LIFES50+

Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m

Project acronym	LIFES50+
Grant agreement	640741
	Collaborative project
Start date	2015-06-01
Duration	47 months

Deliverable D7.9 Guidance and Recommended Methods for Hybrid/HIL-based FOWT Experimental Testing

Lead Beneficiary	SINTEF Ocean
Due date	2019-02-28
Delivery date	2019-03-20
Dissemination level	Public
Status	Final
Classification	Unrestricted

Keywords	Real-Time Hybrid Model testing, HIL, wind tunnel, ocean basin, experimental methods
Company document number	Click here to enter text.

The research leading to these results has received funding from the European Union Horizon2020 programme under the agreement H2020-LCE-2014-1-640741.

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Document information

Version	Date	Description	
0.1	2019-03-08	Advanced Draft	
		Prepared by	Maxime Thys, Alessandro Fontanella, Federico Taruffi, Andreas Manjock, Marco Belloli
		Reviewed by	Petter Andreas Berthelsen, Kolja Müller and Ricardo Faerron Guzmán
		Approved by	Enter names
1.0	2019-03-20	Final version for QA before submission	
		Prepared by	Maxime Thys and Marco Belloli
		Reviewed by	Jan Arthur Norbeck
		Approved by	Petter Andreas Berthelsen
		In order to enter a new version row, copy the above and paste into left most cell.	

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Definitions & Abbreviations

ABL	Atmospheric Boundary Layer
AST	Administrative Support Team
DAQ	Data Acquisition System
DOF	Degree Of Freedom
HIL	Hardware-In-the-Loop
ITTC	International Towing Tank Conference
FOWT	Floating Offshore Wind Turbine
PC	Project Coordinator
PIL	Processor-In-the-Loop
PM	Project Manager
QoI	Quantity of Interest
ReaTHM	Real-Time Hybrid Model
SIL	Software-in-the-loop
WPL	Work Package Leader

Executive Summary

Model testing is an important step in the design process of floating offshore wind turbines and is used for global and partial system verification and characterisation, validation of numerical models, and estimation of extreme loads and responses.

Model testing in hydrodynamic facilities with focus on hydrodynamics only can be used for component testing, marine operations, and partial system identification where simplifications have to be assessed carefully. Model tests in wind tunnels have traditionally been used for understanding complex aerodynamic phenomena at the wind turbine level like dynamic stall and 3D rotational effects, but also at a larger scale like the wake interference for wind turbines operating in array configurations typical of wind farms or for the development of advanced control logics at the level of the wind farms.

For global system verification, validation of numerical codes, system characterisation and estimation of extreme loads and responses, it is advised to model the FOWT as closely as possible. Due to the challenges related to generation of high-quality wind and waves, scaling incompatibility and model construction limitations, the real-time hybrid or HIL approach for performing true-to-scale model testing with FOWT is appealing. Two alternatives are possible: 1) Performing HIL model tests in a wind tunnel with a physical wind turbine connected to a 6DOF actuators controlled by real-time simulations of the floater subject to hydrodynamic loads, or 2) performing real-time hybrid model tests in an ocean basin with a physical model of the FOWT, without the rotor geometry, coupled to a force actuator controlled by the simulated aerodynamic loads. The terms HIL testing, as used by Politecnico di Milano, and Real-Time Hybrid Model testing, as used by SINTEF Ocean, refer to the same testing method coupling experiments and simulations in real-time.

The main advantages of performing HIL model tests in a wind tunnel over full physical model tests in an ocean basin is the increased control over the wind field. HIL model test in a wind tunnel can be used in open-loop (i.e. forced motion) for calibration and validation of aerodynamic models, and in closed-loop mode (measured aerodynamic loads are used as input to the numerical model) for preliminary tuning of the wind turbine controller if performed before ocean basin tests. Advanced tuning of the wind turbine controller can be performed if the numerical model for simulating the platform dynamics has been calibrated previously. A redesign of the model scale wind turbine controller is required due to the differences between the wind turbine characteristics (mass and aerodynamic) at model and prototype scale. Generation of turbulent wind can be required for advanced tuning of the controller due to its influence on the behaviour of the FOWT, see Goupee et al. (2014).

Real-Time Hybrid Model tests in an Ocean Basin enables testing of FOWT. The limitations of classical physical tests due to scaling issues, model construction, and wind generation are removed allowing to test with a true-to-scale model, under realistic environmental conditions (irregular waves with turbulent wind). Real-Time Hybrid Model tests of FOWT in an ocean basin can be used for final system verification, which requires modelling of the complete system, as well as system development such as controller tuning. Validated numerical models for the calculation of the aerodynamic loads are required. Additionally, the tests can be used for calibration of hydrodynamic models.

The following procedure is recommended when performing hybrid/HIL model tests with a FOWT in a wind tunnel and an ocean basin.

1) Perform HIL wind tunnel tests for the validation of the aerodynamic model that will be used in the ocean basin tests. For the verification, wind tunnel tests with realistic platform motions are necessary.

2) The second step consists of using the previously validated aerodynamic model and use it for hybrid model tests in an ocean basin. The tests are used for calibration of the platform and hydrodynamic model as well as for final verification.

Ideally, additional iterations of the process would be preferred but could be difficult to realise since costly and time taking. Note that the recommended approach described above is close to the approach followed in the Lifes50+ project.

Contents

1 Introduction

Model testing of floating offshore wind turbines (FOWT) requires competences in hydrodynamics and aerodynamics, but also in structural and control engineering. This large range of required competences makes model testing of floating wind turbines challenging. The recommendations and guidelines for floating wind turbines should be based on information available in each separate field, as well as additional information required when combining these fields.

The present document is intended to give guidelines and recommendations for model testing of floating wind turbines, with special emphasis on the HIL/hybrid test methodology used when performing the ocean basin and wind tunnel tests in the LIFES50+ project[1].

Chapter 2 details current practice when performing model tests with a FOWT in a hydrodynamic facility with focus on the hydrodynamics only, i.e. without aerodynamic loads. The same is done in chapter 3 but for aerodynamic testing facilities with focus only on the aerodynamic loads. Guidance specific to performing hybrid/HIL model tests is given in chapter 4, while existing guidelines and recommendations are reviewed in chapter 5. In the conclusion, it is detailed how to perform model tests with a FOWT by making optimal use of hydrodynamic and aerodynamic testing facilities.

