the RNA. The aero-control (servo) coupling effects may be approximately represented by the rotor thrust force whose magnitude is expressed as a function of wind speed and the RNA's operational condition. In the parked condition, nacelle yaw misalignment may be included by using appropriate wind force drag coefficients and windage areas. The hull, mooring system and, if needed, power cables are dynamically coupled in this approach.

5.7.3 Uncoupled Analysis *(1 August 2023)*

An uncoupled analysis approximates the tower and the RNA as a concentrated mass attached to the substructure. For FOWTs, the stationkeeping system and cables are modeled quasi-statically in uncoupled analysis.

5.7.3(a) Uncoupled Analysis for BOWTs *(1 August 2023)*

The uncoupled analysis is normally not used for BOWTs. The flexibility of the tower and turbine blades may affect the dynamic responses of the overall system significantly.

5.7.3(b) Uncoupled Analysis for FOWTs *(1 August 2023)*

In an uncoupled analysis for an FOWT, the system of equations accounting for the rigid body motions is solved in the time domain. The tower and the RNA are modeled as part of the hull as a rigid body. Effects of the control system should be suitably considered in deriving the aerodynamic loads on the RNA. The aero-control (servo) coupling effects may be approximately represented by the rotor thrust force whose magnitude is expressed as a function of wind speed and the RNA's operational condition. The effects of the mooring and subsea cable systems are modeled quasi-statically using nonlinear springs based on the quasi-static restoring force characteristics. All other coupling effects between the hull and the mooring system (e.g., contributions from damping and current loading on the mooring lines) need to be pre-calculated and provided as direct input to the analysis.

The same load model may be applied for the hull in coupled, semi-coupled or uncoupled analyses.

5.9 Integrated Load Analysis *(1 August 2023)*

An integrated load analysis performs load and load effect calculations for the entire offshore wind turbine comprising the RNA and the support structure. The design evaluation of the RNA components and the support structure is performed using the results from the integrated load analysis.

The integrated load analysis is normally conducted at the detailed design stage with involvement of the support structure designer and the wind turbine manufacturer. It also involves an independent third party to perform independent verification of the integrated load analysis.

The integrated load analysis is usually performed using the coupled analysis approach in the time domain.

7 Software Tools for Integrated Load Analysis *(1 August 2023)*

Software tools commonly used by the industry to perform the ILA for offshore wind turbines are capable of performing the coupled aero-hydro-servo-elastic analysis in the time-domain. In these ILA software tools, the aerodynamics, elasticity of the blade and tower, hydrodynamics on the substructures, and the control system are solved simultaneously in the time domain.

The analysis methods for different functional modules commonly used in these software tools are summarized in 1/7 TABLE 1.

TABLE 1
Analysis Methods in Software Tools for Offshore Wind Turbines

Functional Modules	*Functions*	*Analysis Methods*
Aerodynamics (Aero)	Aerodynamic loads for RNA	BEM+DW+DS/FVW
Hydrodynamics (Hydro)	Hydrodynamic loads for substructure	Panel(1)+Morison Element
Control System (Servo)	Control system responses and actuation loads	DLL
Structural Dynamics (Elastic)	Modeling flexibility of blade, tower, substructure, and drive train responses	Modal, Multibody, FEM

Note:

1 Results for the Panel model are input from a standalone diffraction-radiation software tool.

In general, these software tools were initially developed for BOWTs. The current start-of-the-art software tools have the capability of performing integrated load analysis for both BOWTs and FOWTs. Software tools may also have an interface to other commercial software for modeling floating substructure, substructure hydro-elastic coupling, mooring/cable system, and complex foundations including Soil–Structure Interaction (SSI).

These software tools can be categorized into two categories:

Category 1: The main function includes the integrated aero-hydro-servo-elastic load analysis for wind turbine generator (WTG) and substructure and foundation or stationkeeping system. These software tools also have the capability of modeling the floating substructures and mooring/cable systems and may provide optional interfaces to other commercial software.

Category 2: The main function includes the aero-servo-elastic load analysis for wind turbine generator (WTG) including RNA, tower, and turbine controller. These software tools may have limited capability of modeling the substructures and foundation or stationkeeping system. They normally can be linked to other commercial software with the capability of modeling the substructure hydro-elastic interaction, floating substructure, mooring/cable system, and foundation. For Category 2 software tools, the aero-servo-elastic program is normally connected to commercial software though an interface dynamic link library (DLL) as shown in 1/7 FIGURE 1.

In these software tools, there are several different approaches for developing the aerodynamic model, hydrodynamic model, control system interfaces, and structural dynamic model as summarized below.

7.1 Aerodynamic Models

7.1.1 Low Fidelity Engineering Model

The blade element momentum method (BEM), together with the dynamic wake (DW) (also called dynamic inflow) model and the dynamic stall (DS) model, is typically used for aerodynamic load calculation. Guidance on aerodynamic models can be found in 2/5.11, 2/7.3, and 3/5.11.

7.1.2 Higher Fidelity Model

ILA software tools may also apply a higher fidelity model based on the free vortex wake (FVW) method for aerodynamic load calculation.

7.3 Hydrodynamic Models

Hydrodynamic models usually include the panel model along with the Morison element model. Guidance on such models can be found in 2/7.7 and 3/7.7.

7.3.1 Panel Model

ILA software tools normally import the diffraction-radiation results of a panel model for hydrodynamic loads on large volume substructure solved through standalone diffraction-radiation analysis software.

7.3.2 Morison Element Model

The Morison element model is normally available within the integrated load analysis software tools to calculate the hydrodynamic loads for slender members and drag loads of the substructure.

7.5 Control System Interfaces

Control systems for the wind turbine can be modeled through an external dynamic link library (DLL) for the turbine controller. Some software tools may allow users to define a subroutine or an interface with specific control design software.

7.5.1 Dynamic Link Library

The control system algorithm is normally compiled into a dynamic link library (DLL) and integrated into an ILA software tool. Such a DLL may be integrated through a predefined subroutine within the ILA software tool together with a predefined number of control parameters and a predefined data transfer format.

DLL can also be linked to the ILA software tools through an application programming interface as an external function. The application programming interface can provide flexibility for accommodating the control parameters and data transfer format in integrating the user developed DLL.

7.5.2 User Defined Subroutine

For some ILA software tools, control systems can be programed as a user-defined subroutine. In such a case, the source code and the user defined subroutine may need to be compiled together. This approach is usually available in open-source programs.

7.5.3 Interface to Control Design Software

Some ILA software tools have an interface to specific control design software for control systems testing and design.

7.7 Structural Dynamic Models

Different methods including multibody-dynamics formulation, finite element method (FEM) and modal superposition method are used to model the structural dynamics of the whole system for rigid bodies motions and flexibility member deflections and loads. Guidance on structural models can be found in Subsections 2/5 and 3/5.

7.7.1 Multibody-Dynamics Formulation

Multibody dynamics formulations are used to account for the degrees of freedom (DOFs) of the overall system. These include rigid body motions, flexible structural model with modal superposition, or FEM for blade and tower, torsional motion of wind turbine drive train.

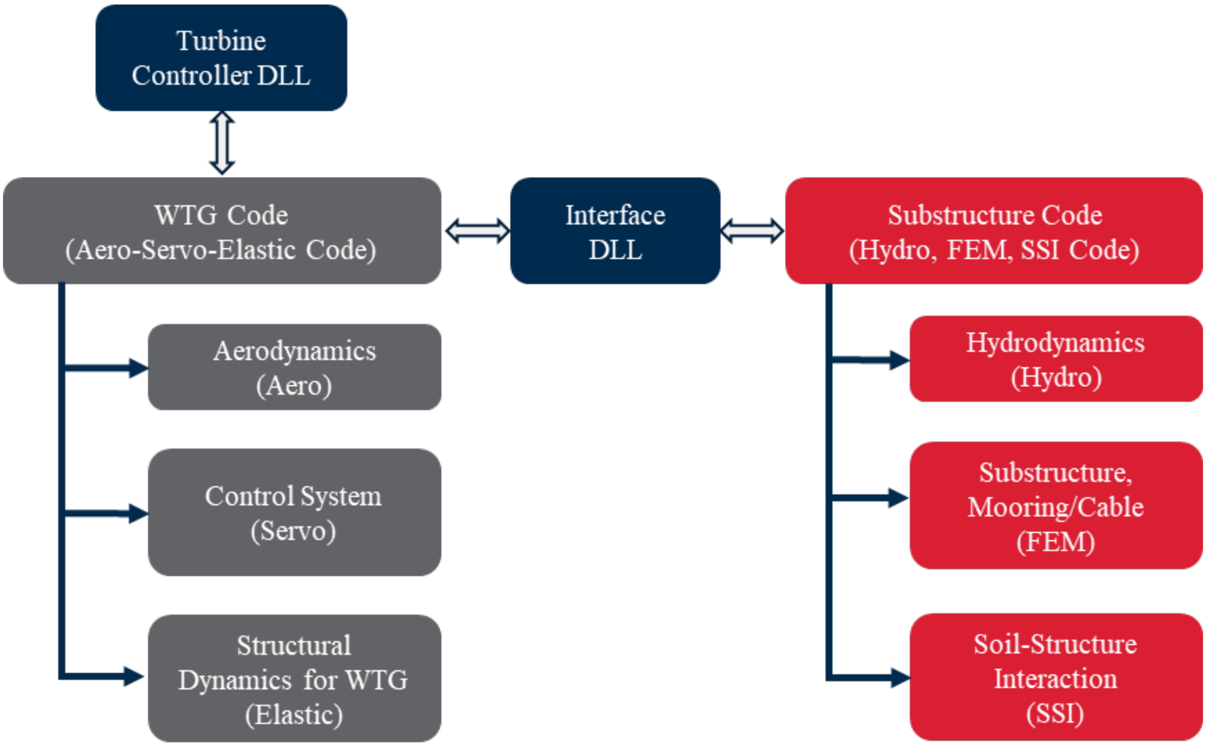
7.7.2 Finite Element Method (FEM)

FEM is usually used for slender members such as blade, tower, shaft, mooring lines, and cables. Blades may be modeled using both the modal superposition method and the finite element method.

7.7.3 Modal Superposition

The modal superposition method is usually used to model the blade and tower mode shapes for the first several vibration modes. A modal analysis is necessary to obtain the modal shapes.

FIGURE 1
Typical Interface between WTG (RNA + Tower) Software and Substructure Software



9 Terms and Definitions

9.1 Terminology

9.1.1 Added Mass

An effective addition to system mass, which is proportional to the mass of displaced water.

9.1.2 Air Gap

The clearance between the highest water surface that occurs during design environmental conditions and the lowest exposed structures not designed to withstand wave impingement.

9.1.3 Bottom-founded Offshore Wind Turbine (BOWT) *(1 August 2023)*

A structure containing a site-dependent substructure (see 1/9.1.46(b)) and its foundation (see 1/9.1.46(c)) supporting the wind turbine RNA and the tower.

The design of the Bottom-founded Offshore Wind Turbine is based on environmental, electrical network, and foundation conditions at a particular offshore site where it is intended to be installed. The sea floor attachment of the substructure may be obtained by use of pilings, direct bearing, or other types of foundation.

9.1.4 Catenary Mooring

A mooring system wherein the restoring action is provided by the distributed weight of mooring lines.

9.1.5 Cut-In Wind Speed (V_{in})

The lowest 10-minute mean wind speed at hub height at which the wind turbine starts to produce power in the case of steady wind without turbulence.

9.1.6 Cut-Out Wind Speed (V_{out})

The highest 10-minute mean wind speed at hub height at which the wind turbine is designed to produce power in the case of steady wind without turbulence.

9.1.7 Design Life *(1 August 2023)*

An assumed period for which a structure, a structural component, a system, or equipment is expected to be used for its intended purpose with anticipated maintenance, but without requiring substantial repair.

9.1.8 Dip and Thrash Zone *(1 July 2020)*

A chain or wire rope section above and close to the seafloor that may touch the seabed due to the motions of the floating substructure.

9.1.9 Dynamic Positioning (DP)

A stationkeeping technique primarily using a system of automatically controlled onboard thrusters to generate appropriate thrust vectors to counter environmental actions and maintain an intended position within prescribed tolerances.

9.1.10 Emergency Stop *(1 July 2020)*

Rapid shutdown of the wind turbine triggered by manual intervention.

9.1.11 Floating Offshore Wind Turbine (FOWT) *(1 August 2023)*

A structure comprising three principal areas:

i) The floating substructure (see 1/9.1.12) for carrying the wind turbine RNA (see 1/9.1.34) and the tower (see 1/9.1.50),

ii) The stationkeeping system (see 1/9.1.44) and

iii) Onboard machinery, equipment, and systems including applicable marine systems and associated equipment and machinery, safety systems and associated equipment, and lifesaving appliances.

9.1.12 Floating Substructure *(1 August 2023)*

A site-dependent offshore structure supported by buoyancy and maintained on location by the stationkeeping system. The floating substructure consists of the Hull (see 1/9.1.16) and topside structures.

9.1.13 Floating Support Structure *(1 July 2020)*

The Floating Support Structure consists of the tower (see 1/9.1.50) and the floating substructure (see 1/9.1.12).

9.1.14 Foundation System (for Tendons)

The structural, mechanical and geotechnical components which are located on and beneath the sea floor and transfer the loads acting on the TLP Tendons into the seabed.

9.1.15 Gust

A brief rise and fall in wind speed lasting less than 1 minute.

9.1.16 Hull

Combination of connected buoyant structural components such as columns, pontoons, and intermediate structural braces; see also "Monohull" (see 1/9.1.24).

9.1.17 hub height

The height of the center of the swept area of the wind turbine rotor above the Still Water Level.

9.1.18 Idling

A condition of a wind turbine that is rotating slowly and not producing power.

9.1.19 Load

An external load applied to the structure (direct load) or an imposed deformation or acceleration (indirect load).

9.1.20 Load Effect

Effect of a single load or combination of loads on a structural component or system (e.g., internal force, stress, strain, motion etc.)

9.1.21 Mean Sea Level or Mean Still Water Level (MSL) *(1 August 2023)*

The average level of the sea over a period long enough to remove variations due to waves, tides, and storm surges (see also 3-5/1 FIGURE 1 of the *BOWT Guide* and 4-5/7 FIGURE 1 of the *FOWT Guide*).

9.1.22 Mean Wind Speed

The statistical mean value of the instantaneous wind speed over a specified time interval.

9.1.23 Minimum Breaking Strength (MBS)

The certified strength of a chain, wire rope, fiber rope, or accessories.

9.1.24 Monohull

A floating structure consisting of a single, continuous, buoyant hull, and geometrically similar to an ocean-going ship or barge.

9.1.25 Mooring Components

A general class of components used in the stationkeeping system.

9.1.26 Normal Shutdown

A wind turbine shutdown operation in which all stages are under the control of the control system.

9.1.27 Offshore Wind Farm *(1 July 2020)*

A group of wind turbines installed at an offshore site. An offshore wind farm may also include other installations such as transformer/converter platforms, meteorological measurement facilities, power cables, and accommodation units.

9.1.28 Omni-directional (Wind, Waves, or Currents)

Acting in all directions.

9.1.29 Parked

The Condition of a wind turbine that is either in the Standstill or Idling condition, depending on the design of the wind turbine.

9.1.30 Pretension

Tension applied to a mooring line or tendon when the floating support structure at its static equilibrium position in mean still water and still air.

9.1.31 Rated Power

The quantity of power assigned, generally by a manufacturer, for a specified operating condition of a component, device, or equipment. For wind turbines, it is the maximum continuous electrical power output which a wind turbine is designed to achieve under normal operating and external conditions.

9.1.32 Rated Wind Speed (V_r)

The minimum 10-minute mean wind speed at hub height at which a wind turbine's rated power is achieved in the case of steady wind without turbulence.

9.1.33 Return Period (Recurrence Period)

The average time duration between occurrences of an event or of a particular value being exceeded. A return period in years is equal to the reciprocal of the annual probability of exceedance of an event or of a particular value of a random parameter such as wind speed, wave height, or sea elevation.

9.1.34 Rotor-Nacelle Assembly (RNA) *(1 July 2020)*

The Rotor-Nacelle Assembly (RNA) of a horizontal axis wind turbine, carried by the floating support structure, consists of:

i) The rotor components, including blades, hub, shaft, and spinner; and

ii) The nacelle, a housing which contains the mainframe, generator frame, drive train components, electrical generator components, wind turbine control and protection components and other elements on top of the tower.

9.1.35 Ringing

A high frequency vertical vibration of the TLP spring-mass system excited by impulsive loading.

9.1.36 Semi-submersible

A floating structure normally consisting of a deck structure connected to submerged pontoons through a number of widely spaced, large cross-section supporting columns.

9.1.37 Set-down

An increase in the draft of a floating structure (for example, TLP) with the increase in the offset due to mooring or tendon system restraint.

9.1.38 Single Point Mooring

A mooring system that allows the floating structure to which it is connected to vary its heading (weathervane).

9.1.39 Spar

A deep-draft, small water-plane area floating structure.

9.1.40 Splash Zone *(1 July 2020)*

Part of the mooring lines or tendons of the stationkeeping system above and below the Mean Sea Level and regularly subjected to wetting due to wave actions, motions of the floating substructure and, if applicable, tide and draft variations. Areas which are only wetted during major storms are not included.

9.1.41 Spread Mooring

A mooring system consisting of multiple mooring lines terminated at different locations on a floating structure and extending outwards, providing an almost constant heading to the floating support structure.

9.1.42 Springing

A high frequency vertical vibration of the TLP spring-mass system excited by cyclic loading at or near the TLP pitch or heave resonant periods.

9.1.43 Standstill

The condition of a wind turbine that is not rotating.

9.1.44 Stationkeeping System *(1 July 2020)*

A system capable of limiting the excursions of the floating substructure within prescribed limits, maintaining the intended orientation, and helping to limit motions at tower top.

9.1.45 Still Water Levels (SWL) *(1 August 2023)*

Abstract water levels used for the calculation of wave kinematics and wave crest elevation. See 3-5/1 FIGURE 1 of the *BOWT Guide* and 4-5/7 FIGURE 1 of the *FOWT Guide*. Still Water Levels, which can be either above or below the Mean Sea Level, are calculated by adding to and subtracting from the effect of tide and surge on the Mean Sea Level.

9.1.46 Support Structure *(1 August 2023)*

A support structure for a BOWT consists of the tower, substructure, and foundation, which are defined as follows:

9.1.46(a) Tower

A structure extending upward from a location above the Still Water Level and connecting the substructure to the Rotor-Nacelle Assembly (RNA).

9.1.46(b) Substructure

A structural component extending upward from the sea floor and connecting the foundation to the tower.

9.1.46(c) Foundation

A structural and/or geotechnical component located on and beneath the sea floor and which transfers the loads acting on the structure into the sea floor.

9.1.47 Tendon

A system of components forming a link between the Hull structure and the foundation system for the purpose of restraining motion of the TLP-type floating support structure within specified limits in response to environmental and other loading.

9.1.48 Tendon Connector

A device used to connect a tendon to the TLP Hull (top connector) or to the foundation template (bottom connector).

9.1.49 Tension Leg

A collective group of tendons associated with one column of the platform.

9.1.50 Tower *(1 July 2020)*

The structural component or assembly that connects the substructure to the Rotor-Nacelle Assembly.

9.1.51 Turbulence Intensity

The ratio of the wind speed standard deviation to the mean wind speed, determined from the same set of measured data samples of wind speed, and taken over a specified period of time.

9.1.52 Taut-line Mooring

A mooring system wherein the restoring action is provided by elastic deformation of mooring lines.

9.1.53 Thruster-assisted Mooring

A stationkeeping system consisting of mooring lines and thrusters.

9.1.54 Tropical Revolving Storm (Hurricane, Cyclone, Typhoon) *(1 August 2023)*

A tropical storm possessing sustained wind speeds in excess of 33 m/s (64 knots or 74 mph). Such a storm is called a hurricane, typhoon, or cyclone based on the storm location. For example, tropical revolving storms are typically referred to as hurricanes in the Gulf of Mexico and North Atlantic, while in the South China Sea and Northwest Pacific they are called typhoons. In the South Pacific and South Indian Ocean, however, they are commonly referred to as cyclones.

9.1.55 Uni-directional (Wind, Waves or Currents)

Acting in a single direction.

9.1.56 Vortex-Induced Motion (VIM)

The motion of the Hull structure induced by vortex when the hull is exposed to a current.

9.1.57 Vortex-Induced Vibration (VIV)

A phenomenon of the vibration of cylindrical structures exposed to a current. Cylindrical structures exposed to a current may create alternating eddies, or vortices, at a regular period. The eddies create alternating lift and drag forces on the cylinder. When a natural period of a structure falls close to the period of vortex shedding, oscillations of the structure can occur.

9.1.58 Water Depth

The vertical distance between the sea floor and the Still Water Level.

9.1.59 Wind Profile (Wind Shear Law)

Mathematical expression for assumed wind speed variation with height above the Still Water Level.

9.1.60 Weathervaning

The process by which a floating support structure passively varies its heading in response to time-varying environmental actions.

9.1.61 Yawing

Rotation of the rotor axis about a vertical axis for horizontal axis wind turbines.

9.1.62 Yaw Misalignment

Horizontal deviation of the wind turbine rotor axis from the wind direction.

9.3 Abbreviations *(1 August 2023)*

ABS: American Bureau of Shipping

AF: Apparent Fixity model

API: American Petroleum Institute

BEM: Blade Element Momentum method

BOWT: Bottom-founded Offshore Wind Turbine

CFD: Computational Fluid Dynamics

DEL: Damage Equivalent Load

DLC: Design Load Case

DLL: Dynamic Link Library

DOF: Degree Of Freedom

DS: Dynamic Stall

DW: Dynamic Wake

FEA: Finite Element Analysis

FE(M): Finite Element (Method)

FOWT: Floating Offshore Wind Turbine

FVW: Free Vortex Wake

GBF: Gravity Based Foundation

IEC: International Electrotechnical Commission

ILA: Integrated Load Analysis

ISO: International Organization for Standardization

LDD: Load Duration Distribution

NPD: Norwegian Petroleum Directorate

PISA: Pile Soil Analysis method

PSI: Pile-Soil Interaction

QTF: Quadratic Transfer Function

RAO: Response Amplitude Operator

RFC: Rain Flow Counting

RNA: Rotor-Nacelle Assembly

SSI: Soil–Structure Interaction

TLP: Tension Leg Platform

VIM: Vortex-Induced Motion

VIV: Vortex-Induced Vibration

WTG: Wind Turbine Generator (RNA and Tower)

9.5 Nomenclature *(1 August 2023)*

1P Rotor Frequency

3P Blade-passing Frequency (for 3-blade wind turbine)

nP Multiples of Rotor Frequency by n times (n=1,2,3…)

2D Two-dimensional

3D Three-dimensional

11 References *(1 August 2023)*

i) ABS *Guide for Building and Classing Bottom-Founded Offshore Wind Turbines (BOWT Guide)*

ii) ABS *Guide for Building and Classing Floating Offshore Wind Turbines (FOWT Guide)*

iii) ABS *Rules for Building and Classing Floating Production Installations (FPI Rules)*

iv) ABS *Rules for Building and Classing Mobile Offshore Units (MOU Rules)*

v) ABS *Rules for Building and Classing Single Point Moorings (SPM Rules)*

vi) ABS *Requirements for Position Mooring Systems*

vii) ABS *Guidance Notes on the Application of Fiber Rope for Offshore Mooring*

viii) API RP 2A-WSD, *Recommended Practice for Planning Designing and Constructing Fixed Offshore Platforms – Working Stress Design*

ix) API RP 2A-LRFD, *Recommended Practice for Planning Designing and Constructing Fixed Offshore Platforms – Load and Resistance Factor Design*

x) API RP 2EQ, *Recommended Practice for Seismic Design Procedures and Criteria for Offshore Structures*

xi) API RP 2FPS, *Recommended Practice for Planning, Designing, and Constructing Floating Production Systems*

xii) API RP 2GEO, *Recommended Practice for Geotechnical and Foundation Design Considerations*

xiii) API RP 2MET, *Recommended Practice for Derivation of Metocean Design and Operating Conditions*

xiv) API RP 2N, *Recommended Practice for Planning, Designing, and Constructing Structures and Pipelines for Arctic Conditions*

xv) API RP 2SK, *Recommended Practice for Design and Analysis of Stationkeeping Systems for Floating Structures*

xvi) API RP 2SM, *Recommended Practice for Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring*

xvii) API RP 2T, *Recommended Practice for Planning, Designing, and Constructing Tension Leg Platforms*

xviii) IEC 61400-1, *Wind Energy Generation Systems – Part 1: Design Requirements*

xix) IEC 61400-3-1, *Wind Energy Generation Systems – Part 3-1: Design Requirements for Fixed Offshore Wind Turbines*

xx) IEC TS 61400-3-2 (Technical Specification), *Wind Energy Generation Systems – Part 3-2: Design Requirements for Floating Offshore Wind Turbines* *xxi)* IEC 61400-6, *Wind Energy Generation Systems – Part 6: Tower and foundation design requirements*

xxii) IECRE OD-502 (Operational Document), *IEC System for Certification to Standards relating to Equipment for use in Renewable Energy applications (IECRE System): Project Certification Scheme*

xxiii) ISO 19901-1, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 1: Metocean design and operating considerations*

xxiv) ISO 19901-2, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 2: Seismic design procedures and criteria*

xxv) ISO 19901-4, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 4: Geotechnical and foundation design considerations*

xxvi) ISO 19901-7, *Petroleum and natural gas industries – Specific Requirements for Offshore Structures, Part 7: Stationkeeping Systems for Floating Offshore Structures and Mobile Offshore Units*

xxvii) ISO 19902, *Petroleum and natural gas industries – Fixed steel offshore structures*

xxviii) ISO 19903, *Petroleum and natural gas industries – Concrete offshore structures*

xxix) ISO 19904-1, *Petroleum and natural gas industries – Floating Offshore Structures, Part 1: Monohulls, Semi-submersibles and Spars*

xxx) ISO 19906, *Petroleum and natural gas industries – Arctic Offshore Structures*

SECTION 2

Integrated Load Analysis for Bottom-founded Offshore Wind Turbines

(1 August 2023)

1 Introduction

1.1 General

The ILA is performed for the following purposes:

- Classification based on the ABS *Guide for Building and Classing Bottom-Founded Offshore Wind Turbines* (*BOWT Guide*), when ILA is recommended
- Certification and verification in compliance with local regulatory requirements, IEC certification scheme based on IECRE OD-502, and IEC 61400 series standards or other industry standards for offshore wind turbines

The ILA involves aero-hydro-servo-elastic analyses that can account for the coupled dynamics of a BOWT including the RNA, control system, tower, substructure, and foundation modeled and solved simultaneously in the time domain.

