ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

Model Tests for Offshore Wind Turbines

7.5	Process Control
7.5-02	Testing and Extrapolation Methods
7.5-02-07	Loads and Responses
7.5-02-07-03	Ocean Engineering
7.5-02-07-03.8	Model Tests for Offshore Wind Turbines

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Table of Contents

Model Tests for Offshore Wind Turbines

1. ACRONYMS USED IN THIS DOCUMENT

BMOWT Bottom-mounted offshore wind turbine
FOWT Floating offshore wind turbine
OWT Offshore wind turbine
RNA Rotor-nacelle assembly
IEC International Electrotechnical Commission
TRL Technology Readiness Level
IPCC Intergovernmental Panel on Climate Change
TLP Tension leg platform
DOF degree of freedom
RCS Recognized Certificate Society
ISSC The International *Ship* and Offshore Structures Congress
API-RP2SK American Petroleum Institute – Recommended Practice: Design and Analysis of Stationkeeping Systems for Floating Structures

2. PURPOSE OF GUIDELINE

The purpose of this document is to offer guidance to researchers to assist in performing model tests of offshore wind turbines (OWTs) according to the state of the art. These tests may include:

- measurements of foundation loads for bottom-mounted (fixed) OWTs;
- measurement of hydro-elastic response of OWT towers;
- measurements of global dynamic response of OWTs, including responses to specified design load cases;
- measurement of natural period of motion, and additional damping for floating offshore wind turbines (FOWTs);
- measurement of maximum offset of moored FOWTs, allowing selecting appropriate length of the dynamic power cable;
- investigation of the interaction between the rotor aerodynamics and the dynamic response of the support structure;
- quantification of technical performance variables; validation of numerical models;
- investigation of serviceability, survivability and accidental limit states, including responses to impulsive loadings, such as object dropping, slamming or collision;
- investigation of transportation and installation methodologies.

This guideline does not address the assessment of the aerodynamic performance of OWTs.

Many aspects of the experiments for FOWT structures are covered by the ITTC Recommended Procedure 7.5-02-07-03.1, "Floating Offshore Platform Experiments".

However, there are some key differences between model tests of OWTs and model tests of other offshore structures. The main distinctive features of the tests of OWTs may include:

- Requirement to simulate complex kinematics and material properties, driving key interactions between aero-elastic response of the blades, dynamics of the rotor and nacelle assembly (RNA), hydro-elastic response of the tower and the support structure, gyroscopic loads, and hydrodynamic response of the floating platform;
- Special requirements for the model construction, in particular related to the rotor;

- Large size of full-scale structures: 12MW turbines are approaching 260m in height with rotor diameters up to 220m;
- Challenges related to the fulfilment of the dynamic similarity of aerodynamic and hydrodynamic loads for scale model testing in wind/wave tanks;
- Challenges of accurate simulation of realistic aerodynamic environments over large areas of the test tank;
- Requirement for analyses of design load cases from International Electrotechnical Commission (IEC) standards;
- Rapid evolution of design of FOWTs: diversity of innovative concepts, some presenting challenges for scaled model testing;
- Requirement for testing throughout the various experimental stages for novel floating concepts: concept validation, design validation, system validation, and prototype and demonstration stages.
- Potential requirement for tests of multiple scaled models corresponding to an array of OWTs.
- Particular challenges in simulation of unconventional, innovative mooring systems. The permanent mooring systems often include synthetic fibre ropes, which require special treatment in model testing.

These features place particular demands upon the experiment design, model construction; facility capability, and experiment procedure.

3. TEST PARAMETERS

3.1 Experimental stages

The development of an OWT, from the original idea to a marketable product, involves a series of test stages including the concept validation stage, the design validation stage, the system validation stage, and the prototype and demonstration stage.

These stages are commonly described in the renewable industry in terms of Technology Readiness Levels (TRLs) (e.g. U.S. Department of Energy (2011)); TRL 1-3 correspond to research stages up to and including proof of concept, TRL 4-6 correspond to concept development and scale testing, TRL 7-8 correspond to prototype demonstration. TRL 9 correspond to commercial demonstration and system development.

The main objectives of the tests in concept validation stages (TRL 1-3) are to validate the OWT concept, to investigate OWT variables and physical properties that affect the dynamic responses, and to optimize the OWT for power production using small-scale models. There are also tests regarding the installation phase and towing methods of OWTs.