1.1 A note on terminology

In marine technology, several names have been used in the past to refer to model testing techniques where a physical substructure was coupled to a numerical substructure, such as Hardware-In-the-Loop testing (Bayati et al., 2013), Real-Time Hybrid Model testing (Sauder et al., 2016), or Software-In-the-Loop testing (Azcona et al., 2014). These three different terms refer to the same technology. A short overview of the origin of the different terms is given below. In this document, hybrid/HIL is generally used for consistency and to refer to the terminology used by SINTEF Ocean and Politecnico Di Milano.

The term *hybrid testing* or *hybrid simulation* is used in seismic engineering. It refers to experiments where the physical building is replaced by a numerical model while only a part of the building is excited physically by use of actuators.

Hardware-In-the-Loop (HIL) testing is a generic term referring to coupling physical and numerical subsystems. Traditional applications of HIL testing are found within the field of electronics and control engineering where it is used in the development and test of complex real-time embedded systems. In any HIL simulation, a single component (physical with its control software) interacts with a mathematical representation of the dynamic system of which it is part. The *Software-In-the-Loop (SIL)* phase is a development phase towards the HIL phase, where a control software is verified by making it interact directly with an emulation of the system on which it has to act, i.e. no hardware is involved as in HIL.

(Sauder, 2018; Sauder et al., 2019) use the term of *Cyber-Physical Empirical Methods* for their work in the field of systems and control and use the following definition: *Cyber-physical empirical methods are empirical methods in which the dynamical system under study is partitioned into physical and nu-*

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[1] www.lifes50plus.eu

merical substructures. The behaviour of the physical substructures is partly unknown, while the numerical substructures are described by validated computational models. The substructures interact with each other through a control system.

The term HIL testing has been used by Politecnico de Milano, to emphasize the coupling of a physical component with a numerical one. SIL testing is used by Azcona et al. (2014), to emphasize the inclusion of a software (or numerical model) in a fully physical system.

Starting from the terminology in seismic engineering, the terminology of *Real-Time Hybrid Model (ReaTHM®*[2]*) testing*, was chosen by SINTEF Ocean for applications in marine engineering. The term *Real-Time* is added to stress the fact that the involved simulations must run in Froude-scale real-time, while *Model testing* was added to emphasize the connection to classical model testing (Sauder, 2018). The new terminology used by SINTEF Ocean was driven by two main differences with the traditional applications of HIL testing: 1) In HIL testing, one traditionally starts from a numerical system, where a physical subpart is included, while it is the opposite in this case. In this sense SIL is more appropriate but it conflicts with the name given to a phase in the development of HIL testing. 2) The design of the interface between substructures to ensure high fidelity becomes a main challenge in our applications, while it was secondary for traditional applications (electronic or electrical quantities are far less challenging to measure/actuate)

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[2] ReaTHM for Real-Time Hybrid Model is a registered trademark of SINTEF Ocean.

2 Hydrodynamic testing of FOWTs

Hydrodynamic testing of offshore structures is current practice in the offshore industry, recommended by several guidelines[3], and often required by classification societies[4]. Model testing can be used to verify/document the following items, as listed in Section 10.2 of DNVGL-RP-C205 and which are also relevant for FOWTs:

1. hydrodynamic load characteristics,
2. global system concept and design verification,
3. individual structure component testing,
4. marine operations, demonstration of functionality,
5. validation of numerical models, and
6. estimation of extreme loads and response.

Although accuracy and computational speed of numerical models is rapidly improving, model testing offers a mean to study systems involving phenomena that are either unknown or difficult to capture by simulations and that therefore need to be studied and verified experimentally. Some of these phenomena are:

- impact loads such as slamming.
- excitation of structure by non-linear wave loads (e.g. sum frequency loads can excite resonant oscillations and difference frequency loads are important for the design of mooring systems).
- viscous loads (e.g. drag and moon-pool motions).

Next, the six items listed as purpose for model testing of offshore structures are considered and applied to model testing of FOWT to give an overview of the required procedures. For global system concept and design verification and estimation of extreme loads and response (see points 2 and 6 above), it is advised to model the system as closely as possible. For FOWT this means including aerodynamic and hydrodynamic loads, which is discussed in Chapter 4.

For validation of hydrodynamic codes and identification of hydrodynamic load calculations (points 1 and 5 above), one could consider different simplifications for the modelling of the rotor loads such as by neglecting the aerodynamic loads and modelling the rotor as a point mass (Ishihara et al., 2007), by modelling the mean aerodynamic thrust by use of a mass connected with a line and through a pulley to the model top (Chujo et al., 2011), or by modelling the mean aerodynamic thrust by use of a drag disk with fans blowing wind on the disk (Ishihara et al., 2007; Roddier et al., 2010). Simplification in the tests should be assessed due to the coupling between the aerodynamic and hydrodynamic loading, e.g. the mean pitch angle due to the rotor thrust will affect the hydrodynamic characteristics of the system. The acceptable level of simplification will therefore depend on the degree of coupling between the aerodynamics and hydrodynamics. Realistic modelling of the complete system is therefore also advised, as presented in Chapter 4.

For individual structure component testing (point 3 above), pure hydrodynamic tests without coupling to the aerodynamics can be used to determine the loads and hydro characteristics such as added mass

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[3] Recommended by DNV-RP C205, which provides rational design criteria and guidance for assessment of loads on marine structures subjected to wind, wave and current loading. Also recommended in DNVGL-RP-0286 which gives guidance for modelling, loads analysis and model testing of the floating offshore wind turbines.

[4] DNVGL-OS-E301 is the offshore standard for position mooring system, where it is stated that "All mooring designs need to be validated towards relevant model test data or full-scale data". For offshore wind turbines, DNVGL-ST-0119 states: "2.6.2.1 For novel designs, model tests shall be carried out".

and damping coefficients, of parts of the structure such as drag plate or column. Tests where the component is fixed and subject to waves or forced motion tests in calm water and waves can be considered. For these types of tests, use can sometimes be made of facilities with smaller dimensions, but care should be taken by evaluating the wave generation capabilities of the structure and its reflection with the tank walls. As shown by Faltinsen (1993), the tank walls can have a significant influence on the mean wave drift forces of floating structures, and to a lesser extent on the linear wave effects, since the mean wave loads are proportional to the square of the incident wave amplitude. For forced motion tests, the stiffness of the structure supporting the hexapod (or other type of actuator) is important to avoid any interference. A natural frequency between 5 and 10 times higher than the frequencies of interest is suggested. Precise synchronisation of the actuation and measurement system is required for post-processing of the experimental results to separate acceleration and velocity dependent components.