In contrast to the sequential analysis methods, the ILA accounts for the coupling effects and damping effects including aerodynamic and hydrodynamic damping in a consistent manner. It can provide a more rational calculation of global motions and loads for the detailed design evaluation of the RNA components, tower, substructure, and foundation.

The software tools for ILA should be compatible with the modeling approaches for individual components of a BOWT and the load transfer strategy for detailed design evaluations for each component.

The numerical modeling and simulation methods should comply with the applicable classification or certification requirements. Where there are no specific requirements, these Guidance Notes may be applied.

1.3 Design Data, Reports and Drawings

The following design data, reports, and drawings are necessary for the ILA:

- Site conditions and environmental data (such as water depth, seabed bathymetry, soil data, wind, waves, current, water level, wind/wave misalignment, and fatigue sea states)
- RNA modeling data (such as geometry, dimensions, airfoil aerodynamic data, drive train properties, blade material properties, stiffness, damping, mass distribution, natural frequencies, turbine power, and thrust curves)
- Tower modeling data (such as geometry, dimensions, material properties, stiffness, damping, mass distribution, and natural frequencies)

- Wind turbine control system modeling data (such as description of the wind turbine control software, the controller dynamic link library (DLL) to integrate to the load analysis software, and operation procedures)
- Substructure modeling data (such as geometry, dimensions, material properties, stiffness, damping, and mass distribution)
- Foundation modeling data (such as geometry, dimensions, material properties, stiffness, damping, and mass distribution)
- Other design considerations pertinent to the BOWTs, if applicable

3 Integrated Load Analysis Procedures

3.1 General

The ILA consists of the following key steps:

i) Build a global performance analysis model

ii) Define environmental load models

iii) Set up data files for each Design Load Case (DLC)

iv) Perform ILA simulations

v) Obtain time histories of loads and motions

vi) Post-process and report results

Modeling strategies for BOWTs are outlined in Subsection 2/5. Modeling methods for environmental loads are provided in Subsection 2/7. Guidance on simulation and post-processing is provided in Subsections 2/9 and 2/11. Interface loads for the tower, substructures, and foundation detailed design evaluations are described in Subsection 2/11.

3.3 ILA Procedure for Bottom Founded Offshore Wind Turbines

The ILA procedure for BOWTs is illustrated in 2/3.3 FIGURE 1.

The ILA model for a BOWT includes the WTG (RNA and tower) model, substructure model and foundation model. The substructure may be simplified as a beam element model. The nonlinearity of the foundation stiffness should be included in the ILA model. Time histories of aerodynamic loads and the associated wave and current loads from the ILA can be used as inputs for the subsequent detailed structural analysis and design code check. The WTG loads and foundation loads calculated through ILA are used for the WTG and foundation design evaluations.

Depending on the ILA software capability, a detailed substructure model together with the WTG model and foundation model can also be developed for the ILA. The calculated loads are used directly within the software tools for the time-domain dynamic structural analysis and design code check for the substructure.

The ILA for a BOWT typically includes the following steps:

i) Build a global performance analysis model

- WTG model including the RNA and tower models
- Wind turbine controller model
- Foundation model
- Substructure model

- Mode shapes calculated through the modal analysis

ii) Define environmental load models

- Wind load models
- Wave load models
- Current load models
- Modeling of ice and snow accumulation induced loads, if applicable
- Modeling of sea/lake ice loads, if applicable
- Modeling of seismic loads, if applicable

iii) Set up data files for each Design Load Case (DLC)

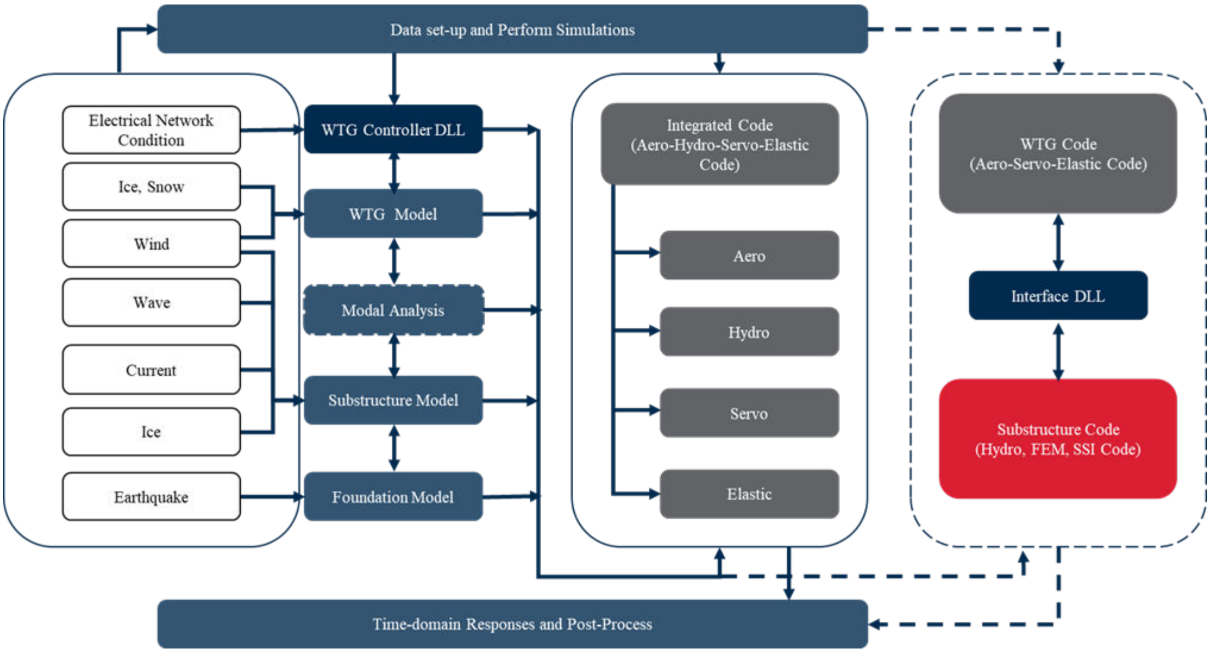
- Simulation time duration, time step, and number of random seeds
- Random seed for each simulation requiring to apply random waves and winds
- For a fatigue DLC, the probability of occurrence or number of occurrences of fatigue design conditions
- Partial load safety factor
- Wind, wave, current and water level models and parameters
- Wind farm wake models
- Wind turbine controller setup
- Wind turbine condition setup
- Nacelle yaw misalignment setup
- Gird condition (electrical network condition) setup
- Other external conditions setup

iv) Perform ILA simulations

v) Obtain time histories of loads of the RNA, tower, substructure, and foundation

vi) Post-process and report results

FIGURE 1
ILA Procedure for Bottom-founded Offshore Wind Turbines



5 Modeling of Bottom-founded Offshore Wind Turbines

5.1 General

In general, dynamic analyses should be carried out to evaluate dynamic responses of an offshore wind turbine subjected to site-specific external conditions and operating conditions. While various simplified analysis methods may be used in the preliminary design, a coupled analysis approach is recommended for the final detailed design. Prototype tests and model tests may be used to supplement the load calculation.

A global performance analysis model should be developed for the ILA and include the following aspects:

- Modeling of foundation
- Modeling of the substructure
- Modeling of flexibility of the tower
- Modeling of rotor blades and control and safety systems
- Modeling of dynamics of drive trains
- Modeling of wind farm wake effects
- Modeling of mode shapes through the modal analysis

The external conditions to be considered in the ILA include:

- Environmental conditions
- Electrical network conditions

In addition, various fault conditions relevant to the electrical system, control and safety systems, and mechanical components should be properly modeled in the analysis.

5.3 Modeling of Foundation

5.3.1 General

Foundation modeling can affect the global dynamics of BOWTs. The soil–structure interaction (SSI) should be developed in the foundation model. Typical types of foundations for BOWTs include:

- Gravity-based foundation (GBF)
- Monopile foundation (large diameter pile)
- Pile foundation (tripod, jacket)
- Other foundations

The gravity-based foundation may be used for soils with a high load-bearing capacity. For soils with relatively low load-bearing capacity, deep foundations such as piles are commonly used. Pile foundations can be either monopiles or pile foundations of jackets or tripods. For TLP-type FOWTs with tendon foundation, the simplified soil-structure interaction (SSI) model is usually employed in the global model.

The foundation model should include the following two aspects:

- Stiffness model
- Damping model

Foundation stiffness affects the natural frequencies of a BOWT. Foundation damping can affect the magnitude of the global dynamic responses. In power production conditions, aerodynamic damping is normally more important than soil damping. While in parked conditions, aerodynamic damping is low, especially in the side-to-side directions, and soil damping may be important for parked and wave-wind misalignment conditions.

The foundation stiffness model should consider the nonlinear stiffness of the soil that can represent the soil reactions ranging from small displacements required for the calculation of natural frequencies of a wind turbine structure and fatigue load cases to the large displacement response required for the calculation of the extreme load cases.

The foundation model may only include the stiffness model, while the damping effects may be separately evaluated and applied to the model. Where no data is available for soil damping, the soil damping may be taken as a percentage of 0.25%-1.5% of the critical damping. To be conservative, the foundation damping may also be neglected. In the time-domain analysis using the finite element method, foundation damping can be added as Rayleigh structural damping. For the modal superposition method, an overall foundation damping may be added to each of the modes.

When the added mass of soil is of importance, the effects can be added separately through an added mass matrix at the top of the foundation.

5.3.2 Gravity-Based Foundation

The shallow gravity-based foundation may be assumed rigid with respect to the underlying soil. For large foundations, the added soil mass is often large and should be included in the model. In general, the finite element method should be used for the flexible foundation structure.

In the global performance analysis model, the following two modeling techniques can be applied:

- Macro-element model
- Distributed springs model

A macro-element model is used to represent a 6-DOF nonlinear force-displacement relations at a point of the foundation in the vertical, horizontal, and rotational directions. A macro-element model can be introduced at the base of the foundation to account for soil-structure interaction. The macro-element model is able to simulate the 3D behavior of a rigid shallow foundation under static and cyclic loading and plasticity and uplift mechanisms. More detailed guidance for a macro-element model is given in 2/5.3.3(c)i).

In the distributed springs model, a number of uncoupled nonlinear horizontal and vertical springs are used to model the soil-structure interaction. The vertical spring is distributed under the foundation to capture foundation rotations, which are often the dominant contributor to the SSI effects. Horizontal springs are attached to the sides of the foundation. The vertical springs model the vertical load-displacement behavior, while horizontal springs model the horizontal load-displacement behavior against the side of a foundation and horizontal sliding behavior at the base of the foundation. In addition, dampers can be included to capture foundation damping. The vertical springs can be modeled to represent compressive yield and detachment at the point of uplift. Foundation stiffnesses and bearing capacity can be calculated from semi-empirical equations based on foundation dimensions and properties, soil properties, soil and foundation testing, or from finite element analysis (FEA). For soil properties and soil and foundation testing, refer to API RP 2GEO and ISO 19901-4 for guidance.

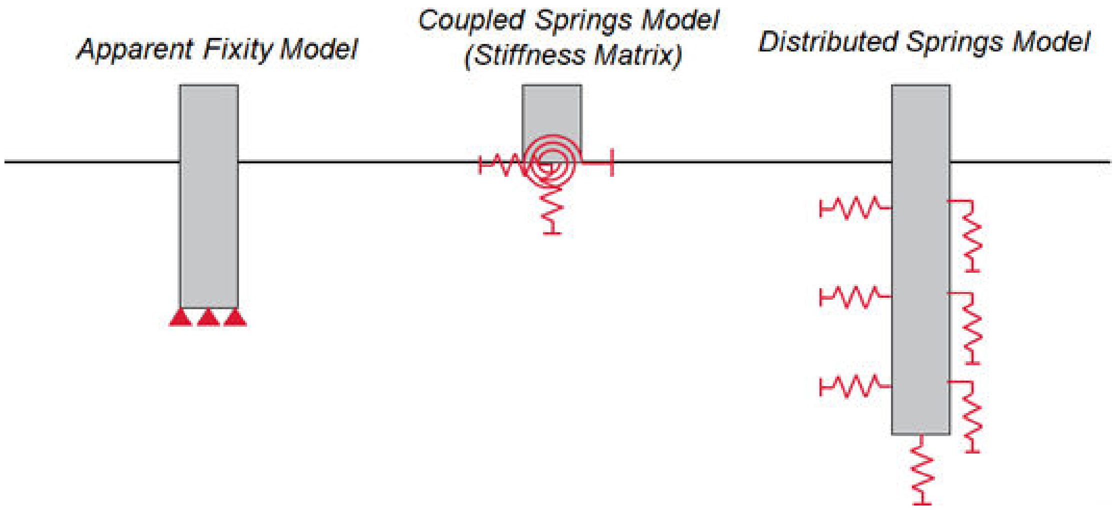
The nonlinear spring stiffness relations may be obtained based on direct analysis using finite element analysis as discussed in 2/5.3.3(c)ii). Horizontal force and overturning moment are applied to the foundation top. The loads are increased at a constant ratio while translation and rotation of the foundation are recorded. Force-displacement and moment-rotation relations can then be obtained. An elastic-plastic soil model may be used to evaluate the soil damping ratio under cyclic loading. The analysis is performed with a loading-unloading-reloading cycle statically or dynamically. The energy dissipation in a loading cycle can be used to estimate the soil damping as a function of loading amplitude.

5.3.3 Monopile Foundation

Foundation models for the global load analysis of monopile-based BOWTs may use one of the following types of techniques as shown in 2/5.3 FIGURE 2:

- Apparent fixity model
- Coupled springs model (i.e., stiffness matrix)
- Distributed springs model

FIGURE 2
Monopile Foundation Models for ILA



5.3.3(a) Simplified Linear Models

i) *Rigid Foundation*

In the rigid foundation model, the pile is clamped rigid at the mudline. This simplified method provides higher stiffness than a real foundation. It is used in some software tools as a modeling option for preliminary analysis of support structures.

ii) *Apparent Fixity Model*

In the apparent fixity model, the monopile is extended to a certain depth below the seabed and is rigidly fixed there. The apparent fixity model assumes that the substructure is fixed (cantilevered, without surrounding soil) at a depth below the original seabed, with a fixity depth and beam properties determined such that it matches the same lateral displacement and rotation at the seabed as the one resulting from the pile embedded in the actual soil profile.

The geometry and material properties of the pile above seabed are used for the extended length of the pile. The extended length is determined to provide the same fundamental eigenfrequency as the pile foundation. The soil damping, if considered, is included separately.

Due to the nonlinear nature of the actual foundation, the response from a linear model is accurate under a particular load level. This method can be used in preliminary design, and it is in general not suitable for detailed design.

iii) *Coupled Springs Model (Stiffness Matrix)*

The coupled springs model or stiffness matrix model is used to model the foundation as a 6 × 6 stiffness matrix. The 6 × 6 stiffness matrix represents a set of linear coupled or uncoupled springs for three translational and three rotational DOFs applied at a point on the pile at the mudline. The stiffness matrix is obtained through linearization of the pile-soil stiffness around a given load level. FEA may be used to calibrate the stiffness matrix. The first and second natural frequencies can be more accurately estimated using a stiffness matrix rather than the apparent fixity model.

The coupled springs model replaces the soil with one linear stiffness matrix located at the seabed that accounts for the six rigid-body DOFs (or fewer) of the base of the monopile.

This approach can be extended to include a viscous damping matrix to account for the energy dissipated by the foundation.

For a nonlinear foundation, this method only accounts for soil stiffness at one load level. This method can be used in preliminary design, and it is in general not suitable for detailed design.

5.3.3(b) Distributed Springs Model based on p-y Curves Method

i) American Petroleum Institute (API) p-y Curves Method

In current industry design practice, the monopile foundation is modeled based on the *p-y* curves method. The pile foundation is modeled by a series of discrete lateral and axial springs distributed along the length of the pile. Most ILA software tools can model linearly distributed springs. Some allow for uncoupled nonlinear elastic springs. In these software tools, the spring models usually represent the API *p-y*, *t-z* and *Q-z* curves. The *p-y* curves model is constructed based on soil and pile test data. The *p-y* curves can also be calibrated to FEA results of the soil and the foundation. Details about this method can be found in 2/5.3.4.

The API *p-y* curves method is developed for the slender piles used for offshore oil and gas platforms. This model was developed based on the measurements from test piles with an outer diameter (D) no greater than 2 m (6.5 ft) and an aspect ratio (length to diameter ratio L/D) larger than 10, which is much greater than those for monopiles. Due to the larger diameter (D) and smaller length to diameter (L/D) ratio of the monopiles, the geometry and load pattern differ from slender piles. In addition to the lateral deflection of the pile, monopiles can also have rigid body motions. Therefore, the API *p-y* curves derived for flexible piles may not be accurate for modeling soil-structure interaction for large diameter short monopiles with the diameter (D) typically ranging from 3.5 m to 8 m (11.5 ft to 26 ft) and the aspect ratio (L/D) between 5 and 12 due to the associated pile rigid motions.

Studies using finite element analysis of large diameter piles showed that the API *p-y* curves method tends to overestimate soil stiffness for large diameter monopiles, particularly at greater soil depths. Using the modified *p-y* curves based on FEA can improve the results. It is suggested that the *p-y* curves be calibrated with FEA results or large-scale test data.

The Pile Soil Analysis (PISA) method includes three other components of soil reaction through distributed rotational springs and lateral and rotational springs at the base in addition to the nonlinear lateral (*p-y*) springs. It can achieve improved predictions of soil-monopile interaction. The details of the PISA method are provided in 2/5.3.3(b)ii).

The foundation damping may be modeled by hysteresis loop created by loading and unloading *p-y* curves. In software tools using the *p-y* curves model, the soil is typically modeled with elastic springs with no foundation damping. Foundation damping values from 0.25% to 1.5% of critical damping may be used in the integrated load analysis for the monopile foundation. Foundation damping can also be calibrated using finite element analysis.

ii) PISA p-y Curves Method

Pile Soil Analysis (PISA) method is a new methodology for the design of offshore wind turbine monopile foundations based on field testing and advanced finite element analysis. The PISA design method retains the advantages of the traditional *p-y* method, while incorporating enhancements to improve the performance of the modeling approach for relatively low length to diameter ratio monopiles.

In the PISA design method, soil reaction curves are defined as four-parameter functions in which the parameters are depth-dependent. In addition to a distributed lateral load, which is modeled by *p-y* curves, three other components of soil reaction are assumed to act on the monopile (i.e., distributed moment, lateral force, and moment at the base). Nonlinear soil reaction curves for lateral loading, rotation, base shear, and base rotation used in the PISA design method are calibrated by 3D FEA with soil properties from site investigation and validated with field tests.

A procedure is developed for the calibration of soil reaction curves using 3D FEA results and can be used for the monopile design. Numerical soil reaction curves are determined from the 3D FEA results using a process to extract the nodal forces acting at the soil-pile interface, and stresses in the interface elements between the pile and the soil.

In addition to the design procedure based on soil reaction curves calibrated from the 3D FEA results, there are predefined soil reaction curves within the PISA design method. These curves may be adopted for design where site investigation data are limited at an early stage of the design process.

The PISA design method is developed for monopiles under monotonic lateral loading. The PSI effects of soil-stiffness reduction and soil damping under cyclic loading can be considered in the design separately.

5.3.3(c) Advanced Foundation Models

i) Macro-element Models

In the macro-element model, the response of a pile and the surrounding soil is condensed to a force-displacement relation at the seabed. The models have input parameters that are predefined based on numerical analyses of the pile and soil or from model testing.

The macro-element adds six (6) DOFs (3 rotational and 3 translational) to the full structural model, fewer than the degrees of freedom required for distributed springs method. Complex macro-element models can account for several fundamental effects such as the effect of cyclic loading in the soil, change in stiffness, gapping, and damping. The computational burden will depend on the complexity of the macro-element. The main disadvantage of the macro-element approach is that the pile itself is excluded from the analyses and needs to be modeled in a separate analysis.

ii) Finite Element (FE) Model

An FE model of the soil and the foundation in an aero-servo-hydro-elastic simulation tool for ILA in the time domain provides the most accurate modeling approach if used together with appropriate constitutive soil models. The main disadvantage is the large computational cost of time-domain 3D FEA with continuum elements, which makes the approach impractical for ILA in the design process.

The FE-based advanced foundation methods are normally used to calibrate the foundation model used for ILA. The results of the finite element analysis can also be used to construct a set of *p–y* curves used for the pile foundation model. Guidance on the development of *p–y* curves using finite element analysis is provided in ISO 19901-4 Annex A.10.5.3.

The FE-based model can be used to evaluate the soil stiffness reduction and damping effects under cyclic loading. The typical nonlinear spring approach used in the ILA normally takes into account these effects separately. The effects of soil stiffness reduction and damping can be considered in the nonlinear spring approach used in the ILA through 3D FEA based on the elastoplastic model.

5.3.4 Pile Foundation

The pile foundations for long and slender tripod and jacket piles are usually modeled using the *p–y* curves method based on API RP 2A-WSD.

In the *p–y* curves method, a series of discretely distributed, uncoupled, nonlinear elastic springs at nodal points along the pile are applied to represent the pile-soil lateral, axial, and tip resistances through the lateral soil resistance deflection *p-y*, axial shear transfer *t-z*, and mobilized end bearing capacity *Q-z* curves as given below:

- *p-y* curve: Relationship between the lateral soil resistance per unit length of pile (p) and pile deflections due to the resistance (y), as a function of depth below the original seafloor (z)
- *t-z* curve: Relationship between mobilized soil-pile shear transfer (t) and local pile deflection (z) at any depth
- *Q-z* curve: Relationship between mobilized end bearing resistance (Q) and axial pile tip displacement (z)

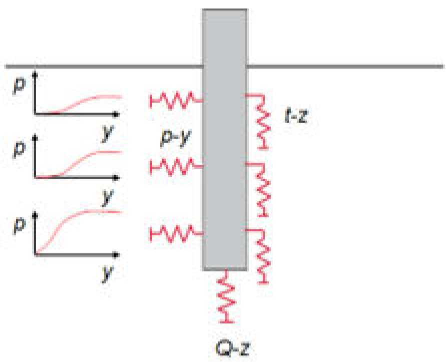
where

p	=	lateral soil resistance per unit length of pile, in N/m (lb/ft)
t	=	mobilized soil-pile shear transfer, in Pa (lb/ft^2)
Q	=	mobilized end bearing resistance, in N (lb)
y	=	deflections of pile due to the lateral soil resistance, in m (ft)
z	=	depth below the original seafloor, in m (ft)
	=	axial local pile deflection, for axial shear transfer *t-z* curves, in m (ft)
	=	axial pile tip displacement, for *Q-z* curves, in m (ft)

The nonlinear curves (*p-y* curve, *t-z* curve and *Q-z* curve) can be constructed using stress-strain data from laboratory soil samples and dated from pile load tests based on the procedures provided in API RP 2A-WSD, API RP 2GEO and ISO 19901-4. The *p-y* curves model can also be calibrated using the finite element model of the soil and foundation.

Foundation design software for oil and gas platforms typically has the capability to model the pile-soil interaction based on the *p-y* curves method. Pile-soil interaction can account for pile finite deflection ("P-delta" effect) and nonlinear soil behavior in both transverse and axial directions. The pile is modeled by beam-column elements subject to axial and bending loads. The soil around the pile is modeled by a series of discrete springs. The pile-soil interaction model based on the *p-y* curves method is shown in 2/5.3 FIGURE 3.

FIGURE 3
Pile-Soil Interaction Model



5.3.5 Other Foundations

Modeling methods as given in 2/5.3 may be applied to other types of foundations such as suction buckets. General guidelines on foundation modeling can be found in IEC 61400-6, API RP 2A, ISO 19902, ISO 19903, and API RP 2T.