The main objectives of tests in the concept development stage (TRL 4-6) are to validate the OWT design, to develop control strategies for improved performance, and to verify the mooring and anchor system using medium scale models. Experimental tests are also sometimes meant for validating a numerical model that will be used for optimizing, improving the proof of concept. The wind/wave spectra at a specific site should be used. For TRL 4, small-scale models can be used; for TRL 5, large-scale model should be applied, while for TRL 6, the tests can be carried out using scaled prototype in an open environment.

Tests in the prototype demonstration stage (TRL 7-8) are carried out in the near-full or full scale in open environment, while tests in the commercial demonstration and system development stage (TRL 9) are carried out at full scale at sea.

3.2 Types of offshore wind turbines

The vast majority of OWTs are currently horizontal axis devices, although some vertical axis devices are also under development. OWTs may also be categorised depending on the nature of the support structure that supports the Rotor-Nacelle Assembly (RNA) and the tower.

3.2.1 Bottom-mounted offshore wind turbines (BMOWT)

Bottom-mounted turbines are currently utilised in water depths up to around 50m. Bottom-mounted turbine foundations include the following:

- Monopile: simple foundation design constructed from tubular steel structure and piled into the seabed, typically used in water up to around 25m.
- Multipile: foundation based on three or four legged structure made of tubular steel, when a guyed monopole is not feasible.;
- Jacket: braced lattice-frame structure typically used in deeper water;
- Gravity-based: substructures held in place by gravity when installation of piles in the seabed is difficult.

3.2.2 Floating offshore wind turbines (FOWT)

Floating offshore wind turbine types continue to evolve rapidly, but currently include the following (Koo *et al.* (2012)):

- Barge
- Spar
- Tension Leg Platform (TLP)
- Semi-submersible

In the FOWT literature (IPCC (2011)), platforms are often categorised as ballast-stabilised (e.g. spars), mooring-stabilised (e.g. TLP) or buoyancy-stabilised (e.g. barges or semi-submersibles).

3.3 Types of facilities suitable for use

Different facilities can be used at different stages of the design process and depending on the type of mooring system (compliant, restrained, single point, etc.). These may include:

- Wave flumes/Towing tanks with wave-makers (including facilities with wind generation)
- Circulating water channel with wave-makers (including facilities with wind generation)
- Ocean basins capable of generating both long- and short-crested waves; (including facilities with wind generation)
- Ocean basins with wind, wave and current facilities
- Shallow water wave tanks.

It should be noted that the scale models required for OWT testing can place substantial demands on wave-making in terms of both wave heights, wave periods and run durations, and on wind-generating in terms of wind speed, turbulence intensity and run durations.

Particular care must be taken to minimise build-up of reflected waves and to maintain the quality of wind/wave field during long duration realisations of large waves.

3.4 Model parameters and scale

The choice of the scale ratio will be based on the OWT size, the goal of the tests, the target wind/wave conditions, the water depth, and the test stage, and the dimensions of the wind generation system. It may be necessary to build models at different scales to assess the performance in operational conditions and survivability in extreme conditions. The scale factor will be limited by the 1) model basin dimensions; 2) wave-making capacity in terms of both wave heights, wave periods and run durations; 3) wind-generation capacity in terms of wind speed, turbulence intensity and run durations; and 4) hybrid system performance for emulating the rotor-induced loads.

In small-scale model tests, viscous hydrodynamic damping and, in particular, damping associated with vortex shedding from sharp edges, cannot be scaled appropriately with Froude similarity and may be overestimated.

For an operational FOWT, the gyroscopic effect due to the rotation of the rotor and the pitching of the platform results in a yaw moment acting on the structure. The response of the turbine to this yaw moment depends on the number of degrees of freedom of the model. If the nacelle is fixed to the tower axis (6-DOF), the yaw moment will result in a yaw motion whose magnitude will depend on the mooring and restoring system in yaw. Hence, correct simulation of the yaw stiffness of the mooring system, as well as the moments of inertia of the rotor, will be important in order to achieve similarity.

On the other hand, when the nacelle part rotates separately from the tower (7-DOF), the observed yaw motion will depend on the correct simulation of the moments generated between the nacelle and the tower (Wang & Sweetman (2012)).

Some particularly complex phenomena, which represent a challenging research area, are involved with the interaction of wind/wave/current flow and a FOWT. Mean offsets, including trim, list and azimuth angles in rotational modes, and drifts in translational modes, may be caused by the second-order effect of waves, waves trapped between columns and pontoons, as well as mean component of wind speed and current. The mean offsets may be detrimental to power generation performance and seakeeping performance, including the stability in waves and wind.

The offsets can be adjusted by the water ballast system and/or the mooring system with delta connections in the mooring lines.