Apart from hydrodynamic testing of offshore structures in installed conditions, it is also possible to perform model tests for marine operations such as installation of FOWT (see point 4 above). Marine operations benefit from model tests where complex phenomena due to viscosity, wave-current interaction, interaction between floating bodies, and shallow water effects can be important and are typically difficult to simulate accurately.

3 Aerodynamic testing of FOWT

Scale model testing complements full-scale field testing in the study of floating offshore wind turbines in many aspects. The design of wind turbines strongly relies on mathematical models and numerical tools that are used to simulate the system response to the environmental conditions of interest. The quality of the design resulting from this process is strictly connected to the fidelity of the used simulation tools, hence validation and verification of these instruments is a critical task and it must be relied on high-quality data (van Kuik et al., 2016). Scale model testing provides data required to fulfil the above-mentioned requirements, reducing costs, time and widening the variety of dynamic conditions that are investigated in a fully controlled environment. Wind tunnel testing of wind turbine scale models has always been a fundamental tool for the development of innovative control logics (Bottasso et al., 2014).

In the wind energy field, it is possible to find different examples of wind tunnel tests of wind turbines and many of these are related to the investigation of complex aerodynamic phenomena to which the rotor is subjected. An exhaustive review of the results achieved in the last 30 years studies is presented in (Vermeer et al., 2003). NASA wind tunnel experiments on a 10 m diameter rotor (see Hand et al. (2001) and Simms et al. (2001)) and MEXICO experiments (see Snel et al. (2009) and Schepers and Snel (2007)) on a 4.5 m three blades rotor generated a large database that is still used to deepen the understanding of complex aerodynamic phenomena like dynamic stall and 3D rotational effects. Measurements shared among the projects participants also represent an invaluable benchmark for numerical codes calibration and validation.

Later experiments focused on the investigation of other phenomena, like the wake interference for wind turbines operating in array configurations typical of wind farms (Adaramola and Krogstad, 2011; Bartl et al., 2012; Krogstad and Adaramola, 2012; Medici and Alfredsson, 2006)

More recent wind tunnel experimental campaigns, as part of different national and international research projects, are aimed at developing advanced control logics for optimizing power extractions in wind farms (Campagnolo et al., 2016; Schreiber et al., 2017; Wang et al., 2017)

4 HIL or Real-Time Hybrid Model testing of FOWT

Performing scale model experiments on FOWT requires to simultaneously reproduce, at model scale, wind and wave loads, gravitational and buoyancy forces, mooring lines dynamics and the flexible response of the wind turbine blades and tower. Past experiences have shown that is not possible to achieve satisfactory results by scaling the floating system starting from a single similitude law. Ocean basin tests are traditionally based on Froude scaling: in any condition, the model and full-scale system are characterized by the same Froude number, given by

$$Fr = \frac{U^2}{gL} \tag{1}$$

where U is the wind speed, g the gravity constant and L an arbitrary length. This scaling approach is preferable for ocean basin tests since it leads to a unity scale factor for accelerations and allows to correctly model gravity-dependent loads. The common wind tunnel practice tries instead to approach Reynolds scaling, and have the same Reynolds number (see Equation 2) for the model and full-scale system. This would ensure scaled flow conditions for the system object of the experiments.

$$Re = \frac{\rho U L}{\mu} \tag{2}$$

where ρ and μ are, respectively, the air density and dynamic viscosity.

The Reynolds number scale factor λ_{Re} for different combinations of length scale factor λ_L and velocity scale factor λ_v is shown by the surface of Figure 4-1 (the scale factor for the generic quantity X is defined as the ratio between a given quantity evaluated at prototype and model scale, $\lambda_x = X_p/X_m$). All values of λ_{Re} are greater than one, thus any combination of λ_L and λ_v results in a Reynolds number for the scale-model lower than for the full-scale system. When Froude number similitude is required, being the gravity constant g fixed for the model and full-scale systems, the velocity scale λ_v directly depends on the length scale λ_L according to Equation 3, represented in Figure 4-1 by the red line.

$$\lambda_v = \sqrt{\lambda_L} \tag{3}$$

If Reynolds similitude is required, being the air (or other fluid) properties the same for the model and full-scale systems, the velocity scale is function of λ_L only, as shown by Equation 4, that corresponds to the yellow line of Figure 4-1.

$$\lambda_v = 1/\lambda_L \tag{4}$$

The incompatibility between Froude and Reynolds scaling is evident and this conflict sets a major constraint for experiments that require to physically scale the complete floating wind turbine. If Froude scaling is used, length scale factors between 35 and 60, required to fit a multi-megawatt wind turbine in a common testing facility, lead to a velocity scale factor between 6 and 8 and a Reynolds number that is between 200 and 470 times lower than the one experienced by the full-scale system. This is problematic for scaling of the wind turbine rotor (de Ridder et al., 2014) and for the correct reproduction of aerodynamic loads in traditional ocean basin tests. Hybrid/HIL experimental methodologies were proposed as a potential solution to the Froude-Reynolds conflict, making possible to correctly reproduce the FOWT aerodynamics and hydrodynamics in scale model experiments. Additional and equally important challenges that are overcome by use of hybrid/HIL testing are challenges related to the environmental modelling (wind in the ocean basin, waves in the wind tunnel), and space constraints.