Geotechnical and foundation engineering applicable to a broad range of offshore structures can be found in API RP 2GEO and ISO 19901-4. The design of pile foundations for fixed offshore steel structures is detailed in API RP 2A and ISO 19902. Requirements for the design of shallow gravity foundations for fixed offshore concrete structures are detailed in ISO 19903. Foundation design for TLP-type FOWTs can be found in API RP 2T.

5.5 Modeling of the Substructures

5.5.1 General

The substructures of a BOWT can be modeled using finite element method or a rigid body with 6 DOFs of motions.

Modeling of the substructures should consider the following loads and load effects:

- Hydrostatic loads
- Gravitational and inertial loads
- Wind, wave, and current loads
- Vortex-induced vibration (VIV)
- Other loads (such as ice loads, ice and snow accumulation induced loads, earthquake loads, impact loads, etc.)

Global structural models may comprise equivalent beams, space frame models, or combined shell element/beam element models, as appropriate. Models should accurately represent the global stiffness of the substructure and the relative stiffness of the major structural components.

In the case where local structures significantly affect the global stiffness and/or response, such effects should be adequately considered when developing the global structural model. A combined global or local structural model may be warranted.

The extent of the global structural model should be defined such that boundary conditions and loads can be imposed at well-defined or well-understood interfaces.

Space frame structures consisting of slender members can be analyzed using the 3D frame analysis to calculate internal member forces and moments. The effects of joint eccentricity and flexibility, where significant, should be accounted for.

The structural members in the substructure can generally be modeled based on linear elastic theory. However, nonlinear relationships between loads and load effects should be properly accounted for, when deemed important.

This Subsection provides guidance on structural modeling techniques for the following types of substructures:

- Gravity based substructure
- Monopile substructure
- Tripod substructure
- Jacket substructure
- Other substructures

Guidance on modeling of environmental loads on substructures is provided in Subsection 2/7.

5.5.2 Gravity-Based Substructure

Gravity-based substructures can be modeled as a 6-DOF rigid body. In order to model the natural frequencies of the tower, the structural flexibility of the connection of the substructure to the tower should be included in the analysis.

5.5.3 Monopile Substructure

The monopile is normally modeled using a beam finite element method. The model should account for the distributed stiffness and mass properties along the axial direction of the monopile. The moment of inertia about the axial direction should be accounted for. For grouted piles, the stiffness and mass of the grouted material should be considered in the global model where applicable.

A detailed local structural analysis using a refined finite element model with beam, shell, and solid elements can be performed with the global loads from the global load analysis for both strength and fatigue analyses of the monopile substructure.

5.5.4 Tripod Substructure

The tripod substructure is normally modeled using a simplified beam finite element model in the global model considering the geometry of the members, stiffness and mass distribution of each member. Joint flexibility may also be included in the model. A detailed FE model is needed for the subsequent dynamic structural analysis using the global loads determined through the global load analysis.

Alternatively, a detailed FE model can be directly incorporated into the global model. The detailed FE model can comprise beam, shell, and solid elements. Joint flexibility should be considered to model the overall stiffness of the substructure. The stiffness of the connection of the tower to the tripod substructure should be appropriately modeled. In general, joints should be modeled using shell elements.

5.5.5 Jacket Substructure

The jacket substructure can be modeled as a 3D space frame using a simplified beam finite element model. The beam FE model should model the geometry of the members, stiffness, and mass distribution of each member. Joint flexibility may also be included in the model. A detailed FE model is needed for the subsequent time-domain dynamic structural analysis using the global loads determined through the global load analysis.

Alternatively, a detailed FE model can be directly incorporated into the global load model. The detailed FE model can comprise beam, shell, and solid elements. Joint flexibility should be considered to model the overall stiffness of the substructure. The stiffness of the connection of the tower to the jacket substructure should be appropriately modeled. In general, joints should be in general modeled using shell elements.

5.5.6 Other Substructures

The substructure can be modeled as one or multiple rigid bodies considering multibody dynamics, finite element models, or a combination of both. For general modeling methods, guidance can be found in API RP 2A, ISO 19902 and ISO 19903.

5.7 Modeling of Flexibility of Tower

The tower can generally be modeled based on linear elastic theory. However, nonlinear relationships between loads and load effects should be properly accounted for, when deemed important. Structural damping of the tower should be properly determined.

The wind loads on the tower should be included. The influence of the tower shadow or tower upwind effects on the wind field perturbation should be properly modeled.

The tower structures can be modeled using the finite element method. The model should account for the distributed stiffness and mass properties along the axial direction of the tower. The moment of inertia about the axial direction should be accounted for.

The dynamic structural response of the tower may also be calculated by the modal superposition method. Sufficient modes should be included in the analysis. As a minimum, the first few orders of bending modes should be included. If the tower does not have sufficient torsional stiffness, torsional modes should also be included in the modeling. Modal analyses of the tower should consider the influences of substructure and foundation for a BOWT.

Guidance on the tower modal analysis is provided in 2/5.17.

5.9 Modeling of Dynamics of Drive Trains

Drive train dynamics should be properly considered in the ILA. As a minimum, the torsional mode of the drive train should be included in the analysis.

The drive train includes all torque-transmitting components from the rotor to the generator, as well as the elastic mounting of the drive train. The parameterization assumptions of the drive train model used in the global load calculation should be verified by the calculation using more detailed drive train models. In most cases, the controlling parameters are “resulting drive train stiffness” and “moment of inertia of generator rotor”. The verification can also be carried out through the comparison of the first eigenfrequency obtained from the detailed drive train model to the corresponding value derived from the global load simulation model. Other verification techniques can also be used, if appropriate.

5.11 Modeling of Rotor Blade and Control and Safety Systems

5.11.1 General

The rotor blades can in general be modeled based on linear elastic theory. However, nonlinear relationships between loads and load effects should be properly accounted for, when deemed important. As a minimum, the edgewise and flapwise bending degrees of freedom should be considered in the evaluation of aero-elastic responses. Structural damping of the rotor blades should also be properly selected.

The blade structural model can be modeled using the finite element method. The model should account for the distributed stiffness and mass properties along the axial direction of the blade. The dynamic structural response of the blade may also be modeled using the modal superposition method.

Modeling of rotor blades and control and safety systems should include the following loads and load effects:

- Gravitational and inertial loads
- Aerodynamic loads
- Actuation loads (or operational loads)
- Other loads (such as wake loads, impact loads, ice load, etc.), if applicable

The influence of the control system on the loads, especially aerodynamic loads, should be properly modeled. Resonance and dynamic amplification of motions due to control system actions should be avoided.

For a three-blade horizontal axis wind turbine, the combined effects of inertial, gravitational, and aerodynamic loads of the RNA include the following frequency components:

- Rotor rotation frequencies (1P)
- Blade passing frequencies (3P)
- Harmonics of 1P and 3P (2P, 6P, 9P, etc.)
- Natural frequencies of rotor blades
- Natural frequencies of other RNA components

Guidance on the blade modal analysis is provided in Subsection 2/5.17.

5.11.2 Gravitational and Inertia Loads

Gravitational and inertial loads are static and dynamic loads that can be induced by gravity, vibrations, rotations, and seismic activities.

In dynamic analyses, structural dynamics properties and the coupling of vibratory modes should be properly modeled. The following items should be considered:

- Elasticity of the blades
- Elasticity of the drive train and generator (drive train dynamics)
- Elasticity of the tower
- Global motions of the floating support structures
- Mass eccentricity of the rotor
- Helideck dynamics (if relevant)
- Stiffness of the floating support structure and mooring system (if relevant)
- Elastic mounting of the machinery, vibration dampers (if relevant)

5.11.3 Aerodynamic Loads

The aerodynamic loads on rotor blades are dependent upon:

- Rotational speed of the rotor
- Average wind speed across the rotor plane
- Intensity of turbulence
- Density of the air
- Aerodynamic shapes of the offshore wind turbine components and their interactive effects, including aeroelastic effects

The calculation method for aerodynamic loads on rotor blades is normally based on the blade element momentum theory (BEM). Other methods such as the potential flow method, computational fluid dynamics (CFD), etc., may also be used. In addition, aerodynamic loads on the nacelle should be considered, if deemed important.

The following aspects should be considered regarding wind loads on the RNA:

- Wind field perturbations due to the offshore wind turbine itself (wake-induced velocities, tower shadow, tower upwind effect, etc.)
- The influence of three-dimensional flow on the blade aerodynamic characteristics (e.g., three-dimensional stall and aerodynamic tip loss)
- Dynamic stall effects of the airflow for the profiles used
- Unsteady aerodynamic effects

- Aeroelastic effects
- Aerodynamic asymmetries that can arise through production or assembly tolerances of the rotor blades

5.11.4 Actuation Loads (Operational Loads)

Actuation loads (or operational loads) are generated by the operation and control of the RNA. The main source of actuation loads is the rotor speed control and/or the torque control through pitching the blades or adjusting other aerodynamic devices. Actuation loads also include the mechanical braking loads as well as the transient loads arising during the startup and shutdown of the rotor, engagement and disengagement of the generator, and nacelle yaw movements. As a minimum, the following should be considered:

- Static and load-dependent bearing friction moments (especially those at the blade pitch bearing and the yaw bearing)
- Behavior of the control and safety systems of the RNA

5.13 Modeling of Wind Farm Wake Effects

Within an offshore wind farm, the turbulence intensity associated with wake flow may be considerably higher than the ambient turbulence intensity. In addition, wake flow is characterized by a reduced mean wind speed and an increased shear profile. In the absence of detailed analysis of the wind characteristics within an offshore wind farm, the design calculation may be performed using increased turbulence intensity based on experience and recognized calculation methods.

The mutual influence of offshore wind turbines through the wake interaction behind the rotor should be considered in a wind farm configuration up to a distance of at least 10 rotor diameters from another wind turbine. Reference can be made to IEC 61400-1 for guidance on the wake effects from neighboring wind turbines.

5.15 Power Cable Considerations

For BOWTs, the power cable can be considered in the integrated load analysis as an appurtenance. The wave and current loads may be included in the analysis by the Morison element model.

5.17 Modal Analysis

5.17.1 General

Modal analysis is used to calculate the natural frequencies, damping, and mode shapes of the wind turbine blades, tower, and substructure. The finite element model is commonly used to perform the modal analysis. The purposes of the modal analysis are to:

- Obtain the mode shapes for the blades and the tower as input for the structural models
- Obtain the natural frequencies for the tower and the support structure (substructure, tower, and foundation) design
- Evaluate the damping level for the global model

The modal superposition method is implemented in some ILA software tools to model the blade and tower flexibility. The mode shapes obtained from the modal analysis are used as input to the ILA software tools for blade and tower modeling.

The overall damping level of the global model is a key element in the prediction of both fatigue and extreme loads for load-carrying components of a BOWT and should carefully be selected.

5.17.2 Bottom-Founded Offshore Wind Turbines

The global model for the ILA or a separate structural finite element model can be used for the modal analysis. Nonlinearity in the system should be linearized at a given load level for the modal analysis. Added mass on the submerged structural member should be included.

Due to the nonlinearity of the foundation stiffness and foundation damping, it is important that the load level used for linearization is comparable to the loads from the ILA of the design load cases.

It should be verified that the fundamental frequencies of the support structure (integrated foundation, substructure, and tower) are away from the 1P rotor frequency and the 3P (for 3-blade turbine) blade passing frequency.

The foundation model has significant effects on the natural frequencies of the support structure (tower, substructure, and foundation), while the effects on blade natural frequencies may be insignificant.

5.17.2(a) Modal Analysis of Tower

The global model for the ILA including an appropriate foundation model may be used for the modal analysis.

Alternatively, modal analysis can be performed using the finite element method. The tower is modeled by the finite element model, while the hub and nacelle can be modeled as a lumped 6 × 6 mass matrix on top of the tower. The same foundation models as used in the ILA can be applied.

A free decay test should be performed to verify the damping level. A force can be added to the top of the tower and then released to simulate the free decay. The displacement of the tower top can be recorded to estimate the damping level to be applied in the ILA.

5.17.2(b) Modal Analysis of Blades

The ILA model with the foundation model can be used for the modal analysis. Alternatively, modal analysis can be performed with a full structural model including blades, tower and substructure, and foundation, as discussed in 2/5.17.2(a).

7 Modeling of Environmental Loads

7.1 General

This Subsection provides guidance on the global load calculation for the ILA for BOWTs.

Model or on-site test data may be employed to establish environmental loads. Alternatively, environmental loads may be determined using analytical methods compatible with the environmental condition models established in compliance with Chapter 3 of the *BOWT Guide* or other relevant standards such as IEC 61400-3-1, API RP 2A, API RP 2T, API RP 2FPS, ISO 19902, ISO 19903 and ISO 19904-1 as listed in Subsection 1/11. Any recognized load calculation method may be employed, provided it has proven sufficiently accurate in practice and it is shown to be appropriate to the system's characteristics and site conditions.

Environmental loads to be considered are listed below:

- Aerodynamic loads on the RNA
- Wind loads on the tower and the substructure
- Hydrodynamic loads on the substructures subject to waves and current
- Dynamic amplification of wave and current loads on the flexible substructure
- Ice and snow accumulation induced loads, if applicable

- Earthquake loads, if applicable
- Ice loads, if applicable

Other loads, such as wave impact loads, wave run-up loads, boat impact loads, and loads due to vortex-induced vibration (VIV) should be considered where appropriate.

7.3 Aerodynamic Loads on RNA

Aerodynamic loads induced by airflow passing through the rotor are determined by the mean wind speed and turbulence across the rotor plane, rotor rotational speed, air density, and aerodynamic shapes of wind turbine components, as well as interactive effects such as aero-elasticity and rotational sampling. Aerodynamic loads due to these effects should be calculated using recognized methods and computer programs. Guidance on the calculation of aerodynamic loads and other loads as well as load effects on the RNA in a global model is given in Subsection 2/5.11.3.

The 10-minute mean wind speed at hub height (i.e., V_{hub} as defined in 3-2/3 of the *BOWT Guide,* and the wind models defined in Section 3-2 of the *BOWT Guide* are used in the definition of design load conditions in Section 4-2 of the *BOWT Guide*.

For BOWTs installed in a wind farm, the potential shadow effect and wake effect on the loads should be considered for both the strength and fatigue analyses. Guidelines for modeling wind farm wake effects can be found in 2/5.13.

Engineering models of aerodynamic loads for the ILA (see Subsection 1/7) are usually based on the blade element momentum (BEM) theory. Some software tools may apply medium fidelity methods such as the free-vortex wake (FVW) model which is more accurate but requires a much longer simulation time than the BEM theory. Advanced CFD analysis and wind tunnel tests can be used to obtain and calibrate the aerodynamic coefficients of airfoils and semi-empirical aerodynamic correction models.

In the BEM theory, the aerodynamic loads of the rotor are calculated based on pre-defined two-dimensional (2D) airfoil aerodynamic coefficients with semi-empirical corrections. The BEM theory is a combination of the blade element method and momentum theory. With the blade element method, the blade is divided into small elements. Each element is independent of surrounding elements aerodynamically as a two-dimensional (2D) airfoil. Aerodynamic forces are calculated based on the local flow conditions using the momentum theory with energy conservation of the upstream wake and energy extracted by the rotor from the wind. BEM theory is simple and efficient and predicts the global performance of wind turbines with acceptable accuracy for ILA.

To account for the 3D effects and unsteady aerodynamics, the following semi-empirical corrections are applied to the BEM:

- Tip loss, hub loss
- Dynamic inflow (also known as dynamic wake) models
- Dynamic stall models
- Skewed inflow (wake) correction
- Tower influence models

These corrections should be included in ILA for the aerodynamic loads on the rotor. In addition, the wind loads on the nacelle should also be included in the ILA. Wind loads on the nacelle can be calculated with the drag coefficients in the longitudinal and transverse directions, projected areas, and wind speed at the nacelle.

7.5 Wind Loads on Tower and Substructures

7.5.1 Wind Loads

Wind loads on the tower are calculated as distributed loads along the tower height. The tower is discretized into small elements, and wind loads are calculated with the drag coefficient and wind speed at the height of each small element.

Wind loads on the substructure can be modeled as distributed loads similar to the wind loads on the tower. In this case, the substructure is modeled as a frame of tubular elements or a collection of discrete elements, each of which has a projected windage area. Wind loads are calculated at each discretized element with drag coefficients and wind speed at the height of the element.

7.5.2 Vortex-Induced Vibration

Vortex-induced vibration (VIV) due to wind on the tower and slender members of a substructure should be considered in the structural analysis.

Both drag and lift components of the load due to vortex-induced vibrations should be accounted for. The effects of wind loading on structural members or components that are not normally exposed to wind loads after installation should be considered where applicable. This would especially apply to load-out or transportation phases.

Guidance on the VIV effects of the tower can be found in IEC 61400-6 and IEC 61400-3-1.

7.7 Hydrodynamic Loads on Substructures

7.7.1 Hydrodynamic Loads

Hydrodynamic loads on substructures are modeled using the panel model, the Morison element model, or a combination of panel and Morison element models.

For large bodies, the wave diffraction forces should be included in the analysis. Hydrodynamic analysis can be performed with a panel model based on the radiation/diffraction theory with a boundary element method. A second-order radiation/diffraction software tool is normally used for the hydrodynamic analysis with the panel model.

Drag loads due to waves and current can be calculated using the Morison equation. The advantage of the Morison element model is to account for the current speed, wave kinematics, and substructure motions in a single model.

For members with a diameter to wavelength ratio larger than 0.2, the Morison equation may not be appropriate. Diffraction effects should be considered for wave inertia loads.

CFD analysis may be applied to calculate the hydrodynamic loads. However, CFD analysis is time consuming and often used as a verification and calibration tool.

Wave impact loads and wave run-up loads are normally considered as local loads. Global effects of wave impact should be evaluated when there is a negative air gap. Global effects of wave impact can be evaluated with advanced numerical simulations, CFD analysis, and model tests.

Guidance on shallow water wave theory, wave impact loads, and hydrodynamic loads on substructures of BOWTs is available in Annex B and Annex C of IEC 61400-3-1.

Further guidance on modeling methods of hydrodynamic loads for offshore structures can be found in API RP 2A, ISO 19902, ISO 19903, API RP 2T, API RP 2FPS and ISO 19904-1.

7.7.1(a) Gravity Based Substructure

Gravity based substructures are normally not slender structures, so the Morison method is not appropriate for calculating wave loads. Gravity based substructures are typically located in shallow water where nonlinear wave loads should be considered in the hydrodynamic analysis.

The Froude-Krylov wave excitation forces induced by incident waves can be calculated to the instantaneous wave surface by integrating the dynamic pressure on the panel model. Nonlinear wave theories can be used for calculating the dynamic pressure. The diffraction forces can be calculated using the second-order diffraction/radiation theory.

7.7.1(b) Monopile Substructure

Monopiles are used in shallow and intermediate water depths. Nonlinear wave loads should be included in the ILA. The diameter of the monopile can be large. For large monopiles, the drag loads due to waves and current on the monopiles can be calculated using the Morison equation, and the inertia wave loads are calculated through the MacCamy-Fuchs formula for a cylinder.

The MacCamy-Fuchs formula is based on diffraction theory to calculate wave inertia loads for large cylinders with a diameter to wavelength ratio larger than 0.2.

Different wave theories and wave stretching methods can be used to account for the nonlinear wave loads.

7.7.1(c) Tripod Substructure

The wave and current loads on the structural members of tripod substructures are normally calculated using the Morison equation. Different wave theories and wave stretching methods can be used to account for the nonlinear wave loads. For members with a diameter (D) to wavelength (L) ratio larger than 0.2, the Morison equation may not be appropriate. Diffraction effects should be considered for wave inertia loads.

7.7.1(d) Jacket Substructure

The wave and current loads on the structural members of jacket substructures are normally calculated using the Morison equation. Different wave theories and wave stretching methods can be used to account for the nonlinear wave loads.

7.7.1(e) Other Substructures

In general, hydrodynamic loads on substructures can be modeled using the Morison element model. For general modeling methods, guidance can be found in IEC 61400-3-1, API RP 2A, ISO 19902 and ISO 19903.

7.7.2 Wave Kinematics

There are several approaches to model wave conditions in the global model:

- Irregular waves
- Regular waves
- User defined wave spectrum
- User defined wave elevation time histories

For irregular waves, a time history of the wave surface elevation can be generated based on a given wave spectrum. Wave kinematics are calculated using the linear superposition of a number of wave frequency bands. To account for the instantaneous wave surface, kinematic stretching methods including linear stretching, vertical stretching, and Wheeler stretching methods are normally used. The second order wave theory may be considered to improve accuracy in shallow water. For a user-defined wave spectrum or wave surface elevation time history, the same methodology for a given wave spectrum can be used.

For regular waves, different wave theories including the Airy, Stokes, and Stream functions and Cnoidal and Solitary wave theories can be applied to account for different nonlinearity of waves.

Guidance on the selection of suitable wave theories and calculation of wave kinematics is provided in Annex B of IEC 61400-3-1, API RP 2A, ISO 19902, API RP 2MET and ISO 19901-1.

7.7.3 Marine Growth

Marine growth could affect the hydrodynamic loads through:

- Increased hydrodynamic diameter
- Increased surface roughness used in the determination of hydrodynamic coefficients (e.g., lift, drag, and inertia coefficients)
- Increased permanent load and inertial mass

The amount of accumulation assumed for design should reflect the extent of and interval between cleaning of submerged structural parts.

Marine growth on the power cables and members of substructures can be modeled using the Morison equation. Increase of diameter, mass, weight, drag, and added mass coefficients can be included in the Morison element model.

If the marine growth thickness is such that certain assemblies of components are completely blocked, the effect should be properly incorporated in the modeling of the hydrodynamic loads on the substructure.

Guidance to account for marine growth can be found in API RP 2A and Annex C of IEC 61400-3-1. General information on marine growth on offshore structures in different geographical offshore areas can be found in ISO 19901-1 and API RP 2MET.

7.7.4 Vortex-Induced Vibration

Vortex-induced vibration (VIV) due to current acting on structural members of a substructure should be considered in the structural analysis. Guidance on VIV analysis for cylindrical members can be found in IEC 61400-3-1 Annex C, API RP 2A, and ISO 19902.

7.9 Ice and Snow Accumulation

7.9.1 General

Where relevant, ice and snow accumulation should be assessed. Cold climate conditions can result in specific design conditions for a BOWT. The effects due to low temperature and icing conditions should be considered in the design load cases to be assessed in the ILA.

Guidance on ice and snow accumulation for the RNA, tower and substructures can be found in the following standards:

- Design requirements for wind turbines in cold climate conditions, additional design parameters for cold climate, assessment and effects of icing climate and design load cases can be found in IEC 61400-1 Clause 14, Annex A and Annex L.
- For ice and snow accumulation on the structural parts, refer to ISO 19906, ISO 19901-1, and API RP 2MET for guidance.

7.9.2 Ice and Snow Accumulation Induced Loads

Icing on an offshore structure requires a combination of water or moisture and surfaces above sea level at sub-freezing temperatures. There are two major types of icing: atmospheric and sea spray. Atmospheric icing generally includes in-cloud icing and precipitation icing.

In load calculations for the RNA in cold climate conditions, the turbine controller behavior and loads are primarily affected by:

- Ice accretion on the rotor blades
- Increased air density

The effect of ice accretion on blade aerodynamic coefficients and inhomogeneous ice distribution on wind turbine blades should be considered for ice accretion induced loads on the blade. The air densities used for load calculation and in the determination of the power curve should be calculated by applying the ideal gas law as given in IEC 61400-1 Annex A.2.

For the wind turbine blade, the ice accretion and effects due to atmospheric icing should be assessed based on IEC 61400-1 Annex L. In the absence of other information, the blade aerodynamic coefficients may be modified for the effects of ice accretion based on IEC 61400-1 Annex L.1.5. The ice mass distribution (mass/unit length) for a wind turbine blade due to atmospheric icing may be calculated based on IEC 61400-1 Annex L.2. The sea spray icing on the blade may be assessed based on ISO 19906 and/or API RP 2N.

Ice and snow accumulation on the nacelle, tower, and substructures could cause:

- Uneven distribution of ice and snow accumulation on the nacelle, tower, and substructure
- Modification of the aerodynamic and hydrodynamic properties and dynamic response of the offshore wind turbine

In order to model these effects, the following factors should be considered according to ISO 19906:

- Mass of the structure should be modified to account for uneven distribution of snow accumulation.
- Calculation of wind, wave, and current loads should be modified to account for ice and snow accumulation on the nacelle, tower, and substructure.
- Strouhal numbers for the assessment of vortex-induced vibration of slender members should be modified.
- Masses of structures and any added masses should be adjusted in accordance with the icing.

The ice and snow accumulation on the nacelle, tower, and substructures should be assessed based on guidance in ISO 19906 and/or API RP 2N. General information on ice and snow accumulation on offshore structures in different geographical offshore areas can be found in ISO 19901-1 and API RP 2MET.

7.11 Earthquake Loads

7.11.1 General

For a BOWT located in seismically active areas, the Strength Level and Ductility Level earthquake induced ground motions (see 3-6/9 of the *BOWT Guide*) should be determined based on seismic data applicable to the installation site.