3.5 Uncoupled hydrodynamic tests

For the tests of BMOWTs focused on determination of loads, it may not be necessary to simulate the coupled effects of wind load and the wave/current load, since these loads and their effects may be considered uncoupled. This may be particularly relevant for simulation of dynamic responses of the tower and support structure in extreme weather, during which the turbine will typically be shut down. Hence, in these cases, hydrodynamic tests can be carried out without the rotor as long as the influence of the rotor mass is correctly represented (e.g. de Ridder *et al.* (2011)).

Decoupling the measurements of wave/current loads from the measurement of wind loads may be advantageous. This is because a larger model can be used for the measurements of wave/current loads, facilities without wind generation may be employed, and measurement uncertainty may be reduced, since the entire range of the load cells can be used for measuring the wave/current loads. However, where tests are aimed at investigating the coupled dynamic response of the structure in operational conditions, including realistic modelling of the structural flexibility and aerodynamic damping, then inclusion of the aerodynamic coupling due to the rotor is necessary. Moreover, investigation of the dynamic response requires modelling of the soil-structure interaction, as it influences the loads and especially the natural frequencies of the structure (Abhinav, Saha, 2015).

Model tests of FOWTs can be carried out without the rotor at the preliminary stage of the tests, or for special purposes, e.g. comparing different support structures in respect of response to waves, validation of numerical models etc. However, final tests aiming in evaluating the global response of the system from the concept validation stage to the prototype and demonstration stage should include at least simplified modelling of the rotor due to strong coupling between rotor and platform dynamics, and in particular the gyroscopic effect.

In facilities without current generation, using a set of linear springs inserted into a mooring cable and a pulley system at the fairlead point for simulation of steady current load may be employed (Chakrabarti (1998)). The initial fairlead angles and pretension at the top end of the mooring cable are adjusted to match the calculated ones. Then, steady current loads can be calculated by the empirical formulas in RCS rules including API-RP2SK (2005), and they depend on the geometry of the exposed structural components and types of floaters. However, this method will not account for the wave-current interaction. The pulley system will also lead to incorrect changes of the static configuration of mooring lines in catenary spread mooring systems.

3.6 Coupled aero-hydrodynamic tests

3.6.1 Simplified Simulation of Rotor

A number of methods may be employed to simulate the presence of the rotor without using an accurate representation of the rotor aerodynamics, although none captures all of the physics of the fully coupled system.

Simulating the steady wind load using a wire attached to a weight will lead to an incorrect inertia of the system during testing (Chakrabarti (2005)). It can only be justified for rough estimation of the maximum mooring offset (e.g. Chujo, *et al*. (2011)). However, using wires attached to dynamic winches is recommended (ISSC (2012)) and an example is shown in 2.6.3.

A solid or porous disc may be used in place of the rotor in conjunction with a battery of fans for generating the incident wind loads. The disc should be sized to generate a drag load corresponding to the thrust on the turbine (at the test wind speed). If a rotating disc or a separate rotating arm is employed with the correct rotational moment of inertia, it is possible to capture the coupled response of the structure taking into account the gyroscopic coupling between the rotor and the platform (see Cermelli *et al.* (2009)).

This approach neglects the aerodynamic torque and other smaller aerodynamic loads in yaw, sway and roll exerted by the rotor on the platform, as well as the blade / tower interactions; furthermore, problems may arise from the unsteadiness of the flow around the disc. In addition, this may not be able to capture the slope of the thrust curve (i.e. the thrust coefficient vs. tip speed ratio curve), which is important for aerodynamic damping.

A further possibility, which may be suitable for small-scale tests in the concept validation stage, is to use the rotor as a fan rotating in otherwise stationary air (e.g. Kraskowski (2012)). This offers a rather simplified approach to the investigation of response of FOWTs in facilities that do not have wind generation capabilities. In this case, separate measurements are required to calibrate the system, i.e. to identify the force vs. rpm characteristics.

This method of modelling the rotor is quite simple and allows for easy adjustment of the mean wind load. However, it is difficult with this approach to control the blade pass frequency and wind load simultaneously, to achieve the correct mean thrust and torque whilst capturing tower interaction effects. Further challenges of this approach include the correct simulation of orientation of gyroscopic moments in relation to steady moments, and the difficulty in realistically simulating the behaviour of the magnitude and direction of the thrust vector as the turbine pitches. It is also difficult to model the correct torque and other smaller aerodynamic loads, as well as the correct slope of the thrust curve.

The simplified methods of modelling the rotor described above are reasonably well suited for preliminary tests in steady wind; however, particular care is required in the interpretation of results from these types of tests for turbulent wind and extreme events. A more sophisticated approach, utilising the actively controlled fan for simulating the rotor thrust obtained from simultaneous numerical simulations, is described in 2.6.3.