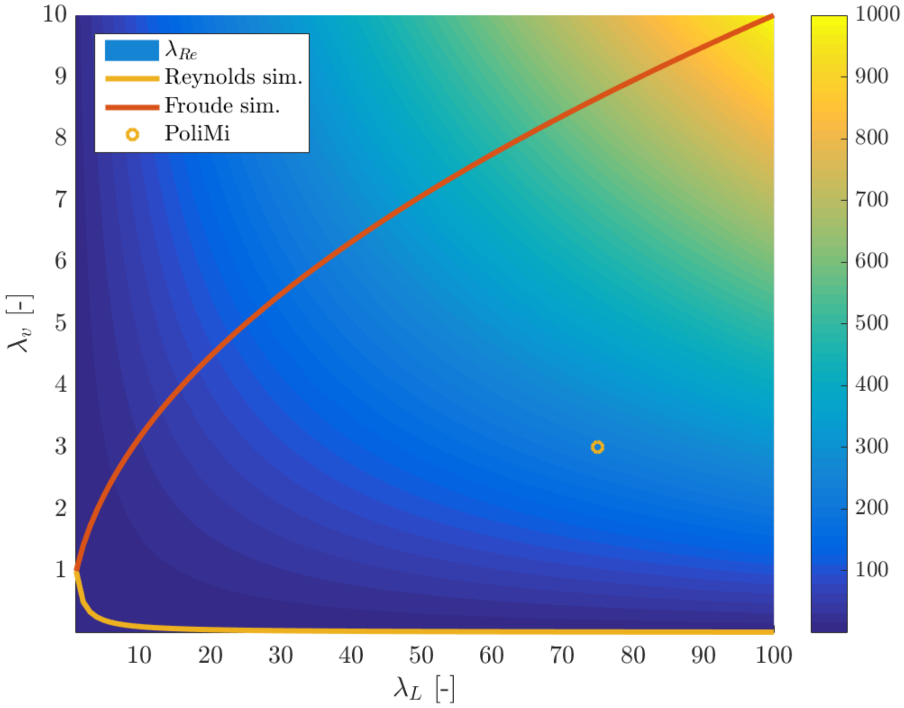

Figure 4-1. Reynolds number reduction factor for different scaling procedures. Froude similitude with a length scale λ_L between 35 and 60 is typically used for model testing of FOWT in hydrodynamic facilities. The yellow circle indicates the Reynolds number reduction used for the L50+ HIL model tests, where the length scale λ_L and velocity scale λ_v were set independently, see Section 4.3.1.

Real-Time Hybrid Model (ReaTHM) testing or Hardware-In-the-Loop (HIL) testing is based on the approach that the physical system under study is divided in different substructures, where some of these are kept physical while others are simulated. These substructures interact in real-time with each other through interfaces. One of the major difficulties with hybrid testing is that a significant amount of mechanical power is transferred between the substructures and that the interfaces should not influence the behaviour of the complete system.

For real-time hybrid model testing of floating offshore wind turbines, there will typically be two substructures, one physical and one numerical[5], where one is aimed at the hydrodynamic part of the system and the other at the aerodynamic part of the system. The communication between the interfaces happens by sensing (force or motion sensing) and actuation (force or motion actuation).

Two options for actuation and sensing exist for each substructure, either controlled in position with force sensing, or force controlled with position sensing, where the dynamic relationship between force and position, velocity and acceleration is conserved. In Bayati et al. (2013) a physical motion controlled substructure is coupled to a numerical force controlled substructure, while the opposite was used in Sauder et al. (2016).

In the numerical substructure, both force and motion control are usually possible while force control is a preferred method for finite element methods. In the physical substructure, sensing motions and forces does not pose any significant challenge while controlling loads or motions is quite different.

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[5] Note that two physical substructures could also be coupled (e.g. a wind tunnel and an ocean basin) for distributed hybrid testing, as long as the model-scale time is the same in both substructures.

The actual choice of motion or force control in the physical substructure will be governed by the following factors:

- **Objectives of the tests.** How will the choice of actuation method influence the quantities of interest in the tests? One of the governing factors is the importance of inertial over restoring loads**:** Correct actuation of inertial loads by motion control requires correct modelling of accelerations which is challenging. On the other hand, correct actuation of restoring loads requires correct modelling of positions, which is more easily achieved by position-controlled actuators.
- **Actuators:** Off-the-shelf actuators are usually designed for position or velocity control, making motion control more straightforward.
- **Constraints from the physical testing facility and safety issues:** Is the space taken by the actuators a constraint? Is the system physically stable when actuators are turned off?

For hybrid/HIL model testing of a FOWT in a hydrodynamic facility, the hydrodynamic loads are physical while the aerodynamic loads are numerical, while the opposite will be true for hybrid/HIL model testing in a wind tunnel. What is left to be defined is the actuation system in the physical substructure, and in which substructure to include the mooring loads and the inertial loads due to the floater, tower, and rotor. For both setups (wind tunnel and ocean basin), it is advised to have as much as possible of the system modelled physically, if accurate.

The main objective for the LIFES50+ ReaTHM tests in the Ocean Basin (Thys et al., 2018) was the correct modelling of hydrodynamic loads and global dynamic response of a FOWT, which is assumed mostly inertia dominated. The following two choices were made due to the importance of correct modelling of the inertial loads: 1) The inertias of the complete system were modelled physically (which was possible due to the large size of the ocean basin) and 2) force control in the physical substructure was chosen to obtain physical inertial loads. Position sensing had to be used as input to the numerical substructure.

For the LIFES50+ HIL wind tunnel tests motion control was used for the physical substructure, due to 1) Space limitations for the actuation system and the possible instability of the experimental substructure since hydrostatic restoring loads are numerical. 2) The main quantity of interest not being the dynamic response but rather the aerodynamics, which require a correct modelling of velocity and position but not of accelerations. Force sensing had to be used as input to the numerical model.

4.1 Design of Hybrid/HIL model tests method

To perform model tests, one needs a testing facility, a physical model, sensors, and a data-acquisition system. For real-time hybrid model tests, on top of the previously needed elements, one also needs a numerical model, actuators, a control system and a real-time compatible instrumentation (sensors and DAQ).

The main steps in the design of a hybrid/HIL model test method for a floating offshore wind turbine subject to wind, waves, and current are the following:

1) **Define objectives:** Define the purpose of tests and select the quantities of interest (QoIs), e.g. platform motions, mooring line tensions, loads at base of tower, loads at wind turbine blade root, etc, that need an experimental analysis under defined conditions (frequency range and environmental conditions).