Earthquake ground motions should be described by either applicable ground motion records or response spectra consistent with the return period appropriate to the design life of the structure. Available standardized spectra applicable to the region of the installation site are acceptable provided such spectra reflect site-specific conditions affecting frequency content, energy distribution, and duration. These conditions include the:

- Type of active faults in the region
- Proximity of the site to the potential source faults

- Attenuation or amplification of ground motion between the faults and the site
- Soil conditions at the site

As appropriate, effects of soil liquefaction, shear failure of soft mud, and loads due to acceleration of the hydrodynamic added mass by the earthquake, submarine slide, tsunamis, and earthquake generated acoustic shockwaves should be accounted for.

Where relevant, earthquake loads (seismic loads) should be considered. A time domain simulation should be performed for the load calculation of the support structures of offshore wind turbines. The evaluation of seismic loading should consider the combination of seismic loading with other significant, frequently occurring operational loads.

Further guidance on the assessment of earthquake loads and design conditions for the seismic analysis of BOWTs can be found in IEC 61400-1 Subclause 11.6 and Annex D, IEC 61400-3-1 Subclause 7.3.7, API RP 2A, ISO 19902 and ISO 19903.

7.11.2 Seismic Load Model

Seismic loads can be provided in the form of a spectrum or a time history. The seismic analysis is performed in the time domain. The aerodynamic loads, hydrodynamic loads, and seismic loads can be applied simultaneously in time-domain simulations. The seismic loading can be modeled by pre-defined time histories of accelerations and/or displacements of the ground motion. The time histories can be measured from the earthquake or can be generated from a response spectrum of the ground motion. Seismic time histories can be applied at one point of the foundation, or at points of individual piles in the global model.

7.13 Ice Loads

7.13.1 General

Ice loads acting on BOWTs may include both static and dynamic loads. Static loads can be generated by temperature fluctuations, ice features lodged against the structure, or changes in water level in a fast ice cover. Dynamic loads are normally caused by moving ice interactions with the substructure.

The global forces exerted by ice on the structure and local concentrated loads on structural elements should be considered. The effects of rubble piles on the development of larger areas and their forces on the substructure should be considered. Possible ice jamming between legs should be accounted for where the substructure is designed to consist of multiple legs.

Where relevant, sea/lake ice load should be assessed and included in the ILA. Guidance on the assessment of sea/lake ice conditions and calculation of ice loads for BOWTs is provided in IEC 61400-3-1 Clause 6 and Annex D.

7.13.2 Ice Load Model

Sea ice loads acting on an offshore wind turbine are both static and dynamic loads. Static loads have their origin either in temperature fluctuations or changes in water level in a fast ice cover. Dynamic loads are caused by wind and current induced motion of ice floes and their failure in contact with the support structure.

The following ice loads should be considered where relevant:

- Horizontal load due to temperature fluctuation in a fast ice cover (thermal ice pressure)
- Horizontal load from a fast ice cover subject to water level fluctuations and in terms of arch effect

- Horizontal load from moving ice
- Pressure from hummocked ice and ice ridges due to both subduction and ridging processes
- Vertical force from fast ice covers subject to water level fluctuations

Calculation of ice loads for the support structures of BOWTs should be based on the criteria provided in IEC 61400-3-1 Annex D.

9 Integrated Load Analysis

The input data for each design load case (DLC) should be prepared prior to the start of the ILA. The number of simulations, simulation time duration, calculation of maximum values, and fatigue loads should be based on applicable design standards.

After completing the ILA, the ILA results should be post-processed in a way that can facilitate the subsequent design evaluation. Output data including time histories of loads, statistics and maximum loads, and damage equivalent loads are typically derived from the ILA. These output data are further used for the design evaluation of the RNA, tower, substructure, and foundation.

The simulation length, number of simulations, and calculation of maximum (or minimum) values should comply with the applicable design standards. When there are no specific requirements, guidance provided in Section 5 can be applied.

Due to the large number of DLCs to be analyzed through the ILA, automation of data preparation and analysis management helps improve efficiency and reduce the likelihood of errors. Data set-up templates and run scripts are normally used to assign parameters for each simulation of DLCs.

11 Results Post-Processing

11.1 General

Time histories of the ILA results should be post-processed to obtain the maximum value for strength analysis and fatigue loads for fatigue analysis. The individual loads on the RNA, tower, substructure, and foundation should be determined.

All DLCs for strength analysis are typically post-processed in a group to obtain the maximum and/or minimum loads for each component of a BOWT.

All DLCs for fatigue analysis together with the probability of occurrence of each DLC are grouped together to calculate the equivalent damage loads (DELs) or the total fatigue damage directly based on the time history of the loads for each component of a BOWT.

Guidance on the assessment of the structural integrity of the RNA using the ILA results under site-specific conditions can be found in IEC 61400-1 clause 11.10. Both loads and deflections calculated from the ILA should be considered. For the fatigue loading conditions, the damage equivalent loads and moments on structural components should be calculated. The equivalent moment of the load duration distribution of the driving torque is normally considered sufficient for the verification of components. For extreme loading, a comparison of contemporaneous loads is not required.

Design of the BOWT support structure, which includes the tower, substructure, and foundation, is generally site specific. Full sets of relevant loads including extreme loads, contemporaneous loads, and fatigue loads in terms of time histories are normally used for the subsequent structural analysis for the tower, substructure, and foundation.

In general, the ILA results are provided in the following forms:

- Time histories

- Statistics of time histories including mean, maximum, minimum, and standard deviations
- Extreme loads for all DLCs for strength analysis including maximum and minimum values
- Damage equivalent loads for the RNA and tower loads for all DLCs for fatigue analysis
- Main shaft equivalent torque based on load duration distribution method

11.3 ILA Results for Bottom-Founded Offshore Wind Turbines

11.3.1 General

The ILA results for BOWTs include the RNA and tower loads, substructure loads, and foundation loads.

The results for strength analysis are normally obtained in the form of maximum and minimum values calculated based on multiple simulations. The critical loads and the associated design load cases for different components should be identified and reported after incorporating applicable partial safety factors for loads.

Fatigue loads for the RNA and tower can be provided as time histories and damage equivalent loads as discussed in 2/11.5.

Fatigue loads for the substructure are provided in the form of time histories for the substructure fatigue analysis in accordance with applicable design standards.

11.3.2 RNA and Tower Loads

The RNA and tower loads include the following:

- Blade loads along the blade span
- Generator torque and power
- Main shaft loads
- Nacelle acceleration
- Blade-tower clearance
- Tower load along the tower
- Tower tilt angle

11.3.3 Substructure and Foundation Loads

In addition to the RNA loads and the tower loads, the following substructure loads and foundation loads should be included:

- Tower interface loads
- Substructure mudline loads
- Substructure member loads
- Pile head loads, if applicable
- Pile deflection and rotation at mudline, if applicable
- Foundation horizontal and vertical forces and overturning moment

11.3.4 Resultant Loads

Loads are normally given in the form of six (6) load components, including three forces, F_x, F_y, and F_z, and three moments, M_x, M_y, and M_z.

When the structural stiffness and strength in response to loading in the plane are similar for the different loading directions, extreme loading can occur when both x and y components are large in magnitude but not at their largest values. Thus, the in-plane vector resultant values should also be calculated. These in-plane resultants loads are defined as:

$$F_R = \sqrt{F_x^2 + F_y^2}$$

$$M_R = \sqrt{M_x^2 + M_y^2}$$

where

F_R = resultant force, N (lb)

F_x = force in x-axis, N (lb)

F_y = force in y-axis, N (lb)

M_R = resultant moment, N-m (lb-ft)

M_x = moment about x-axis, N-m (lb-ft)

M_y = moment about y-axis, N-m (lb-ft)

11.5 Fatigue Loads for RNA and Tower

11.5.1 General

Fatigue is the damage accumulation process in a component caused by cyclic loading. Fatigue loads for the RNA components and the tower are usually calculated as damage equivalent loads (DELs). The methods to calculate the DEL are provided in 2/11.5.2. The load range and the number of cycles of the load range are calculated by the rainflow counting method as described in 2/11.5.3.

For the drive train components, gear and bearing system, the load duration distribution method is normally used for the main shaft fatigue loads calculation as presented in 2/11.5.4.

11.5.2 Damage Equivalent Load

Damage Equivalent Load (DEL) is the equivalent load range for a reference number of cycles that can generate the same amount of fatigue damage as the fatigue loads from all the fatigue DLCs during the design life. Damage equivalent loads are used to equate the fatigue damage caused by a single load range repeating at a single number of cycles to the total fatigue damage.

The Damage Equivalent Load (DEL) is calculated by:

$$L_{eq} = \left(\frac{\Sigma n_i L_i^m}{N_{eq}}\right)^{\frac{1}{m}}$$

where

L_{eq} = damage equivalent load (DEL), N (lb) for force, N-m (lb-ft) for moment

L_i = i^{th} bin load range N (lb) for force, N-m (lb-ft) for moment

n_i = number of cycles of load range L_i

m = slope of the S-N curve

N_{eq} = reference number of cycles for the DEL

The reference number of cycles, N_{eq}, is normally taken as 10^7.

In addition, to compare the fatigue loads from different wind and wave conditions, the fatigue load is also calculated in the form of the 1 Hz damage equivalent load (DEL). The damage equivalent load is the cyclic load occurring N_{eq} times to cause the same fatigue damage as the fatigue damage for the wind turbine exposed to a wind and wave condition within a certain duration. For a typical fatigue load simulation that lasts for 600 seconds, 1 Hz DEL is calculated with N_{eq} equal 600 for the given duration of 600 seconds.

11.5.3 Rainflow Counting Method

The rainflow counting method can be used to calculate the load range and load range cycle numbers for the fatigue loads. The time histories of the loads from the ILA are used for the calculations.

For a load time history, the algorithm in the rainflow counting method decomposes the load time history into load cycles with different load ranges. The rainflow cycle distributions represent the probability of occurrence of each load range. The damage equivalent load (DEL) can then be calculated.

11.5.4 Load Duration Distribution Method

The load duration distribution method is used to derive the load range cycles for the drive train components from the time series of the loads from the ILA.

The main components of the drive train include the hub, main shaft, main bearing, gearbox, coupling, generator, and bedplate. The load range and cycle counting for gears and bearing systems are different than for shafts or other components and depend on the magnitude of the driven load and the speed at which every geared shaft and bearing is turning. The load duration distribution method is a convenient way to describe fatigue loads for the design of bearings and gearboxes.The load duration distribution method is used to derive the load range cycles for the drive train components from the time series of the loads from the ILA.

The shaft loads from the ILA are processed to obtain the load duration distribution (LDD) for the fatigue design of the gears and bearing system. As part of the results of the ILA, the main shaft equivalent torque is calculated using the load duration distribution method as below:

$$T_{eq} = \left(\frac{\Sigma n_i T_i^p}{\Sigma n_i}\right)^{\frac{1}{p}}$$

where

T_{eq} = equivalent torque, N-m (lb-ft)

T_i = i^{th} bin torque range, N-m (lb-ft)

n_i = number of cycles of torque T_i

p = slope of the S-N curve

SECTION 3

Integrated Load Analysis for Floating Offshore Wind Turbines

1 Introduction *(1 August 2023)*

1.1 General

The ILA is performed for the following purposes:

- Classification based on the ABS *Guide for Building and Classing Floating Offshore Wind Turbines* (*FOWT Guide*), when ILA is recommended
- Certification and verification in compliance with local regulatory requirements, IEC certification scheme based on IECRE OD-502, and IEC 61400 series standards or other industry standards for floating offshore wind turbines.

The ILA involves aero-hydro-servo-elastic analyses that can account for the coupled dynamics of an FOWT including the RNA, control system, tower, floating substructure, stationkeeping system, and where applicable, power cables modeled and solved simultaneously in the time domain.

In contrast to the uncoupled analysis methods, the ILA accounts for the coupling effects and damping effects including aerodynamic and hydrodynamic damping consistently. It can provide a more rational calculation of global motions and loads for the detailed design evaluation of the RNA components, tower, floating substructure, stationkeeping system, and power cables.

Software tools for the ILA should be compatible with the modeling approaches applied to individual FOWT components and the load transfer strategy for detailed design evaluations for each component of the FOWT.

The numerical modeling and simulation methods should comply with the applicable classification or certification requirements. Where there are no specific requirements, these Guidance Notes may be applied.

1.3 Design Data, Reports and Drawings

The ILA requires the following design data, reports, and drawings:

- Site conditions and environmental data (water depth, seabed bathymetry, soil data, wind, wave, current, water level, wind/wave misalignment, fatigue sea states, etc.)
- RNA modeling data (geometry, dimensions, airfoil aerodynamic data, drive train properties, blade material properties, stiffness, damping, mass distribution, natural frequencies, turbine power and thrust curves, etc.)
- Tower modeling data (geometry, dimensions, material properties, stiffness, damping, mass distribution, natural frequencies, etc.)

- Wind turbine control system modeling data (description of the wind turbine control software, the controller dynamic link library (DLL) to integrate to the load analysis software, and operation procedures, etc.)
- Sea state limit for shutdown in severe sea states, if applicable
- Hull modeling data (dimensions, material properties, stiffness, mass properties, free decay, motion responses amplitude operators (RAOs), etc.)
- Hull damping from model testing, if available
- Mooring system modeling data (pattern, fairlead and anchor locations, line components properties and pretensions)
- Modeling data of the hull and mooring active control system, if any

In addition, the following design reports are needed for information for the ILA:

- Hull damaged (leakage) condition including the amount of flooded water and induced platform heel motions, if applicable
- Other design considerations pertinent to the FOWTs, if applicable

3 Integrated Load Analysis Procedures *(1 August 2023)*

3.1 General

The integrated load analysis (ILA) consists of the following key steps:

i) Build a global performance analysis model

ii) Define environmental load models

iii) Set up data files for each Design Load Case (DLC)

iv) Perform ILA simulations

v) Obtain time histories of loads and motions

vi) Post-process and report results

Modeling strategies for floating offshore wind turbines are outlined in Subsection 3/5. Modeling methods for environmental loads are provided in Subsection 3/7. Guidance on simulation and post-processing is provided in Subsections 3/9 and 3/11. Interface loads for detailed design evaluations are described in Subsection 3/11.

3.3 ILA Procedure for Floating Offshore Wind Turbines

The ILA procedure for FOWTs is illustrated in 3/3.3 FIGURE 1.

The ILA model for an FOWT comprises the WTG (RNA and tower) model, floating substructure model and stationkeeping system model. The power cable model may also be included in the ILA model. The floating substructure model is normally simplified as a rigid body or multiple rigid bodies. The flexibility of the floating substructure may be modeled through a simple beam element model. The ILA results provide input for the WTG, floating substructure, stationkeeping system and power cable design evaluations.

A separate structural analysis software tool is normally needed for the subsequent floating substructure design evaluation. Global motions and loads calculated through the ILA can be applied to the detailed structural analysis model of the floating substructure.

The ILA for an FOWT typically includes the following steps:

i) Build the global analysis model:

- Wind turbine generator (WTG) model including RNA and tower models
- Wind turbine controller integration
- Floating substructure model
- Stationkeeping system model
- Power cable model, if applicable
- Modal shapes calculated through the modal analysis

ii) Define environmental load models

- Wind load models
- Wave load models
- Current load models
- Modeling of vortex induced motion (VIM), if applicable
- Modeling of ice and snow accumulation induced loads, if applicable
- Modeling of sea/lake ice loads, if applicable
- Modeling of seismic loads, if applicable

iii) Set up data files for each Design Load Case (DLC)

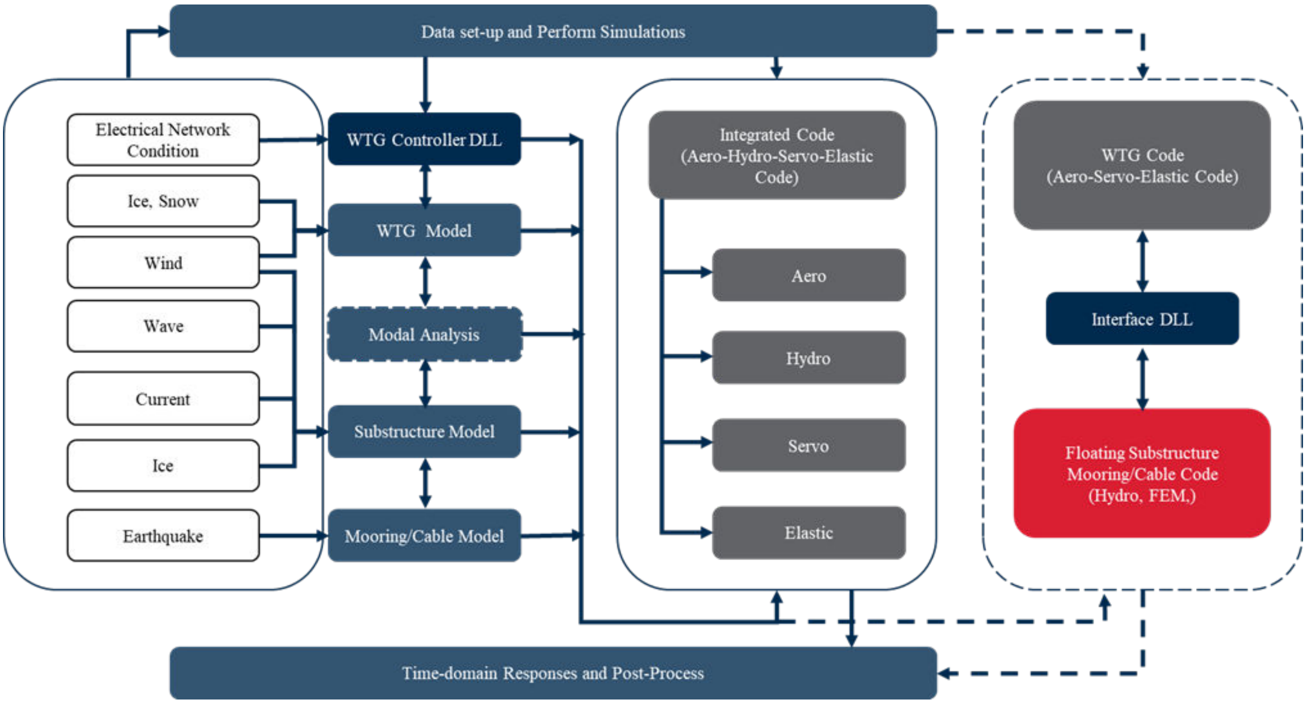
- Simulation time duration, time step, and number of random seeds
- Random seeds for each simulation requiring to apply random waves and winds
- For a fatigue DLC, the probability of occurrence or number of occurrences of fatigue design conditions
- Partial load safety factor
- Wind, wave, current, and water level models and parameters
- Wind farm wake models
- Wind turbine controller setup
- Wind turbine condition setup
- Nacelle yaw misalignment setup
- Hull condition setup
- Stationkeeping system condition setup
- Gird condition (electrical network condition) setup
- Other external conditions setup

iv) Perform ILA simulations

v) Obtain time histories of global motions and loads of the RNA, tower, floating substructure, stationkeeping system and, if applicable, dynamic power cables

vi) Post-process and report results

FIGURE 1
ILA Procedure for Floating Offshore Wind Turbines



5 Modeling of Floating Offshore Wind Turbines

5.1 General *(1 August 2023)*

In general, dynamic analyses should be carried out to evaluate dynamic responses of the FOWT subjected to site-specific external conditions and operating conditions. While various simplified analysis methods may be used in the preliminary design, an integrated (coupled) dynamic analysis approach is recommended for the final detailed design. Prototype tests and model tests may be used to supplement the load calculation.

For the purpose of motion and load calculations in the global performance analysis and integrated load analysis, the analysis model should include the following aspects:

- Modeling of the hull
- Modeling of flexibility of the tower
- Modeling of stationkeeping systems
- Modeling of rotor blades and control and safety systems
- Modeling of dynamics of drive trains
- Modeling of wind farm wake effects
- Modeling of power cables, if needed
- Modeling of mode shapes through the modal analysis

The external conditions to be considered in global performance analysis and integrated load analysis include:

- Environmental conditions
- Electrical network conditions

In addition, various fault conditions relevant to the electrical system, control and safety systems and mechanical components should be properly modeled in the analysis.

5.3 Modeling of the Hull

5.3.1 General *(1 August 2023)*

The hull in general can be modeled as a rigid body or multiple rigid bodies with 6 degrees of freedom (6 DOFs) motions. Where deemed necessary, flexibility of the hull may be modeled using beam elements. The structural flexibility of the connection of the floating substructure to the tower should be included in the analysis.

Modeling of the hull should consider the following loads and load effects:

- Hydrostatic loads
- Gravitational and inertial loads
- Wind, wave and current loads
- Hull vortex induced motion (VIM) and vortex induced vibration (VIV), if applicable
- Other loads (such as ice loads, ice and snow accumulation induced loads, earthquake loads, impact loads, etc.), if applicable

Guidance on modeling of environmental loads on the hull is provided in Subsection 3/7.

5.3.2 Hydrostatic Model *(1 August 2023)*

Balancing mass with buoyancy in the vertical direction is usually the starting point for hydrodynamic analyses. The vertical component of mooring pretensions is part of this load balancing.

Buoyancy of a large-volume floating hull can be calculated directly using the wetted surface of the panel element model created for diffraction-radiation analyses. When an analysis model includes both the panel elements and Morison elements, the buoyancy could still be calculated by most commercial software if actual locations and dimensions of the Morison elements are provided. Correct modeling of metacentric heights (GM_L, GM_T) is as important as modeling the location of the center of buoyancy. Free surface effects in partially filled internal tanks should be considered in determination of metacentric heights.

Stiffness contributions from moorings and cables should be appropriately accounted for. The mass distribution of the hull can be represented by either a global mass matrix or a detailed mass distribution (e.g., FE model). The input coordinate system normally depends on the software employed and its origin may be placed at the vertical center of gravity or on the still water plane. Proper input of roll and pitch radii of gyration is critical and requires a correct definition of reference axis systems.

5.3.3 Hydrodynamic Model *(1 August 2023)*

The hydrodynamic model of the floating substructure consists of the panel model, the Morison element model, or a combination of the panel and the Morison element models. Marine growth could affect the hydrodynamic loads and should be considered in the Morison element model.

A diffraction-radiation analysis is usually performed using the panel model based on the boundary element method to calculate the hydrodynamic loads. The main output of a diffraction-radiation analysis includes the first-order excitation forces and moments in the form of load response amplitude operators (RAOs), hydrostatics, potential damping, added mass, first-order motions in 6 DOFs, and second-order forces and moments in the form of quadratic transfer functions (QTFs).

The load RAOs and QTFs are used as input to calculate the hydrodynamic loads on the large-volume hull in ILA.

Further guidance on the hydrodynamic load calculation can be found in 3/7.7.2.

5.3.4 Instability

Mathieu's instability may occur for dynamic systems with time dependent stiffness. Several effects may cause such time dependent stiffness. Specifically for the FOWT, there are two scenarios that may trigger instability:

- Non-constant heave stiffness caused by the geometric shape of the hull
- Non-constant pitch stiffness caused by a nonlinear heave coupling term

The heave/pitch-coupled instability in the second scenario could be critical for a single column hull with relatively low heave damping.

Instability can be identified through numerical simulations and/or model and field testing.

5.5 Modeling of Flexibility of Tower *(1 August 2023)*

The tower can generally be modeled based on linear elastic theory. However, nonlinear relationships between loads and load effects should be properly accounted for, when deemed important. Structural damping of the tower should be properly determined.

The wind loads on the tower should be included. When wind loads on the FOWT are analyzed, the influence of the tower shadow or tower upwind effects on the wind field perturbation should be properly modeled.

The tower structures can be modeled using the finite element method. The model should account for the distributed stiffness and mass properties along the axial direction of the tower. The moment of inertia about the axial direction should be accounted for.

The dynamic structural response of the tower may also be calculated by the modal superposition method. Sufficient modes should be included in the analysis. As a minimum, the first few orders of bending modes should be included. If the tower does not have sufficient torsional stiffness, torsional modes should also be included in the modeling. Modal analyses of the tower should consider the influences of the floating substructure and the stationkeeping system.

For some types of FOWTs, such as a catenary-moored Spar-type or Semi-submersible-type FOWT, the tower may be modeled as part of the rigid body of the floating support structure in preliminary mooring system designs. However, the tower flexibility should be adequately modeled for the final detailed design.

Guidance on the tower modal analysis is provided in 3/5.17.

5.7 Modeling of Stationkeeping System

5.7.1 General *(1 August 2023)*

There are mainly two approaches for mooring system analysis (i.e., quasi-static analysis and dynamic analysis). Both methods can be pursued in either the frequency domain or the time domain. The quasi-static analysis may be used in the preliminary design stage. For the ILA, the time-domain dynamic method is usually required to account for nonlinearity and dynamic effects of the mooring (or tendon) system.

The formulation for modeling the mooring (or tendon) system is mainly based on the finite element method (FEM) or the lumped-mass method.

Mooring lines are typically modeled as slender cylindrical members. Modeling of the mooring lines should consider the following loads and load effects:

- Hydrodynamic loads induced by current and wave
- Ice-induced loads, if applicable
- Vortex-induced vibrations of the mooring lines, if applicable
- Marine growth

Guidance on modeling environment loads on the mooring line can be found in Subsection 3/7.