3.6.2 Physical modelling of the rotor in fully coupled tests

Direct modelling of an OWT rotor is usually realized by exposing a working, but not necessarily geometrically scaled, rotor to a wind field generated by a battery of fans (see for example Chujo, *et al*. (2011) for spar OWT, Shin, *et al.* (2013) for semi-submersible OWT and Goupee, *et al*. (2012), for spar, semi-submersible, and TLP). The rotor rpm and the spatial variation of wind speed should be carefully calibrated prior to the main experiments.

Particular challenges in this approach with respect to the wind generation include the representation of wind gradients, wind turbulence, and the difficulty of generating wind in a wave tank close to a wavy water surface, particularly in tests with large waves.

The minimum aerodynamic requirement for modelling the presence of rotor in a fully coupled test of a FOWT is the correct reproduction of the mean wind thrust load in order to generate correct aerodynamic overturning moments and mooring offsets. The impact of rotor aerodynamics on pitch damping is also of great importance. Maintaining the Reynolds similarity is in general not possible for typical sizes of basin models, and thus detailed modelling of aerodynamics, including stall phenomena, is usually not possible. Variations in wind speed caused by motions of a floating platform will be driven by wave effects, which are governed by Froude similarity.

Depending on the required outcome of the tests, modelling the rotor will usually also require maintaining the Froude similarity for the rotor RPM to generate the correct representation of the gyroscopic effect of the rotor, as well to allow more accurate representation of the aerodynamic interaction between the rotor and the support structure. This will also involve realistic representation of the mass distribution and possibly the elasticity of supporting structure and rotor blades.

Performance models of OWTs will therefore normally be scaled using Froude similitude. However, some key parameters related to wind loading will not scale in this manner, leading to scale effects when extrapolating to full-scale, particularly for FOWTs. Approaches to address this through redesign of the rotor model are discussed in more detail in 3.1.2.

3.6.3 Combined real-time numerical simulation and physical test

This class of tests refers to methods that combine, in real-time and interactively, numerical simulation of a virtual substructure with a physical substructure tested experimentally in model scale. These hybrid methods often go by the terms *real-time hybrid model testing*, *hardware-in-the-loop*, or *software-in-the-loop*. For model testing of offshore wind turbines in hydrodynamic laboratories, this means that the platform responses (motions, etc.) are measured experimentally and passed into the numerical simulations, whereas actuators, or other means, apply the appropriate aerodynamic/generator loads according to simultaneous simulations of the wind turbine.

One important advantage with this method, adapting a "virtual turbine", is that it solves Froude-Reynolds scaling conflict, i.e. the aerodynamic loads are calculated in full-scale and are then scaled down using Froude scaling. A well-functioning hybrid approach allows for investigating the responses of OWT in operational and survival conditions, as well as in fault conditions such as transient responses in emergency shutdown of the generator in large wind speeds or for blade seize (e.g. loss of pitch control for one blade). Also, it can be used to perform detailed sensitivity studies on the wind modelling, e.g. including the effect of large waves on the wind field - which is difficult to setup accurately in a hydrodynamic laboratory. The aerodynamic simulation tool inherently captures aerodynamic damping. The hybrid approach has also the advantage that the aerodynamic loads in the tests are known, and hence, the uncertainties related to physical modelling of the wind and the turbine are eliminated, which makes it suitable for calibration and validation of hydrodynamic coefficients in numerical tools (Berthelsen et al. (2016)).

When preparing the hybrid setup, it is particularly important to identify the quantities of interest for the tests (e.g. motions, mooring lines tensions, tower-base bending moments, etc.) and the frequencies of interest, i.e. the frequency range of the quantities that have to be captured correctly by the experiment. This, together with the magnitude of the loads and responses, will govern the selection of actuators and the control strategy of the hybrid setup. Further, a numerical sensitivity analysis should be performed to identify what components of the aerodynamic load vector have insignificant effect on the quantities of interest (see Bachynski et al. (2015) and Hall (2014)). The complexity of the hybrid setup may be reduced by removing load components that induce insignificant responses. When the final setup is developed, a numerical tool modelling the entire experimental setup, including the actuators and control system, should carry out a virtual testing of the system, to verify that the system is performing as designed. A suggested summary of the procedure can be found in Sauder et al. (2016). There are different ways of applying the aerodynamic loads on the physical substructure, and a couple of approaches are described in the following.