2) **Select type of facility:** Based on the QoIs, selection of a testing facility (wind tunnel, wave basin, …) such that the main QoIs are physical.
3) **Define actuation envelope requirements**: Based on numerical simulations, define the actuation envelope requirements for motions and loads, at the different locations where the interface between the two substructures is considered (Hall et al., 2018).
4) **Define performance requirements for coupling**:
   - Based on numerical simulations for a selected set of load cases (Hall et al., 2018) or based on more advanced methods using surrogate models (Sauder et al., 2019), define the permitted tolerance on motion and force tracking, as well as system bandwidth and latency.
   - Perform numerical simulations to study the sensitivity to limited actuation, where the effects of not including some components of the simulated loads or motions is studied, similarly as what is done in Bachynski et al. (2015) for real-time hybrid model tests in the ocean basin.
5) **Define the control method (motion or force) b**ased on the information collected in 1) to 4) above.
6) **Define the interface and robot** based on the information collected in points 1) to 5) above. Set the location of the interface between the substructures and design/select the actuator.
7) **Select tool for numerical substructure.** Selection of the appropriate simulation model for the numerical substructure based on a balance between accuracy and the real-time requirements.
8) **Develop the hybrid setup:** Use standard approach towards development of hardware in the loop, starting from model in the loop, then software in the loop and processor in the loop and finally hardware in the loop[6] for stepwise development of the hybrid setup. At early phases, different parts of the hybrid/HIL testing setup (e.g. verification of the numerical substructure, actuator control, etc) may be developed in parallel. They should then be merged at the hardware-in-the-loop phase for a verification/validation of the complete system.
9) **Validate the hybrid setup:** The same tools as in the development phase may then be used for validation of the hybrid setup by modelling limitations and uncertainties and looking at their effects on the QoIs.

Once the hybrid /HIL method is defined, the planning of the experiments for the FOWT can be continued similar to what is done for classical model testing techniques. Section 4.2 is about model testing of FOWT in a hydrodynamic testing facility and Section 4.3 for model testing of FOWT in an aerodynamic testing facility.

4.2 Wave basin testing

4.2.1 Planning of wave basin experiments

The first step in the planning of experiments is the definition of objectives. What is it that you want to test and what do you want to get out of the experiments?

Once the objectives are defined, the following need to be determined: testing facility and actuation system, scale, details about physical and numerical model, and environmental conditions.

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[6] https://se.mathworks.com/help/physmod/simscape/ug/what-is-hardware-in-the-loop-simulation.html

Selection of the testing facility[7], if applicable, will happen simultaneously with the choice of the scale. When selecting the facility, the following should be considered:

- Dimensions of the facility and its influence on the scale and therefore the modelling and measuring accuracy, and
- The quality of the environmental modelling (e.g. amount of wave reflection, tank sloshing modes, and other parasitic waves).
- The system for actuation of the aerodynamic loads since this is typically proposed by the testing facility. Different actuation systems exist, such as cable-driven parallel robot (Chabaud et al., 2018; Sauder et al., 2016), active single fan (Azcona et al., 2014), and active multiple fans (Battistella et al., 2018; Meseguer and Guanche, 2019). Characteristics that should be looked at are actuation time, force tracking, and disturbance rejection.

Usually, Froude scaling[8] is used in hydrodynamic testing facilities to ensure a consistent balance between gravity and inertia loads, in order to model correctly free-surface water waves and resulting hydrodynamic loads. The scale is selected based on the following considerations:

- Wave and current capabilities of the testing facility (maximum values but also optimal range)
- Wind and rotor loads: Specification of the actuators (optimal range of operation regarding load and frequency) and real-time constraints on the numerical simulation model used in the numerical substructure[9].
- Dimensions of the testing facility for mooring system and water depth.
- Measurement accuracy. It is usually recommended to avoid scales below 1/60.
- The size and mass of the model should be large enough to accommodate for the weight of necessary instrumentation.
- Scale should be compatible with the modelling of structural flexibility (if applicable)
- If Froude scale is used, the scale should be selected such as to minimise the difference in viscous effects (which are dependent on Reynolds scaling) between model and prototype scale. In some cases, the drag coefficient is only slightly dependent on the Reynolds number (e.g. due to sharp edges, large turbulence or the possibility to use trigger wires). In other cases, the scale coefficient can be chosen to obtain a similar drag coefficient at model scale as at prototype scale, although at different flow regimes. Other measures can be taken in the case the drag coefficient is different between both scales, such as artificial increase of geometrical dimensions.
- The cost for model construction and testing. Larger scales will usually come at higher model construction costs, as well as longer testing times.

The flexibility of floating wind turbines is increasing in importance with their increasing size. The tower 1st fore-aft flexible mode should be modelled during the model tests in accordance with the definition of the QoIs and the system bandwidth. First and second fore aft resonant modes have been modelled for model tests with bottom fixed wind turbines due to possible excitation by higher order wave components. Higher than first order modes have not been considered so far for FOWT since floaters

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[7] See LIFES50+ deliverable D 7.4 State-of-the-Art FOWT design practice and guidelines, Section 5.1 for an overview over hydrodynamic testing facilities that have proven their testing capabilities for floating wind turbines.

[8] http://www.ivt.ntnu.no/imt/courses/tmr7/lecture/Scaling_Laws.pdf

[9] For physical wind: Acceptable area for wind generation, wind speed, and turbulence intensity (maximum value and optimal range).

have usually been assumed as stiff and therefore the contribution of wave excitation not important. For larger systems, advanced models including more modes and flexible substructures are of interest.

The aerodynamic loads on the rotor are part of the numerical substructure. Additional loads related to the rotor are mass loads (inertia and gravity) which can partly be physical and numerical. For the LIFES50+ tests, the rigid-body mass loads were modelled physically through added mass at the tower top and the elastic inertial loads (from blades) and gyroscopic loads were modelled numerically. Care must be taken to avoid double count.

Simulations can typically be run at full scale following the model scale time, where input and output to the simulation model need to be scaled.

The aerodynamic loads on the wind turbine tower should be included, to a minimum when performing tests with the wind turbine in parked condition. Whether or not including the flexibility of the blades in the numerical model should be decided based on results from sensitivity analysis.

Load case selection for concept validation is best done by use of numerical simulations for screening of the most interesting environmental conditions, based on environments prescribed in the design load conditions. Load case selection should also be based on requirements for the study of underlying phenomena such as complex hydrodynamic loads and coupling effects with aerodynamics. Further details about the selection of the load cases can be found in the recommended practice DNVGL-RP-0286 "Coupled analysis of floating wind turbines", Section 7.4 Test Program and Documentation.