5.7.2 Mooring Line Nonlinearity

There are four primary nonlinear effects that could greatly affect mooring line behaviors:

- *Nonlinear Stretching Behavior of the Mooring Line*. The strain or tangential stretch of the mooring line is a function of the tension magnitude. Nonlinearity occurs mostly in synthetic materials such as polyester, while chain and wire rope can be regarded as linear. In many cases, this nonlinearity is simplified by a linearized behavior using a representative tangent or secant modulus.
- *Changes in Geometry*. The geometric nonlinearity is associated with large variations of the mooring line shape.
- *Fluid Loading*. The Morison equation is most frequently used to represent fluid loading effects on mooring lines. The drag force on the line is nonlinear because it is proportional to the square of the relative velocity between the fluid and the line.
- *Bottom Effects*. In many mooring designs, a considerable portion of the mooring line is in contact with the seafloor. The interaction between the line and the seafloor is usually considered to be a nonlinear frictional process. In addition, the length of grounded line segment constantly changes, causing an interaction between this nonlinearity and the geometric nonlinearity.

In the time-domain method, it is possible to model the non-linear effects described above - the elastic stretch can be mathematically modeled, the full Morison equation can be implemented, the position of the mooring line can be updated at each time step, and the bottom interaction can be simulated using a frictional model. Such a time-domain analysis requires recalculating mass, damping, and stiffness matrices and loading at each time step. Hence, the computation can become complex and time consuming.

The frequency-domain method, on the other hand, is always linear because of the principle of linear superposition. Hence, all sources of non-linearity should be simplified by either a direct linearization approach or an iterative linearization approach.

5.7.3 Finite Element Analysis Approach

The Finite Element (FE) method can be an effective approach for modeling mooring (or tendon) systems in the global performance analysis. The important features that are desirable for adequate modeling and analysis of mooring (or tendon) systems normally include:

- 3D formulation
- Conventional small strain slender beam and bar elements capable of considering material and geometric stiffness and nonlinear material properties
- Hull/mooring (or tendon) connection formulation
- Seafloor/mooring line contact formulation
- Seabed/tendon connection formulation

- Structural damping formulation
- Hydrodynamic loading according to the Morison equation expressed by the relative water/structure velocity and acceleration
- Regular and irregular loading due to waves and hull structure motions.
- Current modeling
- Capability of modeling mooring components such as swivels, hinges, buoyancy modules, clump weights, flex-joints, etc.
- Capability of modeling constant (or variable) line tension devices
- Nonlinear static analysis
- Eigenvalue analysis
- Nonlinear time-domain dynamic analysis

The computational efforts of nonlinear time-domain dynamic analysis can be substantial. This is particularly the case for irregular wave analyses where long simulations are typically required to estimate extreme responses with sufficient statistical confidence. It is therefore beneficial to apply simplified analysis approaches as a supplement to achieve more efficient computer analyses (e.g., linearized time- domain analysis, frequency-domain analysis, etc.).

5.9 Modeling of Dynamics of Drive Trains *(1 August 2023)*

Drive train dynamics should be properly considered in the ILA. As a minimum, the torsional mode of the drive train should be included in the analysis.

The drive train includes all torque-transmitting components from the rotor to the generator as well as the elastic mounting of the drive train. The parameterization assumptions of the drive train model used in the global load calculation should be verified by the calculation using more detailed drive train models. In most cases, the controlling parameters are “resulting drive train stiffness” and “moment of inertia of generator rotor”. The verification can also be carried out through the comparison of the first eigenfrequency obtained from the detailed drive train model to the corresponding value derived from the global load simulation model. Other verification techniques can also be used, if appropriate.

5.11 Modeling of Rotor Blade and Control and Safety Systems

5.11.1 General *(1 August 2023)*

Guidance on the modeling of rotor blades and control and safety systems can be found in 2/5.11. In addition, the following should be considered for FOWTs:

- Inertial loads, including gyroscopic loads, are of special importance to FOWTs due to their potentially additional compliance and increased dynamic response from aerodynamic and hydrodynamic loading.
- The interaction of the turbine control system with the low frequency motions of the floating substructure should be incorporated into the control system design and load analysis.

5.13 Modeling of Wind Farm Wake Effects

Within an offshore wind farm, the turbulence intensity associated with wake flow may be considerably higher than the ambient turbulence intensity. In addition, wake flow is characterized by a reduced mean wind speed and an increased shear profile. In the absence of detailed analysis of the wind characteristics within an offshore wind farm, the design calculation may be performed using increased turbulence intensity based on the past experience and recognized calculation methods.

The mutual influence of offshore wind turbines through the wake interaction behind the rotor should be considered in a wind farm configuration up to a distance of at least 10 rotor diameters from another

FOWT. Reference can be made to IEC 61400-1 for guidance on the wake effects from neighboring wind turbines.

As appropriate, the global yawing moment exerted on the floating support structure due to unbalanced rotor aerodynamic loads caused by the shade effect or the wake effect of neighboring FOWTs should also be considered. Such global yawing moment may be assessed separately and added to the total RNA aerodynamic loads.

5.15 Power Cable Considerations *(1 July 2020)*

The power cable system for exporting generated electricity could have a long suspended segment extending from its connecting point on the hull to the seafloor. The power cable interacts with the floating substructure and the mooring in several aspects. Wave and current actions on the cable could increase the environmental actions to be resisted by the mooring, while the cable system stiffness provides assistance to the mooring. Furthermore, damping from the cable system decreases the low frequency motions and in turn reduces the mooring tensions. The net result of these effects depends on a number of factors such as the type of cable and the water depth. Mooring design should consider the cable loads, stiffness, and damping, unless it can be demonstrated that neglecting the cable in global performance analyses results in a more conservative mooring design.

5.17 Modal Analysis *(1 August 2023)*

5.17.1 General

Modal analysis is used to calculate the natural frequencies, damping, and mode shapes of the wind turbine blades, tower, and substructure. The finite element model is commonly used to perform the modal analysis. The purposes of the modal analysis are to:

- Obtain the mode shapes for the blades and the tower as input for the structural models
- Obtain the natural frequencies for the tower on the floating foundation
- Evaluate the damping level for the global model

The modal superposition method is used in some ILA software tools to model the blade and tower flexibility. The mode shapes obtained from the modal analysis are used as input to the ILA software tools for blade and tower modeling.

The overall damping level of the global model is a key element in the prediction of both fatigue and extreme loads for load carrying components of an FOWT and should carefully be selected.

5.17.2 Modal Analysis for Floating Offshore Wind Turbines

The global model for the ILA or a full structural model can be used for the modal analysis of the tower and the blade. Added mass on the floating substructure, hydrostatic stiffness, mooring stiffness on the floating substructure, and added mass due to mooring lines should be included in the modal analysis. Flexibility of the tower-to-hull connection should be included and can be determined using the structural analysis model for the detailed hull design.

A free decay of the tower top displacement should be performed to verify the damping level used for the tower on an FOWT. The free decay test may be performed with the floating substructure fixed.

Numerical free decay tests of an FOWT should be performed using the ILA model to verify the damping level for the 6-DOF motions. Available model testing, field testing, or computational fluid dynamics (CFD) analysis can be used to verify the damping level.

It should be verified that the fundamental frequencies of the tower and the natural frequencies of 6-DOF motions of the FOWT are away from the 1P rotor frequency and 3P (for 3-blade turbines) blade passing frequency.

7 Modeling of Environmental Loads

7.1 General *(1 August 2023)*

This Subsection provides guidance on the global load calculation for the global performance analysis and the ILA for FOWTs.

Model or on-site test data may be employed to establish environmental loads. Alternatively, environmental loads may be determined using analytical methods compatible with the environmental condition models established in accordance with Chapter 4 of the *FOWT Guide* or other relevant standards such as IEC TS 61400-3-2, API RP 2A, API RP 2T, API RP 2FPS, ISO 19902, ISO 19903 and ISO 19904-1 as listed in Subsection 1/11. Any recognized load calculation method may be employed provided it has proven sufficiently accurate in practice, and it is shown to be appropriate to the system's characteristics and site conditions.

Environmental loads to be considered include:

- Aerodynamic loads on the RNA
- Wind loads on the tower and the floating substructure
- Hydrodynamic loads on the mooring lines (or tendons) and cables
- Hydrodynamic loads on the floating substructures subject to waves and current
- Dynamic amplification of wave and current loads on the flexible substructure members
- Vortex-induced motion (VIM) of floating substructures, if applicable
- Ice and snow accumulation induced loads, if applicable
- Earthquake loads, if applicable
- Ice loads, if applicable

Other loads, such as wave impact loads, wave run-up loads, boat impact loads, and loads due to vortex-induced vibration (VIV) should be considered where appropriate.

7.3 Aerodynamic Loads on RNA *(1 August 2023)*

Aerodynamic loads induced by airflow passing through the rotor are determined by the mean wind speed and turbulence across the rotor plane, rotor rotational speed, air density and aerodynamic shapes of wind turbine components as well as interactive effects such as aero-elasticity and rotational sampling. Aerodynamic loads due to these effects should be calculated using recognized methods and computer programs. Guidelines for calculation of aerodynamic loads and other loads and load effects on the RNA are given in 3/5.11.

The 10-minute mean wind speed at hub height (i.e., V_{hub} as defined in 4-2/3 of the *FOWT Guide*) and the wind models defined in Section 4-2 of the *FOWT Guide* are used in the definition of design load conditions in Section 5-2 of the *FOWT Guide*.

For FOWTs installed in a wind farm, the potential shadow effect and wake effect on the loads should be considered for both the strength and fatigue analyses. Guidelines for modeling of wind farm wake effects can be found in 3/5.13.

Further information on the aerodynamic loads on the RNA can be found in 2/7.3.

7.5 Wind Loads on Tower and Floating Substructures *(1 August 2023)*

7.5.1 Wind Loads

Wind loads on the tower are calculated as distributed loads along the tower height. The tower is discretized into small elements, and wind loads are calculated with the drag coefficient and wind speed at the height of each small element.

Wind loads on the floating substructure can be modeled as distributed loads similar to the wind loads on the tower. The floating substructure is modeled as a frame of tubular elements or a collection of discrete elements each of which has a projected windage area. Wind loads are calculated at each discretized element with drag coefficients and wind speed at the height of the element.

Wind loads can also be calculated using 6-DOF wind force and moment coefficients and wind speed at a given height. The wind and moment coefficient can be calculated with a given wind profile or from wind tunnel tests.

7.5.2 Vortex-Induced Vibration

Vortex-induced vibration (VIV) due to wind on the tower and slender members of a floating substructure should be considered in the structural analysis.

Both drag and lift components of the load due to vortex-induced vibrations should be accounted for. The effects of wind loading on structural members or components that are not normally exposed to wind loads after installation should be considered, especially during the load-out or transportation phases.

Guidance on the VIV effects of the tower can be found in IEC61400-6 and IEC 61400-3-1.

7.7 Hydrodynamic Loads

7.7.1 Hydrodynamic Loads on Mooring Lines and Power Cables *(1 August 2023)*

Hydrodynamic loads on the mooring lines and power cables due to waves and current are modeled using the Morison equation for the drag and inertia load calculation. The current speed, the water particle velocity in the waves, and the velocity of the mooring lines or cables are added vectorially to compute the drag forces. The relative acceleration between the water particle in wave and the mooring lines and cables are used for computing the inertia forces.

The type and accumulation rate of marine growth at the design site can affect mass, weight, hydrodynamic diameters, and drag coefficients of mooring lines. This should be considered for mooring systems not subject to regular marine growth removal.

7.7.2 Hydrodynamic Loads on Floating Substructures

7.7.2(a) General (1 August 2023)

For structures consisting of slender members that do not significantly alter the incident wave field, semi-empirical formulations, such as Morison's equation, may be used. For calculation of wave forces on structural configurations that significantly alter the incident wave field, appropriate methods which account for both the incident wave force (e.g., Froude-Krylov force) and the forces resulting from wave diffraction should be used. In general, Morison's equation is applicable for structures comprising slender members with diameters (or equivalent diameters giving the same cross-sectional areas parallel to the flow) less than 20 percent of the wavelengths.

For installation sites where the ratio of water depth to wavelength is less than 0.25, nonlinear effects of wave action should be accounted for. This may be fulfilled by modifying linear diffraction theory to account for nonlinear effects or by performing model tests. Wave force calculations should account for shallow water effects which increase current due to blockage effects, change the system natural frequency due to nonlinear behavior of moorings, and alter wave kinematics.

Current induced loads on immersed structural members should be determined based on analytical methods, model test data, or full-scale measurements. When currents and waves are superimposed, the current velocity should be added vectorially to the wave induced particle velocity prior to computation of the total force. Current profiles used in the design should be representative of the expected conditions at the installation site. Where appropriate, flutter and dynamic amplification due to vortex shedding should be considered.

Drag loads due to waves and current can be calculated using the Morison equation. The advantage of the Morison element model is to account for the current speed, wave kinematics, and floating substructure motions in a single model.

Drag loads due to waves and current can be modeled separately. Current forces and moments can be calculated through 6 DOFs of current force and moment coefficients with the current speed at a given depth from the water surface. The wind and moment coefficient can be calculated with a given wind profile or from wind tunnel tests. Additional 6 × 6 linear and nonlinear viscous damping matrices can be applied to account for viscous damping effects.

CFD analysis may be applied to calculate the hydrodynamic loads. However, CFD analysis is time consuming and often used as a verification and calibration tool.

Wave impact loads and wave run-up loads are normally considered as local loads. Global effects of wave impact should be evaluated when there is a negative air gap. Global effects of wave impact can be evaluated using advanced numerical simulations, CFD analysis, and model tests.

Marine growth could affect the hydrodynamic loads and should be accounted for.

Further guidance on modeling methods of hydrodynamic loads for offshore structures can be found in API RP 2A, ISO 19902, ISO 19903, API RP 2T, API RP 2FPS and ISO 19904-1.

7.7.2(b) Hydrodynamic Loads by Diffraction-Radiation Analysis (1 August 2023)

The typical hulls are large-volume floating structures that are inertia-dominated with respect to global motions. Radiation/diffraction analyses are commonly used to determine the wave loads on such hulls. Some types of hull such as semi-submersibles and truss spars may also have slender members and braces for which the Morison model is more appropriate.

A linear radiation/diffraction analysis is usually sufficient. The term “linear” means that the average wetted area of a floating structure (up to the waterline) is used in the analysis. The main output of a radiation/diffraction analysis gives the first-order excitation forces, hydrostatics, potential damping, added mass, first-order motions in 6 DOFs and second-order drift forces/moments. Such an analysis can also provide information relevant to the slowly varying responses in roll and pitch that is important for FOWTs based on Spars or other deep-draft floating structures, large semi-submersibles, and TLPs.

Low frequency vessel motions are caused in part by nonlinear second order drift forces. If the natural period of FOWT motions is long (for instance, larger than 25 seconds), a linear frequency-domain solution may be achieved by Newman’s approximation, which eliminates the off-diagonal terms in the QTF (Quadratic Transfer Function) matrix. Newman’s approximation generally gives satisfactory results for low frequency motions in the horizontal plane where the natural periods of FOWT motions are much longer than the wave periods. For low frequency motions in the vertical plane (e.g., the pitch motion of a Spar), Newman’s approximation may underestimate the second order drift forces. If such responses are deemed important for the design, time-domain analyses using a full QTF matrix may be required. When the full QTF matrix approach is used, special attention should be paid to establishing a consistent damping level.

Second-order wave forces at the sum-frequencies in a random sea-state could excite resonant responses in heave, roll, and pitch of TLP-type FOWTs. Such a resonant response, also known as springing, is a stationary time-harmonic oscillation of the TLP-type FOWT at a resonance period of one of the vertical modes (i.e., heave, roll, pitch). In addition, TLP-type FOWTs in deep water may experience excessive resonant high frequency transient ringing response. Time-domain analysis is typically performed to evaluate these high frequency responses. There are methods and computer tools for calculating the sum-frequency QTF. The important aspects to be considered for springing analyses include:

- Discretization (mesh) of wetted surface geometry
- Discretization of free surface and its extension
- Number of frequency pairs in the QTF matrix
- Damping level for the tendon axial response

Wave periods and wave headings should be selected such that motions and forces/moments can be described as correctly as possible. Cancellation, amplification, and resonance effects should be properly captured. Modeling principles related to the panel mesh (size) should in general be followed, e.g.:

- Diagonal length in panel elements should not be larger 20% of the smallest wavelength analyzed.
- Fine panel mesh should be applied in areas with abrupt changes in geometry.
- Finer panel mesh should be applied towards the waterline in order to capture correct wave drift excitations.

Hydrodynamic interactions between multiple (n) floating substructures in close proximity may also be solved using radiation/diffraction analyses, where the floating substructures are normally solved together for motions in $n \times 6$ DOFs.

7.7.3 Wave Kinematics *(1 August 2023)*

There are several approaches to model wave conditions:

- Irregular waves
- Regular waves
- User defined wave spectrum
- User defined wave elevation time histories

For irregular waves, a time history of the wave surface elevation is generated based on a given wave spectrum. Wave kinematics are calculated using the linear superposition of several wave frequency bands. To account for the instantaneous wave surface, kinematic stretching methods including linear stretching, vertical stretching, and Wheeler stretching methods are normally used. The second order wave theory may be considered to improve accuracy in shallow water. For a user defined wave spectrum or wave surface elevation time history, the same methodology for a given wave spectrum can be used.

For regular waves, different wave theories including the Airy, Stokes, and Stream functions, and Cnoidal and Solitary wave theories can be applied to account for different nonlinearity of waves.

Guidance on the selection of suitable wave theories and calculation of wave kinematics is provided in Annex B of IEC 61400-3-1, API RP 2A, ISO 19902, API RP 2MET and ISO 19901-1.

7.7.4 Marine Growth *(1 August 2023)*

Marine growth could affect the hydrodynamic loads through:

- Increased hydrodynamic diameter

- Increased surface roughness used in the determination of hydrodynamic coefficients (e.g., lift, drag, and inertia coefficients)
- Increased permanent load and inertial mass

The amount of accumulation assumed for design should reflect the extent of and interval between cleaning of submerged structural parts.

Marine growth on the mooring lines, cables, and members of floating substructures can be modeled using the Morison equation. Increase in diameter, mass, weight, drag, and added mass coefficients can be included in the Morison element model.

If the marine growth thickness is such that certain assemblies of components are completely blocked, the effect should be properly incorporated in the modeling of the hydrodynamic loads on the substructure.

Guidance to account for marine growth can be found in API RP 2A and Annex C of IEC 61400-3-1. General information on marine growth on offshore structures in different geographical offshore areas can be found in ISO 19901-1 and API RP 2MET.

7.7.5 Vortex-Induced Motions (VIM) of the Floating Substructure *(1 August 2023)*

Floating substructures consisting of large diameter cylindrical components such as Spars, semi-submersibles, and TLPs can experience low frequency motions due to vortex shedding in the presence of currents. These vortex-induced motions (VIM) are most prominent for Spars where most of the industry experience has been acquired. Nevertheless, multi-column floating structures such as semi-submersibles and TLPs can also experience VIM, and this effect should be accounted for in the design.

VIM could have three primary effects on the mooring design:

- Increase in the average in-line drag coefficient
- Large low frequency VIM motion amplitudes relative to the total floating substructure responses
- Additional low frequency oscillating mooring line tensions

These effects should be considered for strength and fatigue design of FOWT stationkeeping systems as well as the power cables. The occurrence of the Loop Current and associated eddies in the Gulf of Mexico makes consideration of VIM particularly important for this geographic area. For example, unlike other extreme events (e.g., winter storms and tropical revolving storms), the Loop Current and associated eddies could affect a particular site for an extended period of time and thus cause a significant fatigue damage accumulation in mooring components.

For FOWTs, vortex-induced motion (VIM) in currents and waves should be considered where relevant. Since the hull VIM is a strongly nonlinear phenomenon, model testing has often been used to determine the hull VIM responses and calibrate the numerical simulations. The amplitudes of in-line and transverse VIM responses to the direction of current and wave can be calibrated against model tests and/or CFD analysis. VIM can be represented by sinusoidal forces in both in-line and transverse directions of the current and waves. Drag augmentation of the floating substructure due to VIM should be considered. Wind, wave, and current forces can be applied together with the sinusoidal forces for VIM.

7.7.6 Vortex-Induced Vibration *(1 August 2023)*

Vortex-induced vibration (VIV) due to current acting on structural members of a floating substructure should be considered in the structural analysis. Guidance on VIV analysis for cylindrical members can be found in IEC 61400-3-1 Annex C, API RP 2A, and ISO 19902.

For slender members, such as mooring lines, tendons, and cables, VIV should be assessed. Increased drag loads on individual components and fatigue damage of individual components due to VIV should be considered. The VIV analysis is normally carried out to evaluate the effect of VIV on the fatigue damage of slender members. Guidance on the VIV analysis for slender members can be found in ISO 19904-1 Subclause 7.4.6 and Annex A.7.4.6, API RP 2FPS Subclause 7.5.6 and Annex A.7.5.6, and API RP 2T Subclause 6.4 and Annex A.

7.9 Ice and Snow Accumulation *(1 August 2023)*

7.9.1 General

Where relevant, ice and snow accumulation should be assessed and included in the analysis model. Cold climate conditions can result in specific design conditions for an offshore wind turbine. The effects due to low temperature and icing conditions should be considered in the design load cases to be assessed in the ILA.

Guidance on ice and snow accumulation for the RNA, tower and substructures can be found in the following standards:

- Design requirements for wind turbines in cold climate conditions, additional design parameters for cold climate, assessment and effects of icing climate and design load cases can be found in IEC 61400-1 Clause 14, Annex A and Annex L.
- For ice and snow accumulation on the structural parts, refer to ISO 19906, ISO 19901-1, and API RP 2MET for guidance.

7.9.2 Ice and Snow Accumulation Induced Loads

Icing on an FOWT requires a combination of water or moisture and surfaces above sea level at sub-freezing temperatures. There are two major types of icing: atmospheric and sea spray. Atmospheric icing generally includes, in general, in-cloud icing and precipitation icing.

In load calculations for the RNA in cold climate conditions, the turbine controller behavior and loads are primarily affected by:

- Ice accretion on the rotor blades
- Increased air density

The effect of ice accretion on blade aerodynamic coefficients and inhomogeneous ice distribution on wind turbine blades should be considered for ice accretion induced loads on the blade. The air densities used for load calculation should be calculated by applying the ideal gas law as given in IEC 61400-1 Annex A.2.

For the wind turbine blade, the ice accretion and effects due to atmospheric icing should be assessed based on IEC 61400-1 Annex L. In the absence of other information, the blade aerodynamic coefficients may be modified for the effects of ice accretion based on IEC 61400-1 Annex L.1.5. The ice mass distribution (mass/unit length) for a wind turbine blade due to atmospheric icing may be calculated based on IEC 61400-1 Annex L.2. The sea spray icing on the blade may be assessed based on ISO 19906 and/or API RP 2N.

Ice and snow accumulation on the nacelle, tower, and substructures could cause:

- Uneven distribution of ice and snow accumulation on the nacelle, tower, and substructure
- Modification of the aerodynamic and hydrodynamic properties and dynamic response of the offshore wind turbine

In order to model these effects, the following factors should be considered according to ISO 19906:

- Mass, buoyancy, and stability of the floating substructure should be modified to account for uneven distribution of snow accumulation.
- Calculation of wind, wave and current loads should be modified to account for ice and snow accumulation on the nacelle, tower, and substructure.
- Strouhal numbers for the assessment of vortex-induced vibration of slender members should be modified.
- Masses of structures and any added masses should be adjusted in accordance with the icing. Consequences for additional vertical actions, stability, static position, reductions of structure freeboard and righting moments of the floating substructure should also be considered.

The ice and snow accumulation on the nacelle, tower, and substructures should be assessed based on ISO 19906 and/or API RP 2N. General information on ice and snow accumulation on offshore structures in different geographical offshore areas can be found in ISO 19901-1 and API RP 2MET.

7.11 Earthquake Loads

7.11.1 General *(1 August 2023)*

For an FOWT supported by a tendon system and located in a seismically active area, the Strength Level and Ductility Level earthquake induced ground motions (see 4-6/9 of the ABS *FOWT Guide*) should be determined based on seismic data applicable to the installation site. Reference should be made to API RP 2T for designing the tendon systems against earthquake loading.

Earthquake ground motions should be described by either applicable ground motion records or response spectra consistent with the return period appropriate to the design life of the structure. Available standardized spectra applicable to the region of the installation site are acceptable provided such spectra reflect site-specific conditions affecting frequency content, energy distribution, and duration. These conditions include:

- The type of active faults in the region
- The proximity of the site to the potential source faults
- The attenuation or amplification of ground motion between the faults and the site
- The soil conditions at the site

As appropriate, effects of soil liquefaction, shear failure of soft mud and loads due to acceleration of the hydrodynamic added mass by the earthquake, submarine slide, tsunamis and earthquake generated acoustic shock waves should be considered.

For earthquake loads (seismic loads) for FOWTs, refer to IEC 61400-3-2 Annex J, ISO 19901-2, API RP 2T and API RP 2EQ for guidance.

7.13 Ice Loads

7.13.1 General *(1 August 2023)*

Ice loads acting on an FOWT are both static and dynamic loads. Static loads are normally generated by temperature fluctuations or changes in water level in a fast ice cover. Dynamic loads are caused by moving ice interactions with the floating substructure. The global forces exerted by ice on the global floating substructure and local concentrated loads on structural elements should be considered. The effects of rubble piles on the development of larger areas and their forces on the floating substructure should be considered.