A simple approach that may be adequate for some concepts is to replace the rotor with a ducted fan driven by an electronic motor (Azcona et al. (2014)). The fan can generate a force representing the thrust force on the turbine, obtained from simultaneous numerical simulations. The simulations can include effects such as turbulence, gusts, aerodynamic damping, and wind turbine control. This approach focuses on the application of the thrust force only. It should therefore be investigated whether the neglected aerodynamic load components have negligible influence on the quantities of interests.

It may be necessary for some concepts to apply a larger number of components of the calculated aerodynamic loads, in order to obtain correct estimates of the quantities of interest. The physical substructure may then be connected to several land-based dynamic winches (actuators), as described in e.g. Sauder et al. (2016). Bachynski et al. (2016) provide examples of tests that are feasible with this approach. The drawback of this method is the need for more hardware, and advanced control and allocation strategies.

One important challenge with real-time hybrid testing is related to the time-delays from numerical simulation, data transfer, and the actuator response. Typically, the time-delay may introduce additional damping or spurious energy that may cause instabilities. A delay compensation strategy is important to prevent any unphysical damping or instability appears in the experiment. Another challenge is related to the physical limitation of the actuators to emulate high frequency loads that may be important for certain types of OWT (e.g. TLP's and monopiles).

The accuracy of the aerodynamic loads is limited by the simplifications and uncertainties in the numerical model. Uncertainties can be related to both the input wind field description (e.g. lack of proper full-scale data), as well as the aerodynamic load modelling (e.g. simplifications and assumptions, accuracy of numerical solvers). On the other hand, hybrid testing allows for full control of the aerodynamic loads, i.e. the actual wind loads applied in the experiments are known, and uncertainties in the numerical modelling can to some extent be evaluated qualitatively and quantitatively by numerical sensitivity studies.

3.7 Environmental parameters

A discussion of key parameters related to environmental properties such as water depth, basin dimensions, calibration of wave characteristics (and current and wind where relevant), and combined environment characteristics can be found in ITTC Procedure 7.5-02-07-03.1, "Floating Offshore Platform Experiments".

In OWTs wind/wave tank testing, particular attentions should be paid to the impact of open air and wave blockage, since OWTs naturally affect the wind and wave field in a more complex manner than conventional offshore floating structures.

Testing in long-crested waves and/or uniform wind is commonly adopted at the concept validation stage, for comparative studies, and for component testing where appropriate. This process may include tests with the OWT oriented at different angles to the direction of wave propagation. Concept validation testing may involve regular wave tests with/without uniform wind, to characterise the frequency response as well as testing in irregular sea states with/without turbulent wind, relevant for the intended deployment site, in order to estimate performance including dynamic responses.

At the later stages of the design process, when accurate estimates of performance in combined external conditions are required, since the performance of OWTs depends greatly on both incident wave direction and misalignment in directions of wind and wave, tests in short-crested irregular waves considering the azimuth of the principal wind/wave direction should be conducted.

For these tests, the directional wave spectral density function can be used to describe the short-crested waves. It is defined as the product of the wave frequency spectrum and the directional spreading function. An overview of the most commonly used principles, methods and definitions for directional wave modelling is given in ITTC Recommended Procedure 7.5-02-07-01.1, "Laboratory Modelling of Multidirectional Irregular Wave Spectra". The most popular model for the directional spreading is a cosine squared ($\cos^{2s}$) function, originally proposed by Longuet-Higgins et al. (1963).

Alternatively, the wave spectrum of an actual site may also be used in the tests. Site data could suggest that sea states composed of multiple wave systems are common at that particular location. When device performance can be compromised by multi directionality, testing in sea states with multiple wave systems should be carried out.

3.8 Mooring Systems

According to IEC61400-3-2 Design requirements for floating offshore wind turbines, four types of mooring system are used for floating OWTs: Catenary, semi-taut, taut and tension-leg mooring states. . Where detailed design information is available, it is important to simulate moorings accurately, since mooring behaviour can affect both power capture and extreme behaviour. This is especially relevant where taut moorings are employed since these can have a significant impact on FOWT motions.

Guidance on mooring installation and calibration can be found in ITTC Procedure 7.5-02-07-03.1, "Floating Offshore Platform Experiments". In the case of FOWTs using catenary moorings, the footprint size at the scale resulting from the maximum capability of the wave-makers may exceed the size of the tank. Where the limitations on the physical size of a testing basin do not allow a full model of a mooring to be accommodated at a reasonable scale within the basin, truncated systems or hybrid modelling is required (e.g. Kraskowski (2012)). Guidance on the use of a hybrid mooring system may be found in the ITTC Recommended Procedure 7.5-02-07-03.4, "Stationary Floating Systems Hybrid Mooring Simulation".