4.2.2 Model construction and Instrumentation

The physical model used in the physical substructure is scaled according to Froude scaling. Mounting of instrumentation on the model should be considered as soon as possible, to ensure adequate mounting options for the instrumentation as well as to account for the instrumentation mass. A major challenge for constructing floating wind turbine models is related to the mass of the instrumentation at the nacelle. The correct elevation of the mass centre of the model is an important characteristic for floating wind turbines and should be taken care of already at the design phase. The use of hybrid testing removes the need for a physical rotor with drivetrain and pitch actuation mechanism at the nacelle making it easier and possible to achieve the required mass distribution.

The flexibility of the tower can be modelled by use of a soft element at the base of a relatively stiff tower, or by use of a flexible tower.

Procedures for scaling of mooring systems are well established from the experience in the oil and gas industry. A scaled model of the mooring system is usually constructed to reproduce the non-linear behaviour of the mooring system. Active or passive truncation can be used when the basin dimensions do not allow for a complete mooring system[10]. The complex behaviour of polyester mooring systems is difficult to model, and the behaviour of the system is often simplified to a static non-linear restoring curve.

Subject to changes depending on the specific objectives of the test campaign, the following minimum instrumentation is advised:

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[10] See ITTC Recommended Procedures and Guidelines: Active Hybrid Model Tests of Floating Offshore Structures with Mooring Lines 7.5-02-07-03.4 and Passive Hybrid Model Tests for Floating Offshore Structures with Mooring Lines 7.5-02-07-03.5.

- Mooring line tensions at fairlead
- Floater position in 6DOF and acceleration in 3 directions
- RNA position in 6DOF; acceleration in 3 directions
- Loads at base of tower
- Current measurement at 2 locations during calibration without the model (at model location and upstream of model) and 1 location during model testing (upstream only).
- Wave elevation measurement at minimum 3 locations during calibration without the model (at model location, upstream of model and on the side of the model) and 2 locations during model testing (e.g. upstream and on the side of the model)
- Reference time signal for synchronisation of experimental and numerical results (from numerical substructure and from wind turbine controller)
- Specific for hybrid tests: force sensors between each actuator and the model

During model testing of a floating wind turbine, use is often made of a numerical substructure, either for the wind turbine controller only, or for the complete aerodynamic simulation model. The results provided by the numerical substructure should be synchronised with the physical substructure and saved to a common data logging system for possible analysis after testing. Typical values to be recorded are, blade pitch angle, rotor rpm, loads at blade root, wind velocity and wind direction.

Data acquisition for real-time hybrid model tests differs significantly from classical data acquisition in the sense that any time delay should be avoided. Therefore, application of filters should be done with caution, to avoid any introduction of delays in the system during the model tests.

Updating frequencies between the numerical and physical system are governed by the degree of coupling between the two systems. Strongly coupled systems will require high frequency updating rate, while soft coupling will allow for lower frequency update between the two substructures.

4.2.3 Carrying out the tests

The different steps when carrying out the tests are

1) Environmental calibration,
2) In place system documentation (physical and numerical)
3) Wave, wind and current tests

4.2.3.1 Environmental Calibration

Environmental Calibration is performed without the model present in the basin for the calibration of the wave and current environments. The wind field does not need calibration since it is emulated numerically.

4.2.3.2 In-place system documentation (physical and numerical)

The system documentation tests are often referred to as the most important tests in a model test campaign. These tests are used for in-place verification and documentation of the hybrid setup, as well as of the basic properties of the system (e.g. mooring stiffness and calm water decay periods and damping). Note that in-place is stressed here due to the possible sensitivity of the hybrid system to the final installation (e.g. stiffness of supports, influence of distance between actuator and model, alignment of actuators).

The two main properties of the force actuation system are force-tracking and disturbance rejection capabilities. Force tracking is the ability of the system to apply a load time series on a fixed object. It can be verified by comparing the commanded and the measured loads measured during tests where the model is fixed and a chirp signal[11] is commanded to the actuators. Disturbances arise from the turbine's motions. Disturbance rejection may then be defined as the ability to apply a prescribed (e.g. constant) load on a moving object. This capability can be verified by performing free decay or wave tests while applying zero loads and by comparing the motions of the platform with and without the actuation system connected to the model. The numerical substructure is verified by comparison to state-of-the-art models.

For documentation of the physical substructure, the following tests are recommended:

- Pull-out tests for documentation of the static restoring characteristic of the mooring system. Note that due to the importance of the pitch and roll motions for a FOWT, it is recommended to also perform pull-out tests in these 2 degrees of freedom (DOFs).
- Calm water decay tests for the documentation of the calm water damping coefficients and natural periods. Due to the large coupling between surge and pitch of floating wind turbines, one could consider new approaches to the traditional manual excitation where the hybrid system is used to excite the generalised modes of motion.
- Current load measurement with fixed model for documentation of the current drag coefficient.

4.2.3.3 Wave, wind and current tests

A stepwise increase in the complexity of the model tests is often suggested when model test results are to be used for numerical calibration. Simplification can then be made on the mooring system by use of a horizontal mooring system allowing tests without hydrodynamic loads on the mooring system, and in the form of environmental decomposition (wind only, wave only and then combined). Longer experiments in the form of seed variations are advised when studying rarely occurring events.

Typical test program would consist of.

- Optional: Model tests with simplified horizontal mooring system. Note that it is then also suggested to perform documentation tests with this simplified mooring system.
- Tests with the moored unit
  - Wind only
    - Constant wind
    - Turbulent wind
    - Decay in constant wind. Tests with an inactive wind turbine controller can also be performed for further simplification of the system.
  - Wave only
    - Regular and pink noise test to document the systems response amplitude operators (RAOs). Only a reduced number of regular wave tests is needed for verification of the results obtained by the pink noise tests. Regular waves can also be used to document the mean drift force. Pink noise tests with different amplitudes can be used to document the non-linearity of the response.
    - Irregular wave tests to study the response of the system to hydrodynamic loading only
  - Current only tests to document the response to current loads.
  - Combined wind, wave, and current tests with wind turbine controller, where different wind turbine controllers may be tested. The use of realistic environmental conditions with irregular seas and turbulent wind is advised.