Where relevant, sea/lake ice load should be assessed and included in the ILA. Guidance on the assessment of ice conditions and calculation of ice loads for FOWTs can be found in ISO 19904-1 Subclause 7.4.7, API RP 2FPS Subclause 7.5.9, ISO 19906 and API RP 2N.

7.13.2 Ice Load Model for Floating Offshore Wind Turbines *(1 August 2023)*

Ice loads occur when the FOWT encounters sea ice or impacts icebergs. The collision load can be determined through theoretical models, model laboratory tests, or full-scale measurements.

Ice loads should be considered in combination with motions of the FOWT due to aggregated loads from ice, wind, waves, and current. If the mooring/tendon system and power cable are exposed to ice loads, such loading should be considered.

When determining the magnitude and direction of ice loads, the following factors should be considered:

- Geometry and nature of the ice
- Mechanical properties of the ice
- Velocity and direction of the ice
- Geometry and size of the ice/structure contact area
- Ice failure mode as a function of the structure geometry
- Inertia effects for both ice and structure

For FOWTs, the ice conditions should be assessed based on ISO 19906 and/or API RP 2N. Guidance on the calculation of ice loads can be found in ISO 19906 Annex A.8.2 and API RP 2N Annex A.8.2.

9 Integrated Load Analysis *(1 August 2023)*

The input data for each design load case (DLC) should be prepared prior to the start of the ILA. The number of simulations, simulation time duration, calculation of maximum values, and fatigue loads should be based on applicable design standards.

After completing the ILA, the ILA results should be post-processed in a way that can facilitate the subsequent design evaluation. Output data including time histories of loads, statistics and maximum loads, and damage equivalent loads are typically derived from the ILA. These output data are further used for the design evaluation of the RNA, tower, floating substructure, stationkeeping system and, if applicable, dynamic power cables.

The simulation length, number of simulations, and calculation of maximum (or minimum) values should comply with the applicable design standards. When there are no specific requirements, guidance provided in Section 5 can be applied.

Due to the large number of DLCs to be analyzed through the ILA, automation of data preparation and analysis management helps improve efficiency and reduce the likelihood of errors. Data set-up templates and run scripts are normally used to assign parameters for each simulation of DLCs.

11 Results Post-Processing *(1 August 2023)*

11.1 General

Time histories of the ILA results should be post-processed to obtain the maximum value for strength analysis and fatigue loads for fatigue analysis. The individual loads on the RNA, tower, floating substructure, and stationkeeping system should be determined.

All DLCs for strength analysis are typically post-processed in a group to obtain the maximum and/or minimum loads for each component of an FOWT.

All DLCs for fatigue analysis together with the probability of occurrence of each DLC are grouped together to calculate the equivalent damage loads (DELs) or the total fatigue damage directly based on the time history of the loads for each component of an FOWT.

Guidance on the assessment of the structural integrity of the RNA using the ILA results under site-specific conditions can be found in IEC 61400-1 clause 11.10. Both loads and deflections calculated from the ILA should be considered. For the fatigue loading conditions, the damage equivalent loads and moments on structural components should be calculated. The equivalent moment of the load duration distribution of the driving torque is normally considered sufficient for the verification of components. For extreme loading, a comparison of contemporaneous loads is not required.

Design of the FOWT support structure, which includes the tower, floating substructure, and stationkeeping system, is generally site specific. Full sets of relevant loads including extreme loads, contemporaneous loads, and fatigue loads in term of time histories are normally used for subsequent structural analysis for the tower, floating substructure, and stationkeeping system.

In general, the ILA results are provided in the following forms:

- Time histories
- Statistics of time histories including mean, maximum, minimum, and standard deviations
- Extreme loads for all DLCs for strength analysis including maximum, and minimum values
- Damage equivalent loads for the RNA and tower loads for all DLCs for fatigue analysis
- Main shaft equivalent torque based on load duration distribution method

11.3 ILA Results for Floating Offshore Wind Turbines

11.3.1 General

The ILA results for FOWTs include the RNA and tower loads, the floating substructure and mooring line or tendon loads.

The results for strength analysis are normally obtained in the form of maximum and minimum values calculated based on multiple simulations. The critical loads and the associated design load case for different components should be identified and reported after incorporating applicable partial safety factors for loads.

Fatigue loads for the RNA and tower can be provided as time histories and damage equivalent loads as discussed in 3/11.5.

Fatigue loads for the stationkeeping system are provided as time histories for the fatigue analysis of the stationkeeping system in accordance with applicable design standards.

11.3.2 RNA and Tower Loads

The RNA and tower loads include the following:

- Blade loads along the blade span
- Generator torque and power
- Main shaft loads
- Nacelle acceleration
- Blade-tower clearance

- Tower load along the tower
- Tower tilt angle

11.3.3 Floating Substructure and Stationkeeping System

In addition to RNA loads and the tower loads, the following floating substructure and mooring line or tendon loads should be included:

- Tower interface loads
- Floating substructure 6-DOF motions
- Floating substructure offset and heel motions
- Accelerations of the points of interest
- Mooring line or tendon tension at the fairlead
- Mooring line or tendon tension for different line components, if applicable
- Mooring line tension at the anchor point or tendon tension at the foundation interface

Loads are normally given in the form of six (6) load components and in-plane loads as discussed in 3/11.3.4. For the floating substructure, the 6-DOF motions are given as x, y, z and R_x, R_y and R_z. In addition, the offset and heel motions for the floating substructure should also be provided. The offset and heel motions (where heel angle ≤20 degrees) are defined as below:

$$Offset = \sqrt{x^2 + y^2} \qquad Heel = \sqrt{R_x^2 + R_y^2}$$

where

Offset	=	floating substructure offset, m (ft)
x	=	floating substructure surge, m (ft)
y	=	floating substructure sway, m (ft)
Heel	=	floating substructure heel motion, degrees (degrees)
Rx	=	floating substructure roll about x-axis, degrees (degrees)
Ry	=	floating substructure pitch about y-axis, degrees (degrees)

11.3.4 Resultant Loads

Loads are normally given in the form of six (6) load components, including three forces, F_x, F_y, and F_z, and three moments, M_x, M_y, and M_z.

When the structural stiffness and strength in response to loading in the plane are similar for the different loading directions, extreme loading can occur when both x and y components are large in magnitude but not at their largest values. Thus, the in-plane vector resultant values should also be calculated. These in-plane resultants loads are defined as:

$$F_R = \sqrt{F_x^2 + F_y^2} \qquad M_R = \sqrt{M_x^2 + M_y^2}$$

where

F_R	=	resultant force, N (lb)
F_x	=	force in x-axis, N (lb)
F_y	=	force in y-axis, N (lb)

M_R = resultant moment, N-m (lb-ft)

M_x = moment about x-axis, N-m (lb-ft)

M_y = moment about y-axis, N-m (lb-ft)

11.5 Fatigue Loads for RNA and Tower

Fatigue is the damage accumulation process in a component caused by cyclic loading. Fatigue loads for the RNA components and the tower are usually calculated as damage equivalent loads (DELs). The calculation method can be found in 2/11.5.

SECTION 4

Global Performance and Mooring Analysis for Floating Offshore Wind Turbines *(1 August 2023)*

1 General *(1 August 2023)*

Global performance analyses determine the global effects of environmental conditions and other loads on the Floating Offshore Wind Turbine (FOWT) and its components including the tower, floating substructure, mooring lines or tendons, anchors, power cable, etc. Global performance analyses should be carried out for all critical conditions in the pre-service and in-service phases, represented by the design load conditions specified in Section 5-2 of the ABS *Guide for Building and Classing Floating Offshore Wind Turbines* (*FOWT Guide*).

Because significant interactions could occur among the Rotor-Nacelle Assembly (RNA) and control system, the tower, the floating substructure, and the stationkeeping system, an integrated ("coupled") model including all these components is recommended to be used for global performance analyses. An alternative method, where the dynamic analyses of the stationkeeping system are performed separately by using the responses of the floating substructure as boundary conditions, may also be acceptable, provided that the coupling effect of the stationkeeping system and the floating substructure is adequately accounted for.

The global performance analysis software should be capable of considering complex interactions among aerodynamic loads, hydrodynamic loads, actions of turbine safety and control systems, and structural dynamic responses of the FOWT. The analysis procedures should reflect the application limits of the selected software. Both publicly available, industry-recognized software and in-house software may be used for the analyses. However, in-house software needs to be adequately calibrated against model tests, field tests, or the industry-recognized software.

General guidance on global performance analyses of the floating substructure and the stationkeeping systems can be found in:

- ABS *Rules for Building and Classing Floating Production Installations (FPI Rules)*, API RP 2T, API RP 2FPS and ISO 19904-1 for the design of floating offshore structures
- ABS *Requirements for Position Mooring Systems*, API RP 2SK, API RP 2SM and ISO 19901-7 for catenary mooring and taut leg mooring systems
- API RP 2T for TLP tendon systems

References are also made to other appropriate ABS Rules, Guides, and Guidance Notes, such as those listed in Subsection 1/11.

Global performance and mooring analysis for FOWTs can be performed with integrated load analysis as given in Section 3. Simplified analysis methodologies in different design phases as provided in this Section may be used.

This Section provides guidance on different methodologies used in the following types of analysis for the floating substructure and the stationkeeping system of an FOWT:

- Global motion analysis of the floating substructure
- Air gap analysis for the floating substructure
- Mooring strength analysis
- Mooring fatigue analysis

For floating substructures, the global motion and air gap analysis should calculate the below items:

- Six degree-of-freedom (6 DOF) motions and accelerations at the points of interest of the hull
- Air gap (or wave clearance) of the deck box and topside of the hull

Mooring analysis is performed to evaluate the stationkeeping system performance as listed below:

- Maximum offset of the floating substructure
- Maximum yaw motion of the floating substructure, if applicable
- Mooring line tension at the top of the mooring line (fairlead)
- Mooring line tension at the different segments along the lines, if applicable
- Mooting line tension at the anchor
- Mooring line lift angle at the anchor, if applicable
- Mooring line clearance to the seabed, water surface, if applicable
- Mooring line clearance between mooring lines and other structures, if applicable
- Clearance between a drag anchor and other installations, if applicable
- Maximum and minimum tendon tension at the top and bottom of the tendon for TLP-type FOWTs
- Mooring strength design safety factor
- Mooring fatigue design safety factor

3 Characteristics of Floating Offshore Wind Turbines

3.1 General *(1 July 2020)*

An FOWT consists of a number of main subsystems including the floating substructure, the tower, the turbine RNA, and safety and control system, as well as the stationkeeping system including mooring (or tendon) system and anchoring systems. This section describes the key issues and characteristics of the main FOWT subsystems relevant to global performance analyses. Representative coupling effects between the components of the FOWT are also identified.

3.3 Floating Substructures *(1 July 2020)*

The floating substructure consists of the hull and topside structure. A common feature of the differing types of floating substructures is that they utilize excess buoyancy to support the tower and the RNA and to provide mooring (or tendon) system tension. For this reason, the design of the floating substructure tends to be weight sensitive.

Depending on specific site conditions, ocean waves typically contain first-order energy in the range of 3 to 30 seconds. For the floating substructure, the natural periods of different modes of motion are of primary interest and, to a large extent, reflect the design philosophy. Typical motion natural periods of different types of floating substructure are summarized in 4/3 TABLE 1.

TABLE 1
Representative Natural Periods of Typical FOWT Floating Substructure
(1 July 2020)

Motions	*Natural Periods (seconds)*		
	Spar-Type	*Semi-submersible-Type*	*TLP-Type*
Surge	> 40	> 40	> 40
Sway	> 40	> 40	> 40
Heave	20-50	17-40	< 5
Roll	25-60	25-50	< 5
Pitch	25-60	25-50	< 5
Yaw	> 3	> 3	> 3

3.3.1 TLP-Type Floating Substructures *(1 July 2020)*

A TLP-type floating substructure is a vertically moored, buoyant structural system wherein the excess buoyancy of the hull maintains tension in the stationkeeping system.

A TLP-type floating substructure consists of the structural components of the hull connecting to the tendon system. It may also include a column top frame and topside deck. The hull consists of buoyant pontoons and columns. The tops of the columns may be connected to the tower directly or to a column top frame or a topside deck forming the global strength of the hull. The tendon system consists of a vertical mooring system that forms the link between the hull and the foundation for the purpose of mooring the floating support structure. The foundation system is used to anchor the tendons to the seafloor.

The TLP-type floating substructure differs fundamentally from the other floating structure concepts, mostly because of the following reasons:

- Tendon stiffness, rather than the "water-plane" stiffness, governs the vertical motions.
- It is normally weight sensitive.
- It has low restraint to horizontal motions (surge, sway, and yaw), but is highly restrained in the vertical direction (heave, roll, and pitch).
- Higher order wave forces at different sum-frequencies may introduce resonant (springing) or transient (ringing) responses in the vertical direction. These effects may significantly increase tendon loads.
- Restrained by the tendon system, the TLP-type floating substructure moves along a spherical surface. This gives rise to the set-down effect, which is a kinematic coupling between the horizontal surge/sway motions and the vertical heave motion. The magnitude of the set-down affects the wave air-gap, tendon forces, and power cable responses.

The TLP-type floating substructure generally experiences horizontal wave frequency motions of the same order of magnitude as those of a semi-submersible of comparable size. On the other hand, the TLP-type floating substructure behaves like a fixed structure with practically no wave frequency vertical motion responses, because the wave frequency forces are counteracted by the stiffness of the tendon system.

The flexibility of the tower could have significant influences on the natural periods of roll and pitch motions of the TLP-type floating substructure. The high frequency loads due to the rotor rotations and aeroelastic responses of the RNA and the tower could introduce resonant and/or transient responses in the vertical motions, which could significantly increase the tendon loads.

3.3.2 Spar-Type Floating Substructures *(1 July 2020)*

A Spar-type floating substructure is a deep draft, vertical floating structure, usually of cylindrical shape, supporting the tower and a topside structure (if any) and moored to the seafloor.

A Spar-type floating substructure typically consists of an upper hull, midsection and lower hull. The upper hull serves to provide buoyancy to support the topside and provides spaces for variable ballast. The midsection connects the upper hull with the lower hull. The midsection can be a cylindrical column or a truss space frame with heave plates. The heave plates are a series of horizontal decks between each bay of the truss space frame and are designed to limit heave motions by providing added mass and hydrodynamic damping. The lower hull normally consists of a fixed ballast tank and, in the case of a truss Spar, a flotation tank. The fixed ballast tank provides temporary buoyancy during a horizontal wet tow and provides the needed ballast in upending by flooding the tank. After upending, the ballast water may be replaced by fixed ballast (a substance with a density higher than water) to lower the Spar’s center of gravity. The ballast in the fixed ballast tank results in a vertical center of gravity well below the center of buoyancy, which provides the Spar with sound stability, as well as desired motion characteristics. The flotation tank is located adjacent to the fixed ballast tank to provide additional buoyancy for wet tow and ballast in upending.

With a deep draft, the Spar-type floating substructure has a large area exposed to current forces, which is usually the dominant mean force on a Spar. Low frequency vortex-induced oscillations may increase the effective drag leading to even higher mean current forces. By installing strakes on the Spar hull, the vortex-induced cross-flow oscillation can be mitigated. However, the strakes increase the added mass and the drag forces on the Spar.

The Spar-type floating substructure is usually compliant to surge, sway, heave, roll, pitch, and yaw motions. The natural periods of motions in all six degrees of freedom are usually outside the range of wave periods. In addition, the Spar-type floating support structure has a low level of vertical wave excitation due to its large draft, which exploits the fact that the first order wave motions and dynamic pressures decay exponentially with depth. These result in very small heave motions.

Due to relatively small wave frequency motions, the Spar-type floating substructure is generally not subjected to large dynamic mooring line forces, although their actual effect should be evaluated by considering the actual location of the fairlead and the increase in horizontal wave frequency motion towards the waterline.

The mooring system for the Spar-type floating substructure can be in the form of catenary moorings, semi-taut-line moorings or taut-line moorings. The motions and mooring loads of the catenary moored Spar-type floating substructure are normally insensitive to the high frequency loads generated by the rotor rotations and aeroelastic responses of the RNA and the tower.

Since the Spar-type floating substructure has a slender hull in the vertical direction and the mooring system tends to have relatively low yaw stiffness, the Spar-type FOWT may experience yaw instability, which should be avoided.

3.3.3 Column-Stabilized (Semi-submersible) Floating Substructures *(1 July 2020)*

A column-stabilized floating substructure, also known as the semi-submersible floating substructure, consists of a topside structure connected to the underwater hull or footings by columns or caissons. The floating substructure depends upon the buoyancy of columns or caissons for flotation and stability. Lower hulls or footings are normally provided at the bottom of the columns for additional buoyancy. The topside structure can be of an enclosed hull type or an open space frame truss construction. The topside structure is interconnected with the stability columns of the hull to form the overall strength. The tower may be connected directly to a column or caisson or to the topside structure.

Current forces could be significant on column-stabilized floating substructure due to the bluff shapes of their underwater columns and pontoons.

The column-stabilized floating substructure is characterized by having free modes of motion, which means that all natural periods of motion are outside the range of energetic wave periods. However, the wave frequency motions of the column-stabilized floating substructure may be significant, especially in extreme environmental conditions.

For the column-stabilized floating substructure, wave impact underneath the deck due to insufficient air gap may influence the global motions and local structural responses.

The spread mooring system in the form of catenary, semi-taut lines or taut lines is normally adopted as the stationkeeping system for the column-stabilized floating substructure. The column-stabilized floating substructure with the catenary mooring system may experience significant dynamic mooring loads due to the wave frequency responses. The motions and mooring loads of the catenary moored column-stabilized floating substructure are normally insensitive to the high frequency loads generated by the rotor rotations and aeroelastic responses of the RNA and the tower.

3.3.4 Other Types of Floating Substructures *(1 July 2020)*

For the floating substructure having a hull configuration or a hull-mooring combination that does not belong to the those described above, general guidance may be found in the ABS *FPI Rules*, API RP 2T, API RP 2FPS, ISO 19904-1, API RP 2SK and ISO 19901-7, as well as other appropriate ABS Rules, Guides and Guidance Notes for the design of floating offshore structures (see Subsection 1/11).

3.5 Stationkeeping Systems

3.5.1 General *(1 July 2020)*

An FOWT stationkeeping system is primarily designed to keep the FOWT within its position tolerances. It is also required to assist in achieving motion limits imposed by operational requirements of the RNA. Because the turbine RNA could exert large yaw moments to the floating substructure that normally has small yaw stiffness, the stationkeeping system may also need to be designed to provide sufficient yaw stiffness to mitigate the FOWT yaw motions.

A stationkeeping system includes a mooring (tendon) system and an anchoring system. The mooring system provides resistance to environmental loading by mobilizing reaction forces as the result of the gross changes in mooring geometry. It essentially works as a collection of spring mechanisms where displacements of the floating substructure from its neutral equilibrium position introduce restoring forces to react to the applied loading. Each mooring line acts as a tension spring and provides its intended functions through one of the following two mechanisms:

- Hanging catenary effect due to gravity acting vertically on the mooring line
- Line elastic effect due to elastic stretch over the length of the mooring line

When FOWTs are expected to be deployed in relatively shallow water, fiber ropes, clump weights, and buoys may be used in addition to chains and wire ropes to provide the required stiffness of the mooring systems.

3.5.2 Catenary Moorings

The geometry of catenary moorings is related to the following parameters:

- Submerged weight of the suspended lines

- Horizontal mooring load
- Line tension
- Line slope at fairlead

The compliance of the catenary mooring line allowing for wave-induced floating support structure motions is provided by a combination of geometrical change and axial elasticity of the lines. Large line geometrical changes could lead to significant dynamic responses in the catenary mooring system due to the large transverse drag loads.

The mooring lines in a catenary mooring system are commonly composed of steel rope and chain segments. If necessary, clump weights and buoys may be used to achieve desired line configurations.

3.5.3 Taut Moorings *(1 July 2020)*

In a taut mooring system, the mooring lines are nearly straight between the anchor and the fairlead, and an uplift force is exerted on the anchor. The compliance of the mooring line allowing for wave-induced floating substructure motions is provided mainly by line elasticity.

Transverse geometric changes in a taut mooring system are typically much smaller than those in a catenary mooring system. Therefore, dynamic effects due to line drag loads are moderate.

Synthetic ropes have been used as mooring lines in taut mooring systems to provide required stiffness and low weight. Compared to steel ropes, synthetic ropes exhibit more complex stiffness characteristics (e.g., hysteresis), which may significantly alter dynamic effects (see the ABS *Guidance Notes on the Application of Fiber Rope for Offshore Mooring*).

3.5.4 Tendons

The TLP tendons are vertical mooring lines similar to those in taut mooring systems. The main difference is that tendons are traditionally made of tubes that are hardly compliant in the axial direction. The TLP tendon system acts as an inverted pendulum, where the stationkeeping capacity is governed by tendon length and pretension.

By restraining the FOWT at a draft deeper than what is required to balance its weight, the tendons are typically under a continuous tensile load that provides a horizontal restoring force when the hull is displaced laterally from its equilibrium position. With very high stiffness in the axial direction, the tendon system limits heave, pitch, and roll responses of the hull to small amplitudes, while its relatively compliant transverse restraints can be designed to achieve surge, sway, and yaw responses within operationally acceptable limits.

The tendons may take one of several forms, for example:

- *Tubular Members with Threaded or other Mechanical Connectors.* These members may be designed to be completely void, partially void, or fully flooded. The tubular member and the connectors may be fabricated as one piece, or assembled from separate tubular segments that are joined with threaded connectors. The tendon components may be made of metal or fiber reinforced composites, with either integral or metallic connectors.
- *Tubular or Solid Rod Members with Welded Connections.* The tubular members are fabricated from seamless or rolled and welded steel and are designed to be welded together, prior to or during offshore installation, to form a continuous tendon element.
- *Tendon Strands.* These tendons are fabricated from small diameter high tensile strength wire or fiber strands and are formed into bundles. These tendons are designed to be installed offshore using a continuous one-piece spooling operation to minimize the need for intermediate connectors.

3.7 RNA and Control and Safety Systems *(1 July 2020)*

The RNA consists of the rotor and nacelle assembly, which includes all the associated mechanical, electrical, and control equipment and systems. A rotor may consist of two, three, or more blades typically made of fiber reinforced composites. A minimum clearance between the rotor blades and other parts of the FOWT and the expected highest wave elevation should be maintained. A deformation analysis should be performed by dynamic and aeroelastic means. The motions of the FOWT should be accounted for.

The RNA control and safety system can optimize operations and keep the FOWT in a safe condition in the event of malfunction. The control system keeps the FOWT within the normal operating limits. The safety function of the system logically subordinates to the control function and is brought into action after safety-relevant limiting values have been exceeded or if the control function is incapable of keeping the FOWT within the normal operating limits. For detailed descriptions of control and safety systems, refer to IEC 61400-1, IEC 61400-3-1 and IEC TS 61400-3-2.

Due to its influence on mechanical loads, the performance of the control and safety system is critical not only for the safety of service personnel and normal operations but the integrity of structures and stationkeeping of the FOWT. The load-relevant functions of the control and safety system, which lead to various RNA operational conditions, should be considered in the load analysis.

3.9 Coupling Effects

3.9.1 General

Coupling effects that should be considered in FOWT global performance analyses include:

- Aero-elastic coupling effects
- Aero-control coupling effects
- Tower-hull and mooring (or tendon) coupling effects
- Hull-mooring (or tendon) coupling effects
- Other coupling effects

The way of simulating these coupling effects is highly dependent on the actual software and analysis approaches employed in global performance analyses and needs to be evaluated on a case-by-case basis.

3.9.2 Aero-elastic Coupling

Aero-elastic coupling is the interaction between the aerodynamic loads on the rotor blades and the tower and the structural deformation due to the elasticity of the rotor blades, tower, and drive train, etc., of the RNA. In the calculation of aerodynamic loads on rotor blades, the aero-elastic coupling effects should be considered.

3.9.3 Aero-control Coupling

Aero-control coupling is the interaction between the behavior of the control system and aerodynamic loads on the rotor blade.

3.9.4 Tower-Hull and Mooring Coupling

The coupling between the tower-hull and the mooring system mainly includes:

- Influences of the hull and the mooring system on the tower modal shapes and natural frequencies
- Influences of the tower flexibility on the hull pitch and roll motion, particularly for TLP-type FOWTs

3.9.5 Hull-Mooring Coupling

Hull-mooring coupling is the interaction between the mooring line restoring, damping, and inertia forces and the hull mean position and dynamic responses.

- Restoring forces include static restoring force from the mooring and electrical cable system as a function of hull offset; current loading and its effects on the restoring force of the mooring and electrical cable system; and seafloor frictions if mooring lines and/or electrical cables have contact with the sea floor.
- Damping from the mooring lines and electrical cables due to their dynamics, current drag, etc.
- Additional inertia forces due to the mooring and electrical cable system

More discussions on this coupling effect can be found in API RP 2SK for applications in floating offshore structures.