3.9 Test Case Parameters

3.9.1 Serviceability Limit State tests

In the tests of serviceability limit state performance (normally limits on operating condition), the ability of the OWT to capture and convert the wind energy is regarded as the most important criterion.

Tests on the serviceability limit state performance should be carried out in both regular and irregular waves with/without wind considering turbulence. The test programmes should aim at investigating the effect of OWT design variables on limit state performance. Details of the design load cases under combined environmental conditions can be found in IEC Standards 61400-3-1 for OWT and IEC Technical Specifications IEC 61400-3-2 for FOWT.

Model tests in irregular waves with/without wind considering turbulence should normally be carried out for a duration corresponding to at least 60 minutes at full scale, in order to gain statistically valid results. Details of procedures for simulation and measurement of irregular short-crested seas can be found in the ITTC Recommended Procedure 7.5-02-07-01.1, "Laboratory Modelling of Multidirectional Irregular Wave Spectra".

3.9.2 Ultimate Limit State Tests

Before undertaking sea trials, it is important to conduct ultimate limit state tests in model basins, to evaluate the seaworthiness of an OWT including hull structure and mooring system. The ultimate limit state tests should be conducted in long and short crested irregular waves with extreme wind considering both gust and turbulence. These tests must provide extreme motions, extreme loads exerted on the hull structure, shutdown and mooring line loads under the design conditions corresponding to the metocean data of the installation site. Tests should follow the principles set out in the ITTC Recommended Procedure 7.5-02-07-02.3, "Experiments on Rarely Occurring Events".

Ultimate limit state tests are typically carried out for a duration corresponding to three hours at full scale. A series of wind and wave angles should be used to evaluate their effect on OWT motion and mooring forces. Tests involving failure modes, with one or more mooring lines disconnected, should be carried out to simulate line-breaking scenarios. The test matrix can be considerably reduced in cases where the most dangerous wave direction in respect of mooring loads can be reliably identified.

Where appropriate the OWT should be tested in design situations other than power production (i.e. occurrence of fault, standing still, idling, start up and shut down), to simulate typical scenarios which could result in excessive body motions.

3.9.3 Fatigue Limit State Tests

Data from regular/irregular wave tests with wind may be used to inform the estimation of fatigue limit states.

Wave and wind misalignment in operational conditions should be investigated due to the significant effect it may have on aerodynamic damping in the wave direction. The reduced aerodynamic damping may increase the wave induced fatigue damage. Sensitivity to the turbulence model and turbulence intensity should also be investigated as this may have an impact on the fatigue damage, e.g. on mooring system for FOWTs.

Structures with natural frequencies close to operational wave spectra range of frequencies should be investigate to assess potential resonance responses.

3.9.4 Accidental Limit State Tests

It is important to perform accidental tests (normally, damaged condition) in model basins. Structural damages due to collision, objects dropping, or fire may lead to the loss of floatability and stability of FOWT in waves and wind. Model tests in irregular/regular waves with/without wind should be carried out to simulate accident-occurring scenarios in both operation condition and extreme condition.

3.9.5 Offshore Wind Turbine Arrays

Testing of arrays can present substantial challenges for many OWT types, especially when realistic mooring systems are deployed, due to the footprint required, and the potential importance of interactions on mooring and foundation loads.

For an array with many OWTs installed, the interaction of OWTs can be determined through tests involving a limited number of systems. Due to the cost and scale constraints, the behaviour of arrays involving a large number of OWTs may be evaluated by numerical modelling.

4. DESCRIPTION OF TEST PROCEDURE

4.1 Model & Installation

4.1.1 Platform Model

Guidance on preparing the model of a FOWT platform, including model geometry, ballasting and loading, can be found in the ITTC Procedure 7.5-02-07-03.1, "Floating Offshore Platform Experiments".

In case of ballast-stabilised floating structures, the design and manufacturing of the model of OWT may be more demanding than the corresponding process for models of vessels or other offshore platforms, due to the extreme sensitivity of the draft to the accuracy of ballasting and the limited possibility of adjusting the mass distribution for correct reproduction of the moments of inertia.

It should be also noticed that small water absorption or deformation due to hydrostatic pressure can influence the model draft and mass distribution. For that reason, it is recommended that the total mass and mass distribution of the model are taken into account as parameters at the model design stage, so as to minimize the need of ballasting the finished model.

4.1.2 Rotor / Nacelle Assembly Model

The Rotor-Nacelle Assembly (RNA) and associate instrumentation must be carefully considered. Special care should be taken where flexible models of components, such as blades, are constructed; for flexible models, it is important to scale the magnitude and frequency of the modes of vibration.