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[11] A chirp is a signal in which the frequency increases (up-chirp) or decreases (down-chirp) with time.

4.2.4 Evaluation of results

Due to the high complexity of real-time hybrid model tests, it is necessary to have a quality-check procedure to verify the results. During testing, it is for example possible to track the input to the numerical model and the difference (amplitude and phase) between the commanded and the measured loads to be applied by the actuator. After testing, extensive system identification should be performed to model errors at the interface. All errors and uncertainties should be propagated to the QoIs by mean of state-of-the-art aero-hydro-servo elastic numerical models. Probabilistic representations of uncertainties may be considered, see Sauder (2018).

Uncertainty during model testing of complex systems such as floating wind turbines has been studied recently (Desmond et al., 2019; Robertson, 2017), for model tests with physical rotor and hybrid tests, respectively, while the uncertainty for model tests under hydrodynamic loading only is discussed in (Robertson et al., 2018). Uncertainty estimation is a necessary activity during model tests for possible validation of numerical codes.

(Robertson, 2017) found that the uncertainty in hydrodynamic testing facilities due to hydrodynamic loads is minimal and that one should primarily focus on the tests with aerodynamic loads. The tests analysed in this research are with a physical rotor and one of the conclusions is that it is advised to look at hybrid approaches to reduce uncertainty due to the uncertain wind field. (Desmond et al., 2019) looked at the repeatability or precision of hybrid model tests where the aerodynamic loads were applied by use of fans. The repeatability was found to be much better without the aerodynamic loads. (Bachynski et al., 2016) looked at the repeatability of real-time hybrid model tests with a cable driven parallel robot. The repeatability during wind and wave tests was found to be good, with less than 2% difference in the statistical results. Note that only one repetition test was performed, while it is usually advised to perform up to 10 repetitions.

4.3 Wind tunnel testing

Wind tunnel HIL testing methodologies are aimed at investigating the complete dynamics of floating offshore wind turbines, by lowering the uncertainty in the reproduction of rotor loads exploiting high-quality flow conditions. To achieve this goal, the floating wind turbine is divided into two complementary subsystems: the first one, that models the wind turbine aerodynamic and rotor loads, is reproduced by a physical scale model of the wind turbine operated inside the wind tunnel test section. The other subsystem, that is implemented relying on a numerical model, reproduces the floating structure rigid-body dynamics, the hydrodynamic loads due to incident waves and mooring lines response. The floating structure rigid-body displacements and rotations, resulting from real-time integration of the floating system numerical model, are fed to an actuation system that consistently moves the wind turbine scale model.

4.3.1 Planning of wind tunnel tests

The adoption of the HIL methodology relaxes the scaling constraints for the experiment and allows to independently set the length and velocity scale factors. For example, according to the experimental methodology developed at PoliMi, λ_L was fixed to 75 to limit the wind tunnel blockage effect avoiding, at the same time, an excessive miniaturization of the model components. The velocity scale factor λ_v was instead set to 3 to limit the Reynolds number reduction and have reasonable design requirements for the model actuators and for the natural frequencies of aeroelastic components. The other scale factors for HIL experiments were derived from dimensional analysis and are reported in Table 4-1. As shown in Figure 4-1 the combination of λ_L and $\lambda_v$chosen for the PoliMi experiments (yellow ○) leads to a much lower Reynolds number reduction than what would have been achieved with Froude scaling for the same model size.

Table 4-1. Scale factors for the PoliMi WTM.

Scale	Expression	Value
Length	λ_L	75
Velocity	λ_v	3
Mass	$\lambda_M = \lambda_L^3$	75^3
Time	$\lambda_T = \lambda_L/\lambda_v$	25
Frequency	$\lambda_\omega = \lambda_v/\lambda_L$	1/25
Acceleration	$\lambda_a = \lambda_v^2/\lambda_L$	$3^2/75$
Force	$\lambda_f = \lambda_L^2\lambda_v^2$	$75^2 \cdot 3^2$

4.3.1.1 The numerical subsystem

The numerical subsystem models the floating structure response, the hydrodynamic loads and the mooring line dynamics while respecting the hard-real-time constraints required by the HIL methodology. For this reason, it is difficult to use standard codes, commonly employed for the design of FOWTs, but an ad-hoc model should specifically be developed for the application. A set of simplifications may be required to lower the computational resources required for the numerical model real-time integration, without losing the consistency with the physical phenomena. The HIL numerical model should be verified against higher-order models and certified codes considering still-air simulations.

Platform loads include buoyancy, restoring loads, added-mass and hydrodynamic contributions. The general structure of the numerical model is fixed and is not platform dependent. Minor modifications are introduced in the floating platform model in order to accommodate design peculiarities of different platform designs.

Nonlinear mooring line dynamics should be simulated by the numerical model in order to correctly reproduce mooring stiffness, inertia, damping, weight, buoyancy, seabed forces and hydrodynamic drag. Bending and torsional stiffness, as well as seabed friction forces could be neglected in order to lower the lines model complexity. If the simulation of complete mooring line dynamics requires excessive computational resources, quasi-static models can be used. With this kind of model, it is not possible to reproduce structural inertial loads, hydrodynamic line drag, bending and torsional stiffness and three-dimensional shape effects.

The calculation of wave forces can be challenging when performed under the strict real-time requirements of HIL testing. For the LIFES50+ tests, the first and second-order wave excitation forces are implemented as pre-computed time histories stored in multidimensional lookup tables. These are obtained combining the wave spectrum and the complex, frequency-dependent transfer functions resulting from panel code pre-simulation that are run for each platform to be tested.

Viscous loads are generally modelled solving Morison equation and accounting for wave kinematics for the different platform members. If this approach is not feasible, e.g. for the computational effort or the lack of information about the platform members characteristics, a 6x6 quadratic damping matrix is used.

4.3.1.2 The physical subsystem

According to the wind tunnel HIL experimental methodology, the reproduction of wind turbine dynamics is entirely demanded to the physical wind turbine scale model. Whenever the study of the interaction between flexible wind turbine dynamics, controller action aerodynamic and hydrodynamic loads is among the goals for the experiment, the wind turbine model components (usually tower and blades) should be aero-elastically scaled. If the investigation of flexible dynamics is outside the scope of the experiment, a rigid wind turbine scale model can be used.

