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Model Tests for Offshore Wind Turbines

1. PURPOSE OF GUIDELINE

The purpose of this document is to offer guidance to research organisations on performing model tests of offshore wind turbine~~s~~ (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 OWTs, allowing selecting appropriate length of the power umbilical;
- 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 operational and survivability characteristics limits, including responses to impulsive loadings, such as slamming or collision;
- investigation of transportation and installation methodology

This guideline does not address the assessment of the aerodynamic performance of offshore wind turbines.

Many aspects of the experiments for floating offshore wind turbine 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 within the OWT system between aero-elastic response of blades, dynamics of rotor and nacelle assembly (RNA), hydro-elastic response of towers and support structures, gyroscopic loading, and hydrodynamic response of floating platforms
- Special requirements for the model construction, in particular related to the rotor;
- Large size of full-scale structures: 7MW turbines are approaching 200m in height with rotor diameters up to 170m;
- Challenges related to dynamic similarity and scaling for aerodynamic and hydrodynamic flows for model testing in wind/wave tanks;
- Challenges of accurate simulation of realistic aerodynamic environment over large areas of test tanks;
- Requirement for analyses of design load cases from International Electrotechnical Committee (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: the concept validation stage, the design validation stage, the system validation stage, and the prototype and demonstration stage.
- 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.

2. TEST PARAMETERS

2.1 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. Mankins (1995)); TRL 1-3 correspond to research stages up to and including proof of concept, TRL 4-5 correspond to stages up to and including design of components, sub-systems, TRL 6-7 correspond to the system validation stage in laboratories and/or simulated operational environments. TRL 8-9 correspond to prototype and demonstration stage in operational environment through to system proving via successful deployment.

The main objectives of tests in concept validation stages (TRL 1-3) are to validate the OWT concept, to investigate OWT variables and physical properties that affect the performance or energy capture, and to optimize the OWT for power production using small scale models. The scale range in this stage is typically between 1:80 and 1:150.

The main objectives of tests in the design validation stage (TRL 4-5) 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. If known, the wind/wave spectra at a specific site should be used. The scale range in this stage is normally between 1:40 and 1:80, however smaller scale models may be used to investigate survivability in extreme wave conditions.

Tests in the system validation stage (TRL 6-7) are carried out in the scale range between 1:20 and 1:40, while tests in the prototype and demonstration stage (TRL 8-9) are typically carried out at large or full scale at sea.

2.2 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 foundation which supports the blades, the Rotor-Nacelle Assembly (RNA) and the tower.

2.2.1 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, typically used in water up to around 25m.
- Multipile: foundation based on multiple piles; tripod structures are also a possible alternative, when the guyed monopile is not feasible;
- Jacket: braced lattice-frame structure typically used in deeper water;
- Gravity base: used when installation of piles in seabed is difficult.

2.2.2 Types of 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, platforms are often categorised as ballast-stabilised (e.g. spars), mooring-stabilised (e.g. TLP) or buoyancy stabilised (e.g. barges or semi-submersibles).

2.3 Types of facilities suitable for use

Different facilities can be used at different stages of the design process. 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.

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.

2.4 Model parameters and scale

The choice of 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. It may be necessary to build models at different scales to assess performance in operational conditions and survivability in extreme external conditions. Achievable scale will be limited by the model basin dimensions, its wind/wave generation capability, the mooring system to be employed, and the simulation approach for control strategies.

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 of the combination of the rotation of the rotor and the pitching of the platform in waves 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 sea-keeping 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. The maximum drift of conventional offshore structures is usually recommended to be less than 5% of the water depth.

2.5 Uncoupled hydrodynamic tests

In 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 as these loads may be considered independently. This may be particularly relevant for simulation of dynamic responses of the tower and support structure in extreme weather for 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 measurements of wave / current loads from measurement of wind loads may be advantageous due to the fact that 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 flexibility and aerodynamic damping, then inclusion of the aerodynamic coupling due to the rotor is necessary.

Model tests of FOWTs can be carried out without the rotor at a 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.

2.6 Coupled aero-hydrodynamic tests

2.6.1 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 weight should be avoided due to the incorrect inertia of the system. It can only be justified for rough estimation of the maximum mooring offset (e.g. Chujo, *et al*. (2011)).

It is possible that a solid disc may be used in place of the rotor in conjunction with a battery of fans. The disc should be sized to generate a drag load corresponding to the thrust on the turbine. If a rotating disc or a separate rotating arm is employed with the correct rotary moment of inertia, it is possible with the correct moment of inertia, 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 exerted by the rotor on the platform as well as blade / tower interactions; problems may result due to the unsteadiness of the flow around the disc.

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 which 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. Particular care is required in the interpretation of results from this type of test.

2.6.2 Direct simulation of the rotor in fully coupled tests

Direct modelling of an OWT rotor is usually realized by exposing a working 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. This method allows for the most accurate modelling of actual conditions of the rotor operation and is recommended to be used whenever possible.