During model tests with a working rotor, the rotation of the rotor can sometimes result in vibration. The mass and stiffness characteristics of the components of the model change the degree and the position of the vibration. Hence where the model construction does not allow all aspects of similarity to be maintained simultaneously, the priority of similarity, (i.e. the mass distribution, inertia distribution or distribution of the elasticity of supporting structure and blades) should be selected depending on the main purpose of the test.

Manufacture of a rotor with the correct mass properties and adequate stiffness can prove very challenging. Martin *et al.* (2012) describe a test of a 1/50 scale model of a 5MW turbine involving construction of a blade 1.23m in length with a mass of 140g. Muthanna *et al.* (2013) discuss challenges in manufacture of small-scale rotor models.

Maintaining the correct aerodynamic behaviour of the rotor is a substantial challenge in fully coupled model tests. If Froude scaling is adopted for the rotor rpm, in order to maintain the gyroscopic moments, then use of Froude-scaled wind speed in conjunction with an accurate geometric model of the rotor will generally lead to unrealistically low rotor torque and thrust due to the reduced Reynolds number. This is because the foil sections typically utilised in OWTs will exhibit substantially reduced lift and increased drag compared to the full-scale foils at the low Reynolds numbers generated by Froude-scaled wind.

Martin *et al.* (2012) discuss three possible approaches to address this challenge. In the first approach, the wind speed is increased beyond the Froude-scaled value to compensate for the low thrust coefficient. If rotor speed is maintained at Froude-scaled values, to retain correct gyroscopic moments, then the tip-speed ratio will be incorrect, resulting in incorrect torque. However, this may be justified as an approximation, since the overturning moment due to thrust is typically much higher than the one due to torque. The ratio of unsteady velocity (caused by platform motions) to mean velocity will be reduced, leading to incorrect modelling of effects of unsteady inflow on the rotor. However, results show that the aerodynamic damping of the platform pitch generated by the turbine is modelled with a reasonable degree of accuracy.

A second approach addressing low Reynolds number effects is the placement of studs or other roughened materials as a turbulence stimulator along the leading edge of a blade. However, this is unlikely to improve the turbine performance adequately on its own to yield comparable performance with the full-scale device, and can yield unrealistic results if laminar separation occurs, as well as unrealistic unsteady aerodynamic loads during flow re-attachment.

A third possible approach is to redesign the rotor blade sections to account for Reynolds number effects, or even more radical solutions such as changing the number of blades and the rotor diameter. This can involve the choice of laminar flow sections for the model scale rotor, so that the model rotor design can simulate as closely as possible the correct full-scale mean thrust and torque coefficients at the model-scale Reynolds number (based on blade chord), whilst still maintaining the correct mass properties. Martin et al. (2012) demonstrate an example showing blade redesign leading to broadly correct values of scaled thrust and aerodynamic damping using Froude-scaled wind speed.

In order to minimize these errors, tests with large scales are recommended where possible.

Complete modelling of the RNA with respect to its influence on global response of the FOWT includes actual representation of the blade pitch control system (e.g. Chujo, *et al.* (2013)). Neglecting the influence of blade pitch control can result in underestimation of the pitch angle of the floater (Wang & Sweetman (2011)). Simplifications assumed for the tests should then be carefully studied and documented.

4.1.3 Tower Model

Special care should be taken where flexible models of tower are constructed; for flexible models, it is important to scale the magnitude and frequency of the modes of vibration.

Tower structures should also be investigated in operational/extreme sea states, to investigate possible resonance responses near the 3P period, where P is the rotational frequency of the rotor.

4.1.4 Moorings and Foundation

In the measurements of support sub-structure loads due to waves for bottom-mounted OWTs, it is important to pay attention to the stiffness of the measurement devices; unrealistically flexible foundation of the model can influence the resulting wave loads.

In case of mooring systems utilising synthetic fibre ropes, special care should be taken with correct modelling of their stiffness during the tests. Viscoelastic properties of the material result in increased stiffness of the ropes under dynamic loads, which should be taken into account in model tests (Falkenberg (2011)). For ropes characterized by increased stiffness under dynamic loads, it is usually not possible to reproduce correctly both the maximum mooring loads and the mean offset of the structure.

4.1.5 Installation

Model preparation and installation should follow the principles set out in ITTC Procedure 7.5-02-07-03.1. The installation of small-scale testing of moored structures or free-floating structures should be clearly documented, as installation approach could impact motions or loading.

4.2 Calibration of Environment

Details of the calibration of environment parameters can be found in the ITTC Procedure 7.5-02-07-03.1. In testing offshore wind turbines, including direct modelling of the rotor, particular attention must be paid to the correct representation of the wind field, which should be measured prior to the main experiments and documented.