3.9.6 Other Coupling

Other coupling phenomena relevant to an FOWT may also exist, such as:

- Interaction between hull motions and behavior of the control system
- Interaction between hull motions and aerodynamic loads on the rotor blades
- Interaction between hull motions and wind, wave, and current loads on the hull
- Change in hydrodynamic loads, added mass, and damping on the hull as the hull is offset and set-down
- Ringing and springing responses (TLP tendons)
- Loop Current/VIV effects/responses

5 Global Motion Analysis

5.1 General *(1 August 2023)*

Dynamic global motions of FOWTs can be simulated using frequency-domain analyses, time-domain analyses or combined frequency and time-domain analyses, as described in 1/5.3. All three approaches include various techniques of approximation and therefore may not yield consistent results. It is recommended that the approach selected for the mooring design be verified by model testing, full-scale testing, or the use of a different analytical approach.

Environmental loads and load effects on the floating substructures can be categorized into the following types according to their frequency range.:

- Steady loads such as wind, current, and wave drift forces that are constant in magnitude and direction for the duration of interest.
- Low frequency cyclic loads (often referred to as slow drift) with characteristic periods between 1 and 10 minutes. Low frequency cyclic loads typically induce dynamic excitations of the floating substructures at their natural periods of surge, sway, yaw, and in the case of Spar-type FOWTs, pitch and roll.
- Wave frequency cyclic loads with typical periods ranging from 3 to 30 seconds. Wave frequency cyclic loads result in wave frequency motions, which are normally independent of mooring stiffness. The approach of neglecting mooring stiffness in wave frequency motion calculations is considered relatively conservative. However, for small floating substructures where the first order wave loads are not large, accounting for mooring stiffness can yield more realistic wave frequency motions. In addition, if the natural period of the FOWT is close to the wave periods, the wave frequency motions could be dependent on the mooring stiffness. In this case, the effect of stiffness should be properly accounted for.

- High-frequency cyclic loads with characteristic periods from 1 to 5 seconds. High-frequency cyclic loads typically induce dynamic excitation of TLP-type floating substructures at their natural periods of heave, roll, and pitch.
- High frequency vibration due to the RNA and the tower dynamic loads with frequency higher than 0.5 hz (periods lower than 2 seconds). Such high frequency loads may be transmitted to the TLP-type floating substructure and its tendon system.

FOWT global motions contain the following components:

- Static and mean responses due to wind, wave, and current
- Low frequency motions induced by wave/current effects and dynamic wind loads
- Wave frequency motions induced by waves
- High frequency motions induced by waves for TLP-type floating substructures
- Vibrations induced by the loads exerted by the tower and the RNA, if applicable
- Hull VIM, if applicable (see 3/7.7.5)

The steady or mean forces result in the mean offset of the FOWT. The low frequency forces excite the motions which are at frequencies lower than wave frequencies but close to the surge, sway, or yaw natural frequencies of the floating substructure. The wave frequency forces excite wave frequency surge and sway motions. Because of its weathervaning nature, an FOWT with a single point mooring may experience large low frequency yaw motions. These yaw motions may significantly affect FOWT and mooring system responses, and therefore should be considered in global motion analyses and model testing.

Global motion analyses are normally performed in conjunction with mooring (or tendon) analyses. However, they may also be carried out separately when only global motions are of interest. In such cases, either the quasi-static or the dynamic analysis approach can be used to analyze the mooring system in global motion analyses. If the quasi-static analysis approach is used, special attention should be given to the appropriate simulation of the coupling effects.

5.3 Static and Mean Responses

Static and mean response analyses are carried out to determine the static equilibrium position with no wind, wave, or current present, as well as the mean positions with steady environmental loads acting on the FOWT. The determination of the equilibrium and mean positions is essential before any dynamic analyses are undertaken.

The following steady forces should be considered in the analysis:

- *Mean Wind Forces*. Mean wind forces should be calculated using the average wind speed measured for an extended period, normally on the order of one hour, under a given design environmental condition.
- *Current Forces*. The drag forces on the mooring lines (or tendons) and cables subject to the current under a given design environmental condition should be included in the calculation of total steady forces.
- *Steady Wave Drift Forces*. Steady wave drift forces acting on the hull due to wave diffractions and second-order viscous effects. The interaction between waves and currents can also result in steady forces which should be considered.

5.5 Low Frequency Motions

Low frequency motions of FOWTs can be obtained using either frequency-domain or time-domain analyses.

In frequency-domain analyses, assuming that low frequency wind and wave forces are independent, the total low frequency force spectrum is given by the sum of the low frequency wave force spectrum and the low frequency wind force spectrum. This total force spectrum can then be multiplied by appropriate motion transfer functions to obtain desired motions.

In time-domain analyses, because low frequency motions are dominated by the surge, sway, and yaw resonances with natural periods typically ranging from 60 to 150 seconds, a long simulation duration is necessary to obtain a sufficient number of cycles for developing an accurate estimate of the statistical extreme. Time histories of low frequency forces could be generated either from wind and wave force spectra or directly from wind velocity and wave profile time histories.

The estimation of damping is important because low frequency motions are dominated by resonant responses. Further discussion of damping is provided in 4/5.13.

5.7 Wave Frequency Motions

Wave frequency motions are induced by first-order wave forces. Wave frequency motions can be obtained using either the frequency or time-domain analyses.

5.9 High Frequency Motions

High frequency motions are induced by second and higher order wave forces. High frequency motions can be obtained using either the frequency or time-domain methods.

5.11 Tower and Turbine RNA Load Induced Vibrations

Due to the flexibility of the tower and the RNA, there are high frequency load components at the natural frequencies of the tower and the RNA. These loads may be transmitted to the hull and result in hull vibrations.

5.13 Damping

5.13.1 Damping of Low Frequency Motions *(1 July 2020)*

Low frequency motions of a moored FOWT are narrow banded in the frequency domain because they are dominated by the resonant responses at the natural frequency of the moored FOWT. Amplitudes of low frequency motions are highly dependent on the stiffness of the mooring system and damping. There is a substantial degree of uncertainty in the estimation of low frequency motions, particularly in the area of damping that could in general come from five sources:

- Aerodynamic damping
- Viscous damping of the floating support structure (tower and floating substructure), including wind, wave, and current drag
- Wave drift damping of the floating substructure
- Mooring system damping
- Cable system damping

The technology for estimating viscous damping has been well established, and viscous damping is normally included in the low frequency motion calculations. Wave drift damping, mooring system damping, and cable system damping, however, are more complex and are sometimes neglected because of a lack of understanding. Nevertheless, these damping components could be important and neglecting them may lead to significant over-estimation of low frequency motions. Where low frequency motions are considered important, it may be warranted to evaluate the damping from all these sources either by appropriate analytical approaches or model testing.

5.13.2 Damping of High Frequency Motions

The TLP-type FOWT could experience high frequency motions and vibrations in the vertical motion modes including heave, roll, and pitch motions. Damping in the vertical motion modes is affected by structural and soil damping, as well as hydrodynamic and aerodynamic damping, and should be estimated either by appropriate analytical approaches or model testing. This is especially important in the calculation of the springing and ringing responses and the tower and the RNA induced vibrations that could contribute significantly to the tendon fatigue damage.

5.15 Analysis Methods

For global motion analysis the following approaches may be used:

- Frequency-domain analyses
- Time-domain analyses
- Combined time-domain and frequency-domain analyses

5.15.1 Frequency-Domain Approach

Mean, low frequency, and wave frequency responses of FOWTs are calculated separately in frequency-domain analyses. The mean responses are calculated by the static equilibrium or mean position. The low frequency motions and set-down associated with offset are calculated in the frequency domain with appropriate consideration of damping effects from wind and current and mooring/cable. The wave frequency responses due to wave radiation/diffraction and wave asymmetry effects are calculated with consideration of wave loads only. Damping effects from wind and current and mooring/cable should be properly modeled. Total motions are obtained by combining the mean, wave, and low frequency motions.

When the frequency-domain approach is used to compute the hull motion responses, the extreme values of the motion responses are defined as the mean plus or minus the maximum estimated value of the time-varying excursion due to combined wave frequency and low frequency hull motions.

The extreme values of the hull motion, $S_{\max}$ and $S_{\min}$ can be determined by:

$$S_{\max} = S_{mean} + \mathrm{MAX}\left(S_{dyn1}, S_{dyn2}\right)$$

$$S_{\min} = S_{mean} - \mathrm{MAX}\left(S_{dyn1}, S_{dyn2}\right)$$

$$S_{dyn1} = S_{lf\max} + S_{wfsig}$$

$$S_{dyn2} = S_{wf\max} + S_{lfsig}$$

where

MAX	=	the larger of the absolute values of the terms in parenthesis
$S_{\max}$	=	maximum hull motion
$S_{\min}$	=	minimum hull motion
S_{mean}	=	mean hull motion
$S_{lf\max}$	=	maximum expected value of low frequency hull motion
S_{lfsig}	=	significant value of low frequency hull motion
$S_{wf\max}$	=	maximum expected value of wave frequency hull motion
S_{wfsig}	=	significant value of wave frequency hull motion

The total offset should be defined as the vector sum of the individual offset components of different degrees of freedom (e.g., surge and sway). The total heel should be defined as the vector sum of the individual component angles of different degrees of freedom (e.g., roll and pitch).

5.15.2 Time-Domain Approach *(1 August 2023)*

The fully coupled, semi-coupled, and uncoupled analysis methods can be used when FOWT global motion analyses are carried out in the time domain. In the case of semi-coupled and uncoupled analyses, the applied damping level should be calibrated by fully coupled analyses and/or model testing. When the tower accelerations are of interest, a fully coupled analysis should be used and flexibility of the tower should be properly considered.

Guidance on the integrated load analysis in the time domain can be found in Section 3.

5.15.3 Combined Time-Domain and Frequency-Domain Approach

FOWT mean, low frequency, and wave frequency responses are calculated separately when combined time-domain and frequency-domain analyses are employed in global motion analyses. The mean responses are calculated by the static equilibrium or mean position. The wave frequency responses due to wave radiation/diffraction and wave asymmetry effects are calculated with consideration of wave loads only in the frequency domain. Damping effects from wind and current, and mooring/cable should be properly considered. The low frequency motions and set-down associated with offset are calculated in the time domain. The total motions are obtained by combining the mean, wave, and low frequency motions.

7 Air Gap Analysis

7.1 General *(1 July 2020)*

Air gap analysis should be performed for the design load cases associated with the extreme environmental conditions (i.e., DLC 1.6, 6.1, 6.2, 10.1, 10.2, 10.3 as defined in 5-2/3.5 TABLE 1 of the *FOWT Guide*) and the survival load cases (see 5-2/5 TABLE 2 of the *FOWT Guide*). The most important parameters to be evaluated in the air gap analysis are the wave crest height and the hull roll, pitch, and heave motions.

In the air gap analysis, the following global hull motions should be considered:

- Static and mean responses due to wind, wave, and current
- Low frequency motions induced by wave/current effects and dynamic wind loads
- Wave frequency motions induced by waves

High frequency motions and vibrations, as well as the tower flexibility, may be neglected for the air gap analysis.

For the wave crest height, the nonlinearity of wave profile, wave diffraction and run-up, tide and water level effects, and variations of draft of the floating support structure should be considered.

General guidance for air gap and wave crest effects assessment can be found in in API RP 2FPS for semi-submersibles and spars and API RP 2T for TLPs.

7.3 Air Gap Analysis Methods

For the air gap analysis, the following methods may be used:

- Frequency-domain analyses
- Time-domain analyses
- Combined time-domain and frequency-domain analyses

7.3.1 Frequency-Domain Analysis

FOWT mean, low frequency, and wave frequency responses are calculated separately in frequency-domain analyses. The mean responses are calculated by the static equilibrium or mean position. The low frequency motions and set-down associated with offset are calculated in the frequency domain with appropriate consideration of damping effects from wind, current and mooring/cable. The wave frequency responses due to wave radiation/diffraction and wave asymmetry effects are calculated with consideration of wave loads only. Damping effects from wind, current, and mooring/cable should be properly modeled. Total motions are obtained by combining the mean, wave frequency, and low frequency motions. The air gap is determined based on relative wave elevation and the pitch, roll, and set-down of the hull obtained from frequency-domain analyses.

7.3.2 Time-Domain Analysis *(1 August 2023)*

Fully coupled, semi-coupled, and uncoupled time-domain analyses may be used. In the case of semi-coupled and uncoupled analyses, the applied damping level used in the analyses should be calibrated with fully coupled analysis and/or model testing. Wave surface elevations should be calculated with consideration of the wave radiation/diffraction effects and wave asymmetry effects.

Guidance on the integrated load analysis in the time domain can be found in Section 3.

7.3.3 Combined Time-Domain and Frequency-Domain Analysis

In this method, the wave frequency motions and wave elevation are calculated in the frequency domain with consideration of radiation/diffraction effects and wave asymmetry effects. The high frequency motions of roll, heave, and pitch for TLP-type FOWTs may be neglected. The low frequency surge, sway, and yaw motions, for Spar-type and semi-submersible-type FOWTs the low frequency pitch, roll and heave motions, and for the TLP-type FOWTs the set-down associated with offset, are calculated in the time domain. The air gap is determined based on relative wave elevation from frequency-domain analyses and the pitch, roll, and set-down of the hull obtained from time-domain analyses.

7.3.4 Other Considerations

The dynamic effects and coupling behaviors may not be important for the air gap analysis. As a result, any of the above three methods may be used in both preliminary and final detail designs provided the platform roll, pitch, and heave motions are properly calculated. For TLP-type FOWTs, the set-down effect should be considered.

For TLP-type FOWTs, the minimum air gap, also known as the deck clearance, is governed by a combination of an increasing water level and a decreasing deck height. The increasing water level is caused by incident wave elevation, tide, storm surge, and radiation/diffraction effects from the hull. In very steep sea conditions, the diffraction effects could be significant. The decreasing deck elevation is caused by the hull set-down with offset. The hull set-down increases nonlinearly at large offsets, leading to a rapid decrease of the deck clearance with increasing environmental severity. In this case, a correction to the predicted offset should be made.

Radiated or diffracted waves generally cause local wave impacts on the deck. In some cases, local impacts may need to be accounted for in the design and, as a result, may lead to local structural stiffening, increased weight of the deck, and tendon ringing, which affects the peak loads in the tendons and the porch structure. Increased tendon load responses could also affect the minimum tension, which in turn affects the design pretension.

The deck height could significantly affect the vertical position of the center of gravity and, in turn, the maximum and minimum tendon tensions. The deck elevation also affects the wind load and wind overturning moments. In general, a higher deck contributes adversely to the tendon tensions.

On the other hand, if the deck does not have a sufficient air gap, large tendon tension variations could occur when waves strike the deck.

9 Mooring Strength Analysis

9.1 General *(1 July 2020)*

Mooring strength analyses are performed to predict extreme responses such as line tensions, anchor loads, and hull offsets under the design environment and other external conditions. These extreme global responses are then used to check against allowable values to verify the strength of the system against overloading and the sufficiency of clearance to avoid interference with other structures. The design load conditions and design criteria for stationkeeping systems are given in Chapter 8 of the *FOWT Guide.*

The mooring line diameter used in the mooring analysis should be the nominal value (i.e., inclusive of corrosion and wear allowance) when calculating mass, weight, and hydrodynamic loads of the mooring line, unless otherwise noted. Installation tolerances of anchor placement and line length should be accounted for in the mooring system design.

Dynamic excitations originating from the floating support structure, including the tower and the floating substructure and the RNA, could result in mooring system responses in the following distinct frequency bands:

- Mean responses
- Low frequency responses
- Wave frequency responses
- High frequency responses for the tendons or taut lines
- Vibrations induced by the loads exerted by the tower and the RNA, if applicable.

Responses of the mooring system to mean forces can be predicted by a static model of the mooring system. In general, the responses to low frequency motions can also be predicted by a static model because of the long periods of these motions. The responses to wave and high frequency hull motions and hull vibrations may be predicted by either quasi-static or dynamic analyses. However, the quasi-static analysis method should only be used in preliminary designs. In final detailed designs, dynamic analyses should be employed.

9.3 Mooring Strength Analysis Methods

For the mooring strength analysis, the following methods may be used:

- Frequency-domain analyses
- Time-domain analyses
- Combined time-domain and frequency-domain analyses

These methods incorporate different degrees of approximation and are affected by various limitations, and therefore do not necessarily yield consistent results. If verification of the approach selected for the mooring design is necessary, model test data or an alternative approach of similar reliability should be used.

Because there is no established analytical method for determining FOWT motion responses undergoing VIM, model testing should, in general, be performed if VIM is deemed important in the design. In the case that current loads and VIM are determined to be important, it is usual practice to perform well planned model tests to determine motion amplitudes and drag coefficients for use in mooring designs. Full-scale in-field measurement data may be employed to confirm the scalability of model testing.

In general, time-domain analyses are recommended for the mooring strength analysis. When the effects of high frequency motions and vibrations are expected to be relatively insignificant, frequency-domain analyses may yield satisfactory results, and the analysis procedures in this case are similar to those described in API RP 2SK.

9.3.1 Frequency-Domain Analyses for Spread Mooring Systems *(1 July 2020)*

When using frequency-domain analyses for the spread mooring system design, the mean position of the hull is first determined from static equilibrium calculations for surge, sway, and yaw. The surge, sway, and yaw responses to wave and low frequency excitations are then calculated and superimposed to the mean position. The procedure outlined in API RP 2SK may be used.

Where the floating substructure has a small water plane area, alternative procedures incorporating all six DOFs of motion should be used.

To obtain extreme (maximum) values, the combination of different components of the motions and mooring line tensions may follow the approach recommended in API RP 2SK.

9.3.2 Frequency-Domain Analyses for Single Point Mooring Systems

When using frequency-domain analyses for a single point mooring system design, assumptions on the hull's design heading should first be made. The design headings at which the mooring system responses are to be calculated should be determined with consideration of the mean equilibrium heading and low frequency yaw motions. The procedure outlined in API RP 2SK may be used.

9.3.3 Time-Domain Analyses *(1 August 2023)*

The following three analysis approaches as defined in 1/5.7 may be used for the time-domain mooring strength analysis:

- Fully coupled analysis approach
- Semi-coupled analysis approach
- Uncoupled analysis approach

In general, the fully coupled (integrated) analysis approach is preferred for the following two important advantages:

- Low frequency damping from the hull, mooring lines, and cables can be internally generated in the simulation; and
- Coupling between the floating substructure, the tower, the turbine RNA and control system, the stationkeeping system, and the cable system can be fully accounted for.

The fully coupled analysis approach should be used with a time-domain mooring analysis tool that is capable of solving the equations of motion for the combined responses of the floating substructure, the tower, the turbine RNA and control system, the stationkeeping system, and, if applicable, the cable system.

Guidance on the integrated load analysis in the time domain can be found in Section 3.

9.3.4 Combined Time-Domain and Frequency-Domain Analyses

In this approach, the mean and low frequency responses are typically simulated in the time domain to model the nonlinearity of the stiffness of the mooring lines and cables and the nonlinearity of the hull forces due to quadratic terms and yaw angle variations. Constant or variable thruster forces may also be modeled in the time domain. Transient responses resulting from line breaking or thruster failure may be evaluated by specifying the time of failure in the time-domain analysis. Unlike the full time-domain approach, evaluation of low frequency damping cannot be included as part of such simulations because of the absence of wave frequency components. Damping will need to be evaluated separately and treated as an input parameter.

Wave frequency hull motions are calculated separately in the frequency domain using the hull's motion RAOs and a given wave spectrum. These wave frequency motions may be combined with the low frequency motions in two ways:

- *Method 1*: The frequency-domain solution of wave frequency hull motions is first transformed to a time history, which is then superimposed to the mean and low frequency hull displacement time histories to obtain the combined hull displacement. In this process, the seed values for generating the wave frequency and low frequency time histories should be the same.
- *Method 2*: The mean and low frequency motion time histories are statistically analyzed to determine the peak values, which are then combined with the peak values of the wave frequency motions to calculate the maximum hull offset, as described in API RP 2SK.

9.3.5 Maximum and Minimum Tendon Tensions

For the TLP-type FOWTs, the tendon tension can be calculated either in the frequency domain or the time domain. In addition to wind, wave, and current loads, tidal effects, and weight variations, the calculation of maximum and minimum tendon tensions should also account for the effect of foundation mis-positioning, individual tendon load sharing differential, and tendon VIV. Reference is made to API RP 2T for further guidance. A time-domain fully coupled (integrated) analysis should be used to calculate maximum and minimum tendon tensions.

9.5 Suggested Time-Domain Analysis Procedure *(1 July 2020)*

A suggested procedure for FOWT global performance analyses in the time domain is outlined below:

i) Determine environmental criteria relevant to the global performance analysis of a specific FOWT stationkeeping system (see Section 8-2 of the *FOWT Guide*)

ii) Determine the external electrical network conditions

iii) Identify the mooring pattern, the characteristics of chain, wire, and fiber rope to be deployed, and the initial tension

iv) Define corrosion and wear allowance of the chain and wire rope used in analysis

v) Determine the tower dimensions, properties, modal shapes, and wind force coefficients

vi) Define the RNA and control system configuration and create the models to be used in the simulation

vii) Identify the startup and shutdown procedures and the associated settings of turbine RNA and control system

viii) Identify the fault conditions in the RNA and control system

ix) Define the hull structure's wind and current force coefficients and create the hydrodynamic model of the FOWT system including the hull, stationkeeping system, and if necessary, power cables

x) Perform time-domain simulations for the expected storm duration using a time-domain mooring analysis program and applying different seed values for generating the wave and wind time histories

xi) Perform statistical analyses to establish expected extreme values of hull offset, line tension, anchor loads, and grounded line length

xii) Check the extreme hull offset, line tension, anchor load, and grounded line length from step *xi)* against the design criteria (see 4/9.7, 4/9.9 and 4/9.11)

9.7 Design Checks *(1 July 2020)*

Extreme line tension values should be checked against the design criteria in 8-3/3 TABLE 1 and 8-4/3 of the *FOWT Guide*. The minimum breaking strength of the chain should be determined based on the diameter excluding the corrosion and wear allowance.

For the TLP-type FOWTs, the minimum tendon tension should be checked against the design criteria in 8-3/3 of the *FOWT Guide*.

9.9 Line Length and Geometry Constraints

Depending on the type of mooring system, the type of anchors, and the mooring line material, a number of line length and geometry parameters should be evaluated and assessed for compliance with design criteria.

For catenary moorings with drag anchors not specifically designed to withstand uplift forces, the minimum length of each grounded line (i.e., the mooring line segment always resting on the sea floor) should be computed and compared with a design criterion to be prescribed on a site-specific basis.

For anchors designed to withstand uplift forces, compliance with appropriate design criteria applicable to that specific type of anchor should be verified.

For some types of mooring line, the grounded line is highly undesirable and, therefore, the portion of the line closest to the anchor is typically replaced by a chain. In such cases, the minimum elevation of the line-to-chain connection should be computed and verified against a minimum elevation criterion prescribed on a site-specific basis.

For some types of mooring lines, exposure to the splash zone or to friction against the fairleads is undesirable and, therefore, the upper portion of the line is typically replaced by a chain. In such cases, the position of the upper termination should be evaluated and compared with a minimum depth criterion prescribed on a site-specific basis.

For mooring lines in proximity to other underwater and surface installations, additional clearance requirements and geometric constraints may apply. In such cases, displacements at particular points of concern should be verified against applicable design criteria or be prescribed on a site-specific basis.

Guidance on line length and geometry constraints for fiber rope mooring lines can be found in the ABS *Guidance Notes on the Application of Fiber Rope for Offshore Mooring*.

9.11 Anchor Forces *(1 July 2020)*

In general, the highest mooring line tension obtained from the mooring analysis should be used to predict the maximum anchor force. Additional considerations should also be given to the case where a smaller mooring line tension acts in a less favorable direction. The results should be verified against the design criteria in 8-5/13 TABLE 2 of the *FOWT Guide*, as applicable.

11 Mooring Fatigue Analysis

11.1 General *(1 July 2022)*

Typical mooring fatigue analysis procedures are presented below. Alternative procedures may be used, provided they can be demonstrated to achieve at least the same level of reliability as those presented herein.

Miner's Rule can be used to determine accumulated fatigue damage. For main components of the mooring lines (i.e., chain, wire rope, and connecting links), Miner's Rule may be implemented in terms of tension range (the T-N curve approach) as described below, or stress range (the S-N curve approach). For other structural components of the stationkeeping system, such as anchor pile details and attachments, the S-N approach is normally used.

T-N curves for chain and wire rope can be found in API RP 2SK. Special considerations of fiber rope fatigue analysis can be found in the ABS *Guidance Notes on the Application of Fiber Rope for Offshore Mooring*.

In addition to the tension-tension induced fatigue, the tension-bending induced fatigue for chain and wire rope should be properly considered according to recognized industry criteria such as API RP 2SK. The ABS *Requirements for Position Mooring Systems* provides requirements for the bending and tension induced fatigue for chain and wire rope in 1/7.5.3 and guidance on the mooring chain fatigue due to bending in Appendix 3.

As indicated in 8-3/3 of the ABS *FOWT Guide*, corrosion and wear should be suitably considered in the fatigue analysis. The general guidance is given in 4/11.3 of these Guidance Notes.