Particular challenges in this approach with respect to the wind generation include the representation of wind gradients, the 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 naturally be driven by wave effects 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 section 3.1.2.

2.7 Environmental parameters

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

In OWT 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 frequency response as well as testing in irregular sea states with/without turbulent wind appropriate to the intended deployment site in order to estimate performance including dynamic responses.

At 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. The most popular model for the directional spreading is a cosine squared ($\cos^{2s}$) function originally proposed by Longuet-Higgins et al. (1963).

Goda (2010) suggests that the value of s varies with wave frequency, with the largest value s_{max} at the spectral peak frequency, and with the values decreasing for both lower and higher frequencies. For deep-water waves Goda recommends use of $s_{max} = 10$ for wind driven seas, $s_{max} = 25$ for swell with short decay distance and relatively large steepness, and $s_{max} = 75$ for swell with long decay distance and relatively low steepness. These values typically increase in shallower water.

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.

2.8 Mooring Systems

FOWT concepts utilise a range of mooring systems including single point and spread moorings as well as catenary, taut, TLP and multi-element systems. Where detailed design information is available it is important to simulate moorings accurately, since mooring behaviour can impact 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 Recommended Procedures for Floating Offshore Platform Experiments (7.5-02-07-03.1). In the case of FOWTs using catenary moorings, the footprint size at the scale resulting from the maximum capability of the wavemakers 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, a truncated system or a hybrid modelling approach is required (e.g. Kraskowski (2012)). Guidance on the use of a hybrid mooring system may be found in ITTC Recommended Procedure 7.5-02-07-03.4 *Stationary Floating Systems Hybrid Mooring Simulation*.

2.9 Test Case Parameters

2.9.1 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 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 ITTC Recommended Procedure 7.5-02-07-01.1 *Laboratory Modelling of Multidirectional Irregular Wave Spectra*.

2.9.2 Survivability Limit State test

Before undertaking sea trials, it is important to conduct survivability (normally, extreme condition) tests in model basins, to evaluate the seaworthiness of an OWT including hull structure and mooring system. The survivability 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, shut-down 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 ITTC Recommended Procedure 7.5-02-07-02.3 *Experiments on Rarely Occurring Events*.

Survivability 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 for which the most dangerous wave direction with respect to mooring loads can be reliably identified.

Where appropriate the OWT should be tested both in the fully un-damped condition and in the fully parked condition in order to simulate typical failure scenarios which could result in excessive body motions.

2.9.3 Fatigue Limit State test

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

2.9.4 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.

3. DESCRIPTION OF TEST PROCEDURE

3.1 Model & Installation

3.1.1 Platform Model

Guidance on preparing the model of a FOWT platform including model geometry, ballasting and loading can be found in the ITTC Recommended 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 offshore platforms due to the extreme sensitivity of draught to 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 draught 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 design stage, so as to minimize the need of ballasting the finished model.

3.1.2 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 and towers are constructed; for flexible models it is important to scale the material properties correctly to achieve the correct elastic behaviour at model scale. Particular attention should be paid to the design of moving parts with minimal static and dynamic friction in order to limit uncertainty related to extrapolation, since frictional forces will not be scaled correctly according to Froude similitude.

The model should be equipped with a damping unit that simulates the characteristics of an actual OWT RNA system. As the experimental stage advances from the concept validation stage to the design validation stage, the model scale increases and a more sophisticated RNA simulator should be used.

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, since 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 very much greater than that 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. Other challenges for simulation of rotor behaviour include the representation of the blade pitch control system.

3.1.3 Moorings & Foundation

In the measurements of foundation 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.

3.1.4 Installation

Model preparation and installation should follow the principles set out in ITTC procedure 7.5-02-07-03.1 *Floating Offshore Platform Experiments*. 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.

3.2 Calibration of Environment

Details of the calibration of environment parameters can be found in the ITTC

Recommended Procedure 7.5-02-07-03.1 *Floating Offshore Platform Experiments*. In testing offshore wind turbines including direct modelling of the rotor, particular attention must be paid to correct representation of the wind field, which should be measured prior to main experiments and documented.

3.3 Collection and analysis of data

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

3.3.1 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.

3.3.2 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 sub-set 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 Complexity – simplified, system, component.
- iii) Model function/operation
- iv) Model installation: Mooring, Foundation and constraints
- v) 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, number of channels, sequential or simultaneous sampling, noise levels/floors

h) Data Analysis
i) Date calibrations and corrections – bias errors, blockage corrections, Zeroes or Tares,
ii) Normalizations
iii) Statistical Analyses; Steady v dynamic studies
iv) Uncertainty analyses

3.4 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 section 2.5. Reproduction of its damping characteristics, inertia and angular momentum is recommended whenever possible; the characteristics of 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:

Sensitivity of the motion response characteristics to mass distribution and, on the other hand, limited possibility of adjusting the mass distribution;

Sensitivity of the response characteristics to the accurate installation of FOWTs' scaled models including the mooring system with anchors ;

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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