4.3 Collection and analysis of data

General guidance on collection and analysis of data can be found in the ITTC Procedure 7.5-02-07-03.1. In the case of OWTs, the accelerations at key locations in full scale are critically important parameters for the operation and maintenance of the systems, so particular care should be taken with the collection and analysis of this data.

4.3.1 Extrapolation to Full Scale

Model values of forces and motions are scaled to full scale by applying Froude's similitude law. Special treatment may be required to address the challenges posed by difficulties in reproducing the vertical wind speed distribution correctly in model tests.

Particular care must be taken to account for the relationship between the mean torque and thrust and the dynamic forces and moments, with regard to the impact of gyroscopic effects.

Extrapolation of model test results to the full-scale will require some empirical correction methods, taking into consideration the correlation allowance in order to make up for the modelling deficiencies of the small scale model test. Due to the relatively early stage of development of the methodology for scale model tests of offshore wind turbines, and different testing methods being in use, feedback from full scale devices should be used to elaborate empirical corrections, specific for device type and testing method, in order to make up for the modelling deficiencies in the small scale model test.

4.3.2 Presentation of Results

The following provides a recommended outline of a generic test procedure and report. An actual test procedure is likely to consist of a subset of these elements, and may vary dependent on the test purpose and device type.

a) Purpose of the Test

b) Facility Characterization
- i) No-model baseline performance
- ii) Facility dimensions and model size capacity
- iii) Operating ranges and test capabilities

c) Model & Installation
- i) Model Scale
- ii) Model dimensions
- iii) Model mass and inertia properties
- iv) Model Complexity – simplified, system, component
- v) Model function/operation
- vi) Model installation: Mooring, Foundation and constraints
- vii) Model Measurements / calibration

d) Measurement Systems
- i) Purpose of the measurements and required performance/accuracy
- ii) Instrumentation Type: Invasive / non-invasive; embedded / free-field; Steady / dynamic; Operational characteristics and requirements
- iii) Resolution – Spatial and temporal
- iv) Calibration requirements

e) Types of Measurements
- i) Model motion and deformation
- ii) Flow field measurements
- iii) RNA measurements
- iv) Environmental measurements

f) Test Matrix
- i) Test parameters and conditions – Scaling parameters (Fr, Re, etc.), operating conditions
- ii) Measurement Locations
- iii) Recommended practices

iv) Design and off-design testing (specify what is meant by off-design testing – e.g. is platform / rotor yaw regarded as off-design).
v) Steady vs. unsteady performance
vi) Shutdown conditions
vii) Testing in waves for floating devices
viii) Component & Sub-component testing: Component and system loading; Sub-component function
ix) Test repeatability and required number of repeat conditions for desired accuracy
x) Installation & Recovery tests

g) Data Acquisition
i) System performance – rates, resolution, sequential or simultaneous sampling, number of channels, and noise levels/floors

h) Data Analysis
i) Data corrections – bias errors, blockage corrections, Zeroes or Tares
ii) Normalizations
iii) Statistical Analyses; static vs. dynamic studies
iv) Uncertainty analyses

4.4 Uncertainty Analysis

The most important potential source of uncertainty in model tests of the OWTs is the accuracy of modelling the rotor, as discussed in 2.5. Reproduction of its damping characteristics, inertia and angular momentum is recommended whenever possible; the characteristics of the rotor at model scale (mass, moment of inertia, RPM, and blade pitch angles) should be documented. Other potential sources of uncertainty specific to FOWTs are the following:

- Sensitivity of the motion response characteristics to mass distribution and, on the other hand, limited possibility of adjusting the mass distribution;
- Sensitivity of the motion response characteristics to additional inertia of a bundle of instrument cables hung from RNA, on the other hand, limited possibility of reducing the weight of instrument cables;
- Sensitivity of the response characteristics to the accurate installation of FOWTs' scaled models including the mooring system with anchors;
- Sensitivity of the motion response characteristics to viscous damping of FOWTs around the resonance range, on the other hand, limited possibility of matching the damping at low Reynolds number;

In the case where it is required to model a mooring system consisting of synthetic fibre ropes - large sensitivity of extreme mooring loads to correct reproducing the stress-strain characteristics of the material. Dynamic characteristics of the synthetic ropes and effects of the delta connection on yaw should be taken into account.

Standard aspects of valuation and expression of uncertainty can be found in the ITTC Recommended Procedure 7.5-02-01-01, "Guide to the Expression of Uncertainty in Experimental Hydrodynamics".

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