In the mooring fatigue analysis, due consideration should be given to the following aspects:

- Dynamic wind effects
- Dynamic wave effects
- Hull VIM, if applicable
- Mooring line/tendon VIV, if applicable
- Transient effects due to the startup and shutdown of the RNA
- Coupling effects among the subsystems of the FOWT
- Number of RNA startups and shutdowns in the FOWT design life
- Duration of each operation such as installation, startup, power production, shutdown, parked, etc., that contributes to the mooring fatigue damage

Either time- or frequency-domain dynamic analysis approaches may be applied for mooring tension range predictions. It is suggested that time-domain coupled analyses along with the rainflow counting method be used in the mooring fatigue analysis. Alternatively, mooring tension ranges may be obtained from model testing.

In general, quasi-static analysis should not be used to calculate tension ranges due to its deficiency in estimating wave frequency mooring tensions.

Guidelines for the mooring fatigue analysis can be found in the ABS *Requirements for Position Mooring Systems*, API RP 2SK and API RP 2T. Appendix A2 of the ABS *Requirements for Position Mooring Systems*, Appendix H of API RP 2SK and API RP 2T provide guidance on the hull VIM induced mooring fatigue.

11.3 T-N Curve

The fatigue life of a mooring line component is calculated by comparing the long-term cyclic loading in that component with its resistance to fatigue damage. For mooring systems, the T-N curve approach is commonly used to determine the number of cycles to failure for a specific mooring component as a function of constant normalized tension range. The T-N curve for a specific type of mooring component is established based on experimental results.

The equation for a representative T-N curve is:

$$N \cdot T^m = K$$

where

N = number of permissible cycles of tension range ratio, T

T = ratio of tension range (double amplitude) to the reference breaking strength of the component (see the guidance given below)

m = inverse slope of the T-N fatigue curve

K = constant coefficient or mean load dependent coefficient

When determining the reference breaking strength of the mooring chain or connecting links, the diameter for different periods of service life can be established if the corrosion and wear rate can be predicted. If the corrosion and wear rate is uncertain, a conservative approach using the nominal diameter minus the corrosion and wear allowance should be considered for the fatigue analysis. The reference breaking strength for a wire rope should be its minimum breaking strength (MBS).

11.5 Accumulated Fatigue Damage *(1 July 2020)*

The total annual fatigue damage is the sum of the fatigue damage arising in a set of design states chosen to discretize the long-term environmental and operational conditions that the mooring system is subjected to:

$$D = \sum_{i=1}^{i=k} D_i$$

where

D_i = annual fatigue damage of the component in the design state i

Miner's Rule should be used to calculate the annual cumulative fatigue damage ratio D_i:

$$D_i = \sum \frac{n_j}{N_j}$$

where

n_j = number of tension cycles within the tension range interval j encountered in the design state i per year

N_j = number of cycles to failure under the normalized tension range j per year as determined by the T-N curve

The discretization into i = 1,…,k design states should have a sufficient resolution to avoid any significant error due to the discretization. Each design state is defined in terms of the wind, wave, and current parameters and directions, as well as the RNA operating condition required to compute the mooring system responses. The probability of occurrence, P_i, should be determined for each design state. The calculated fatigue life of the mooring system is:

$$L = 1/\ D(\text{years})$$

The annual fatigue damage accumulated in each individual design state can be computed as:

$$D_i = \frac{n_i}{K} E[R_i^m]$$

where

n_i = number of tension cycles encountered in the design state i per year

$E[R_i^m]$ = expected value of the normalized tension range R_i raised to the power of m in the design state i per year

m and K are defined in 4/11.3.

The number of tension cycles per year in each design state is:

$$n_i = v_i T_i = v_i P_i \cdot 3.15576 \times 10^7$$

where

v_i = zero up-crossing frequency of the tension spectrum in the design state i, in Hz

T_i = time (portion of years) spent in the design state i per year

P_i = probability of occurrence of the design state i

The effects of pretension and environmental loads due to wind, wave, and current, as well as the RNA operating conditions, should be considered when determining the normalized tension ranges. Total fatigue damage should be calculated with consideration of the fatigue damage from various fatigue load cases as described in Section 5-2 of the *FOWT Guide*. When suitably qualified, previously used mooring components are considered for re-use, fatigue damage from previous operations should be accounted for.

11.7 Time-Domain Fatigue Analysis Method *(1 August 2023)*

The tension ranges are obtained from time series as the results of time-domain dynamic analyses. The number of cycles should be obtained based on the rainflow counting method.

Guidance on the integrated load analysis in the time domain can be found in Section 3.

11.9 Frequency-Domain Fatigue Analysis Method *(1 July 2022)*

The frequency-domain dynamic analysis method may be used in the fatigue analysis provided the nonlinear effects are properly linearized. For further guidance on fatigue analyses in the frequency domain, refer to the ABS *Requirements for Position Mooring Systems*, API RP 2SK, and API RP 2T.

11.11 Tendon Fatigue Analysis *(1 July 2020)*

Either the S-N-curve-based fatigue analysis approach or the fracture mechanics analysis method can be used for tendon fatigue analysis. Total fatigue damage should be calculated by considering the fatigue damage from various fatigue load cases as presented in Section 5-2 of the *FOWT Guide*.

In addition to the conventional fatigue life calculation using a set of design states based on discretized long-term environmental conditions and the turbine’s operational conditions, the tendon components should demonstrate robustness against low-cycle, high-stress fatigue due to more prolonged events that exceed the probabilistic predictions.

In order to confirm a minimum level of robustness, tendon fatigue damage should be assessed for all components considering a single event based on the 50-year return extreme storm, including the ramp-up and ramp-down before and after the storm. The duration to consider should be determined by the designer based on the data available and the response characteristics of the components. The unfactored damage accumulated during this event should be no more than 0.02.

Other 50-year return period events that may induce substantial tendon fatigue, such as the Loop Current in the Gulf of Mexico, should also be considered in the same manner.

Damage calculated for single event fatigue should not be added to the damage predicted in the long-term scatter-diagram-based fatigue analysis, nor compared to the associated safety factors. The intent, as a robustness check, is to screen for components that may incur excessive fatigue damage in prolonged extreme environmental conditions.

Fatigue analysis for tendon components should consider local load effects in addition to global loads. Reference is made to API RP 2T for more details for tendon fatigue analysis.

11.13 Fatigue Design Checks *(1 July 2020)*

The calculated fatigue life, which is $1/D$, should be greater than the design life multiplied by a fatigue design factor (FDF) defined in 8-3/5 TABLE 2 and 8-4/3 of the *FOWT Guide*.

SECTION 5
Suggestions for Numerical Simulations

1 General *(1 August 2023)*

In time-domain numerical simulations of global performance analysis and integrated load analyses, appropriate settings of the following parameters are crucial in order to obtain reliable results:

- Time step
- Transient time or ramp time
- Grid size and range for wind field data generation
- Number of wave components for generating random waves
- For the deterministic events, the onset time of the events
- For the stochastic events, the number of simulations with different random seeds and the time duration of each simulation
- For fatigue sea states, the discretization of fatigue bins
- Setting of the control system, generator, blade pitch, nacelle yaw, rotor azimuth angle, rotor speed and degrees-of-freedoms for drive train, and tower and blade flexibilities for different turbine operating or parked conditions
- Parameters for the aerodynamic load calculation, especially the tower shadow model and the static or dynamic stall models
- Wind average speed, turbulence intensity, and wind shear for different wind models used in the wind field data generation

Convergence test should be performed to determine:

- time steps in time-domain simulations;
- grid size and range for wind field; and
- number of wind and wave components and seed numbers.

Sensitivity analysis may be performed to determine the discretization of the fatigue bins.

For load cases involving start-up and shut-down of the RNA, the analysis procedure should be consistent with the actual operational procedure of the RNA.

3 Time Step

Choice of time step is crucial for the stability and accuracy of the time-domain solution, and is often dependent on the periods of the responses, degree of nonlinearity, and analysis formulation. Time step should be determined by a sensitivity check.

5 Initial Transient Response

The length of a time-domain simulation must allow for transient responses during the initial part of the simulation. The time required for dissipating transient responses is normally a function of the period and damping of the response.

Since initial conditions used for the dynamic analysis could affect the statistics of the response during the starting part of the simulation time duration, the first 5 seconds to 10 minutes (or longer, if necessary, depending on the period and damping of the response) of time history data should be discarded when stochastic wind and/or wave are applied.

7 Wind Generation and Grid Size *(1 August 2023)*

10-minute, 1-hour or 3-hour simulation time duration may be used in numerical simulations for the different design load cases (DLCs) and survival load cases (SLCs) (see Subsection 5/13). Since statistical values of wind conditions for wind turbine design are normally based on 10-minute averaging time duration, input wind conditions should be adjusted for 1-hour and 3-hour numerical simulations in order to achieve statistical equivalence. In the absence of site-specific data for the wind conditions with an averaging time duration other than 10 minutes, Section 5, Table 1 may be used to calculate the mean wind speed and turbulence intensity at hub height for 1-hour and 3-hour simulations by adjusting the 10-minute wind conditions at hub height.

TABLE 1
Adjustment of Wind Conditions with Different Averaging Time Durations
(1 August 2023)

Simulation Time Duration	*10 minutes*	*1 hour*	*3 hours*
Adjustment factor applied to the 10-minute mean wind speed	1.00	0.95	0.90
Adjustment applied to the 10-minute turbulence intensity (σ_{10min})	1.00	σ_{10min} + 0.2m/s	Case-by-case

Notes:

1 Adjustments are applied to the hub height wind conditions.

2 Adjustment for the turbulence intensity is valid for the wind spectra recommended in IEC 61400-3-1. For the NPD (Frøya) wind spectrum and tropical revolving storm wind spectrum, see the guidance provided in this Subsection.

3 For 3-hour simulations, additional guidance is provided in this Subsection.

When using the IEC-recommended wind spectrum to perform a 3-hour simulation, the following methods may be used to generate wind field data:

- *Method 1:* Use 1-hour mean wind speed and turbulence intensity to generate time series of a turbulent wind field for 3 hours
- *Method 2:* Use 3-hour mean wind speed and adjust the turbulence intensity (or use site measurement data) to generate time series of turbulent wind field for 3 hours such that the resultant maximum wind loads or load effects match those obtained using either 10-minute or 1-hour simulations.

The adjustment relative to the 10-minute turbulence intensity, as shown in Section 5, Table 1, is applicable to the wind spectra recommended in IEC 61400-1. When the NPD (Frøya) wind spectrum is used (see 3-2/3.5 of the ABS *BOWT Guide* and 4-2/3.5 of the ABS *FOWT Guide*), the adjustment factor of the 1-hour average wind speed relative to 10-minute average wind speed still applies, but the turbulence intensity is a function of the 1-hour wind speed and is embedded in the wind spectrum formulation. When the NPD (Frøya) wind spectrum is used in 3-hour simulations, the mean wind speed and turbulence intensity may be taken the same as those used in 1-hour simulations. For the tropical revolving storm wind, the adjustment factor of the 1-hour average wind speed relative to 10-minute average wind speed should be calculated based on the wind gust factor given in A2/7 of the ABS *BOWT Guide* and A2/7 of the ABS *FOWT Guide*. For the tropical revolving storm wind in a 3-hour simulation, the mean wind speed and turbulence intensity may be taken the same as those used in 1-hour simulations.

The wind generation should consider the 3D effects. Sensitivity analysis may be needed to determine an appropriate grid size of the 3D wind field.

9 Simulation of Wave Conditions

10-minute, 1-hour or 3-hour simulation time duration may be used in numerical simulations for the different design load cases (DLCs) and survival load cases (SLCs) (see Subsection 5/13). Since statistical values of wave conditions are normally based on a 3-hour time window, input wave conditions should be adjusted for 10-minute and 1-hour numerical simulations in order to achieve statistical equivalence. In the absence of site-specific data, the adjustment factors of 10-minute and 1-hour significant wave height relative to 3-hour wave conditions may follow 5/9 TABLE 2.

TABLE 2
Adjustment of the Significant Wave Height

Simulation Time Duration	*10 minutes*	*1 hour*	*3 hours*
Adjustment factor applied to the significant wave height *Hs*	1.00 (for simulations using the constrained wave method; or otherwise 18 simulations with different random seeds)	1.09	1.0

For 10-minute simulations, the wave height is not factored. In order to obtain the same level of extreme value as a 3-hour simulation, 18 simulations (a total of 3 hours long) with different random seeds should be performed and the maximum wave height should be taken as the maximum of the 18 simulations. If the constrained wave method is used, the number of random seeds may be reduced. The applicability of the constrained wave method should be verified with 3-hour simulations. The advantage of using 10-minute simulations is that wind conditions do not need to be adjusted.

The number and range of discrete frequencies representing the hull transfer functions should be carefully chosen to cover the peaks in the transfer functions and the area of significant wave excitations. It is also important to identify how the employed computer program handles possible excitations outside the frequency range of the hull transfer functions since this can be a source of error. A small frequency spacing may be required to avoid repeating a time history within one simulation. Variable frequency spacing may also be used, but the repetition period of a time history is more difficult to assess. The number, range, and spacing of discrete frequencies should be determined and verified by sensitivity analyses.

11 Flexibility of RNA and Tower *(1 August 2023)*

For the tower, rotor blades and drive train, the mass distribution, stiffness, natural frequencies and damping used for the calculation should be specified. In general, the DOFs of the tower, rotor blades, and drive train should be modeled in accordance with 5/11 TABLE 3, as a minimum.

The stability analysis normally is performed in the design of the RNA. This stability analysis should be used to assist in determining the modes that are important to the load calculations in the global performance analysis and the integrated load analyses.

TABLE 3
Suggested Minimum DOFs for Modeling Flexibility of the RNA and the Tower

Components	*DOFs*
Tower	1st and 2nd fore-aft and side-to-side bending modes If necessary, 1st torsional mode should be included.
Each Blade	1st edge-wise, 1st and 2nd flap-wise modes If necessary, torsional modes should be included.
Drive train	1st torsional mode

13 Simulation Length and Number of Random Seeds *(1 August 2023)*

For the design of floating offshore oil and gas platforms, a 3-hour duration is often used for model testing and time-domain global performance analyses. This duration is generally sufficient for calculating standard deviations of wave frequency responses because it represents approximately 1,000 cycles of those responses having a natural period of around 10 seconds. Low frequency responses of floating systems, however, typically have natural periods on the order of several minutes. A 3-hour simulation may contain less than 50 cycles of a low frequency response and therefore is insufficient to provide good statistical confidence for the calculated standard deviation. The required simulation time duration may even be longer for predicting extreme values of responses. In order to obtain statistically meaningful wave frequency extreme responses, for instance, several 3-hour simulations may be needed.

An acceptable length of global load simulation time duration depends on many factors, such as natural periods of wave frequency and low frequency responses, contribution of wave frequency and low frequency responses to the total response, degree of nonlinearity, and system damping, etc. The simulation time duration should be determined and verified by sensitivity check. Recent studies indicate that, for typical floating oil and gas platforms in deep water, five to ten 3-hour simulations with different random seed numbers (equivalent to a continuous 15 to 30 hours simulation) may be needed in order to obtain standard deviations and extreme values of responses with good confidence.

For the design load cases (DLCs) and survival load cases (SLCs) defined in Section 4-2 of the *BOWT Guide* and Section 5-2 of the *FOWT Guide*, time histories of turbulent wind and irregular wave conditions should be long enough to provide statistical reliability of the estimate of the characteristic responses. In general, at least eighteen 10-minute stochastic realizations (or a continuous 3-hour realization) should be generated for each turbulent wind condition and sea state considered in the simulations. Additional guidance is given below:

- For the DLC1.2, 1.3, 1.4, 1.5, 2.1, 2.2, 2.3, 2.4, 2.5, 3.x, 4.x, and 5.1, as defined in 4-2/3 TABLE 1 of the *BOWT Guide*, and for the DLC 1.2, 1.3, 1.4, 1.5, 2.1, 2.2, 2.3, 2.4, 2.5, 3.x, 4.x, 5.1 and 9.3, as defined in 5-2/3.5 TABLE 1 of the *FOWT Guide*, at least one set of eighteen 10-minute stochastic realizations should be generated for each wind condition and sea state considered in the simulations. Three to six sets of eighteen 10-minute simulations are recommended for the DLC 1.4, 1.5, 2.1, 2.2, 2.3, 2.5, 3.2, 3.3, 4.2, 4.3 and 5.1 when the RNA involves a transient event. Fewer realizations may be used if it can be demonstrated that the estimated extreme response is not less than that obtained using 3-hour realizations or a total of 3 hours of realizations. For DLC 1.2, 2.4, 3.1, and 4.1 for fatigue analysis, the number of simulations may be reduced.
- For the DLC 1.6, 6.1, 6.2, 6.3, 7.1, and the SLCs, as defined in 4-2/3 TABLE 1 and 4-2/5 TABLE 3 of the *BOWT Guide*, and for the DLC 1.6, 2.6, 6.1, 6.2, 6.3, 7.1, 9.1, 9.2, 10.x and the SLCs, as defined in 5-2/3.5 TABLE 1 and 5-2/5 TABLE 2 of the *FOWT Guide*, at least six 1-hour stochastic

realizations should be generated for each turbulent wind and sea state considered in the simulations. Six 3-hour simulations are recommended for the DLC 6.1, 6.2, 6.3, 7.1, 10.x and the SLCs when the RNA is in the parked conditions. Realizations with a shorter simulation time duration may be assumed if it can be demonstrated that the estimated extreme response is not less than that obtained using 1-hour or 3-hour realizations.

- For the DLC D.1, D.2, D.3, and D.6 as defined in 4-2/3 TABLE 2 of the *BOWT Guide*, at least six (6) 10-minute stochastic realizations should be generated for each wind condition considered in the simulations.

The values of mean wind speed, turbulence standard deviation and significant wave height referenced in the DLCs and the SLCs requiring dynamic simulations should be appropriate to the chosen simulation time duration. More specifically:

- For the DLC 1.6, 6.1, 6.2, 6.3, 7.1, and the SLCs, as defined in 4-2/3 TABLE 1 and 4-2/5 TABLE 3 of the *BOWT Guide*, and for the DLC 1.6, 2.6, 6.1, 6.2, 6.3, 7.1, 9.1, 9.2, 10.x and the SLCs, as defined in 5-2/3.5 TABLE 1 and 5-2/5 TABLE 2 of the *FOWT Guide*, the values of mean wind speed, turbulence standard deviation and significant wave height should be adjusted for different simulation time durations in accordance with Subsections 5/7 and 5/9 of these Guidance Notes.
- For the load cases using 10-minute simulations, at least 18 simulations (a total of 3 hours) should in general be performed. No adjustment is needed provided the wind conditions are based on a 10-minute averaging time duration.

The suggested simulation time duration and number of random seeds for each DLC are summarized in 5/13 TABLE 4. The suggested values for the DLC 6.1 may also be applied to the SLCs. The extreme statistical values for different load cases may be obtained as follows:

- For the DLC 1.4, 1.5, 2.3, 3.2, 3.3, 4.2 and 4.3 with the occurrence of events such as the extreme wind gust, extreme wind shear, severe sea state, etc., the maximum value of a response should be determined based on the transient value in each set of 18 10-minute simulations computed randomly in the worst case. The occurrence of the event can be at any moment during the simulation. For multiple sets of simulations, the maximum value of a response should be determined based on the average of the maximum responses of each set of simulations.
- For the DLC 1.3 and 9.3 with the turbulent wind together with irregular sea states, among all combinations of wind and wave conditions, the largest mean value of the maximum responses of stochastic realizations should be taken.
- For the DLC 2.1, 2.2, 2.5 and 5.1 and with the turbulent wind together with irregular sea states and with the occurrence of events such as a fault or a shutdown, the maximum value of a response should be determined based on the mean value of the largest half of the maximum responses in each set of 18 10-minute simulations computed randomly in the worst case. The occurrence of the event can be at any moment during the simulation. For multiple sets of simulations, the maximum value of a response should be determined based on the average of the maximum responses of each set of simulations.
- For the DLC 1.6, 2.6, 6.1, 6.2, 6.3, 7.1, 9.1, 9.2 and 10.x as well as the SLCs with the turbulent wind together with irregular sea states, among all combinations of wind and wave conditions, the largest mean value of maximum responses of stochastic realizations should be taken.
- For the DLC D.1, D.2, D.3, and D.6 for BOWTs with the turbulent wind conditions, the largest mean value of maximum responses of stochastic realizations should be taken.

TABLE 4
Suggested Simulation Time Duration and Number of Random Seeds for the DLCs *(1 July 2020)*

Turbine Condition		*DLC*	*Type of Analysis**	*Simulation Time Duration and Number of Random Seeds*
1)	Power production	1.2	F	18 × 10-minute simulation with different random seeds
		1.3	S	18 × 10-minute simulation with different random seeds
		1.4	S	Six sets of 18 × 10-minute simulation with different random seeds
		1.5	S	Six sets of 18 × 10-minute simulation with different random seeds
		1.6	S	1-hour simulation with 6 seeds
2)	Power production plus occurrence of fault	2.1	S	Three sets of 18 × 10-minute simulation with different random seeds
		2.2	S	Three sets of 18 × 10-minute simulation with different random seeds
		2.3	S	Six sets of 18 × 10-minute simulation with different random seeds
		2.4	F	18 × 10-minute simulation with different random seeds
		2.5	S	Three sets of 18 × 10-minute simulation with different random seeds
		2.6	S	1-hour simulation with 6 seeds
3)	Start-up	3.1	F	18 × 10-minute simulation with different random seeds
		3.2	S	Six sets of 18 × 10-minute simulation with different random seeds
		3.3	S	Six sets of 18 × 10-minute simulation with different random seeds
4)	Normal shutdown	4.1	F	18 × 10-minute simulation with different random seeds
		4.2	S	Six sets of 18 × 10-minute simulation with different random seeds
		4.3	S	Six sets of 18 × 10-minute simulation with different random seeds
5)	Emergency stop	5.1	S	Three sets of 18 × 10-minute simulation with different random seeds
6)	Parked (standing still or idling)	6.1	S	1-hour or 3-hour simulation with 6 seeds
		6.2	S	1-hour or 3-hour simulation with 6 seeds
		6.3	S	1-hour or 3-hour simulation with 6 seeds
		6.4	F	---
7)	Parked and fault conditions	7.1	S	1-hour or 3-hour simulation with 6 seeds
		7.2	F	---

Turbine Condition		DLC	Type of Analysis*	Simulation Time Duration and Number of Random Seeds
8)	Temporary (installation, maintenance and repair)	8.1	S	---
		8.2	S	---
		8.3	F	---
		8.4	F	---
9)	Power production	9.1	S	1-hour simulation with 6 seeds
		9.2	S	1-hour simulation with 6 seeds
		9.3	S	18 × 10-minute simulation with different random seeds
10)	Parked (standing still or idling)	10.1	S	1-hour or 3-hour simulation with 6 seeds
		10.2	S	1-hour or 3-hour simulation with 6 seeds
		10.3	S	1-hour or 3-hour simulation with 6 seeds

Note:
* For each DLC in the Table, the "Type of Analysis" is denoted "S" for the strength analysis or "F" for the fatigue analysis.

15 Analysis Methods *(1 August 2023)*

The suggested analysis methods for the global performance analysis for different subsystems are summarized in 5/15 TABLE 5 for the design load cases specified in the applicable design standards. Although the time-domain fully coupled dynamic analysis method is preferred, global performance analysis using less sophisticated methods may still be used, especially in preliminary design stages.

For the integrated load analysis in the detailed design stage, the time-domain aero-hydro-servo-elastic coupled analysis approach is used. The simulation software is normally developed by combining aero-elastic codes originally developed for land-based turbines with hydrodynamic codes and mooring dynamic codes used for designing offshore oil and gas platforms. A typical aero-elastic code contains an aerodynamic part, which is mostly based on the Blade Element Momentum (BEM) Method, and a structural part with various levels of complexity in modeling the drive train and elasticity of the blade and the tower. Control system modeling is usually designed by users and linked to the aero-elastic codes through a dynamic link library.

TABLE 5
Suggested Analysis Methods *(1 August 2023)*

OWT Type	Design Stage	Subsystem	Analysis Type	Analysis Method
BOWT	Preliminary design stage	Substructure	Fatigue	Frequency-Domain Analysis Combined Time- and Frequency-Domain Analysis Sequential Time-Domain Analysis Coupled Time-Domain Analysis
			Strength	Sequential Time-Domain Analysis Coupled Time-Domain Analysis
	Final detailed design stage	Integrated support structure and RNA	Fatigue	Integrated Load Analysis
			Strength	Integrated Load Analysis

OWT Type	*Design Stage*	*Subsystem*	*Analysis Type*	*Analysis Method*
FOWT	Preliminary design stage	Floating substructure	Global motion	Frequency-Domain Analysis Combined Time- and Frequency-Domain Analysis Time-Domain Analysis (Coupled, Semi-Coupled, Uncoupled)
			Air Gap	Frequency-Domain Analysis Combined Time- and Frequency-Domain Analysis Time-Domain Analysis (Coupled, Semi-Coupled, Uncoupled)
		Stationkeeping system	Mooring analysis (fatigue and strength)	Frequency-Domain Analysis Combined Time- and Frequency-Domain Analysis Time-Domain Analysis (Coupled, Semi-Coupled, Uncoupled)
	Final detailed design stage	Integrated support structure and RNA	Global load analysis	Integrated Load Analysis
			Global motion	Integrated Load Analysis
			Air Gap	Combined Time- and Frequency Domain Analysis Integrated Load Analysis
			Mooring analysis (fatigue and strength)	Integrated Load Analysis