The choice of having a rigid or aero-elastic scale model has important consequences on the HIL measurement and actuation chain. For the LIFES50+ tests, the wind turbine loads to be fed to the floating platform numerical model were extracted from loads measured at tower base by a 6-components load cell. In particular, wind turbine loads are obtained by subtracting the loads due to inertia and gravity, associated with the wind turbine rigid-body motion, and loads due to flexible dynamics. The first two contributions were discarded through the “force correction” procedure, whereas loads due to flexible dynamics were excluded by filtering the load cell signals. In particular, a notch filter was applied to filter out the harmonic component at the tower 1st fore-aft frequency, whereas a low-pass filter excluded harmonic contributions associated to flexible modes at frequencies above 3P (i.e. tower higher modes and rotor modes).

For a rigid wind turbine model, the wind turbine scale model components are designed to have vibration modes at as high as possible frequencies and to avoid that these could be excited by wind and wave excitation. Having a rigid scale model favors the extraction of wind turbine loads from the tower-base load cell. The cut-off frequency of the low-pass filter and the notch frequency of the notch filter would be at high-enough frequency to avoid distortion of the wind turbine loads in the wave-frequency and low-frequency range. On the other side, a rigid wind turbine model does not obviously allow to directly investigate the floating system coupled aero-servo-hydro-elastic dynamics.

For an aeroelastic wind turbine model, the wind turbine scale model components are designed so that the model vibration modes are a scaled reproduction of those of the full-scale system. In that case, it is possible to investigate the interaction between flexible modes and wind turbine controller or have a realistic estimate of strains and fatigue loads in blades and tower. By equipping the wind turbine model with proper measurement devices, it is possible to include states associated with flexible dynamics to the wind turbine controller.

The adoption of an aero-elastic scale model makes extraction of wind turbine loads from the tower-base load cell measurement more difficult since the effect of the notch and low-pass filters would be significant also in the low-frequency and wave-frequency range. In the case of the LIFES50+ wind tunnel tests, even if wind turbine components were aero-elastically scaled, the HIL setup was not able to reproduce any effect of coupling between platform rigid-body motion modes and wind turbine flexible modes. The harmonic components of wind turbine loads associated with flexible modes were filtered out.

4.3.1.3 Load case selection

Selected HIL test cases include:

- Free decay tests, both in no-wind and laminar wind conditions;
- Pink noise tests, both in no-wind and laminar wind conditions;
- Irregular wave tests, both in no-wind and laminar wind conditions.

Decay tests are performed imposing to a single platform DOF a perturbation with respect to the static equilibrium and allowing the system to move freely. No-wind tests are performed in the 6 DOFs in order to evaluate how the reproduction of the floating system rigid-body dynamics is affected by the HIL methodology. Decay tests are repeated in laminar wind conditions, for different hub-height mean wind speeds, to assess how the natural period and damping of the platform rigid-body motion modes are affected by rotor and wind turbine controller loads.

Pink noise tests are performed in order to assess the non-linear response of the floating system to broad-band hydrodynamic loads. In particular, the excitation provided by wave loads allows to identify the frequency response function for the platform DOFs in the low-frequency range, where platform rigid-body motion modes are found. Pink noise waves are also run for different laminar wind conditions in order to investigate how the floating system response is affected by rotor and control-induced loads.

Irregular wave tests are performed to investigate the response of the floating system to irregular waves for different wave amplitudes and periods. Experiments are performed in still-air and under different laminar wind conditions. From these tests it is possible to evaluate how the platform DOFs response and wind turbine loads change for different wind turbine operating conditions.

4.3.2 Model construction and instrumentation

The physical subsystem of the HIL experimental setup is the wind turbine scale model. The fundamental model dimensions are defined by scaling the full-scale reference wind turbine according to the scale factors defined for the experiment (e.g. those of Table 4-1 for PoliMi tests). Some modifications could be introduced with respect to the ideally scaled parameters to accommodate technological issues as well as to avoid an excessive level of miniaturization of the machine components.

4.3.2.1 Wind turbine model rotor

The wind turbine rotor should be the result of a performance scaling procedure (Bayati et al., 2017), where blades are re-designed to match the full-scale wind turbine aerodynamic performance and aeroelastic response. The aero-elastic optimization procedure should be designed to achieve the reference thrust coefficient, commonly considered of major importance for FOWT dynamics, and the main dynamic properties influencing the blade flexible response.

4.3.2.2 WTM control system

The wind turbine model should have the same control functionalities as the full-scale reference wind turbine. This should make it possible to investigate how control logics impact the platform response, the related instability problems, and measure realistic loads for the wind turbine components.

The coupled FOWT dynamics measured during HIL wind tunnel tests when the wind turbine controller action is enabled are simultaneously set by ideally-scaled terms (e.g. hydrodynamic loads, platform inertial properties, …) that are reproduced by the HIL numerical model and the real properties of the wind turbine model rotor. The wind turbine model rotor mass may exceed the scaled target value due to the use of commercial components required for model actuation (i.e. usually it is not possible to retrieve commercial electronic components that respect the scale factors defined for the experiment) and limitations of the blade manufacturing process. These issues result in a greater rotor inertia that affects the response of the wind turbine drivetrain DOF and the wind turbine control system action.

The FOWT coupled dynamics are also strongly affected by the aerodynamic forcefield generated by the wind turbine rotor. Even if a performance-scaling procedure is put in place to design the model rotor, some differences are expected between the aerodynamic performance of the model and full-scale wind turbine rotor. The aerodynamic forcefield is responsible of the coupled response of drivetrain and platform DOFs. Thus, different rotor aerodynamics may result in an inaccurate reproduction of the full-scale FOWT behavior.

The wind turbine model control logic must then undergo some modifications in order to accommodate the non-ideally scaled properties and achieve, at model scale, the target dynamic response of platform and drivetrain DOFs.

When a wind turbine is coupled with a floating platform, a specific coupling is observed between the drivetrain rigid mode and the floating platform rigid-body motion modes, since this is set by the blade-pitch control logic, drivetrain properties, rotor aerodynamics and the floating platform characteristics. The wind turbine model may not be a perfectly scaled version of the full-scale wind turbine, however, when part of the HIL system, it is implicitly coupled with an ideally scaled floating structure. A pitch control logic tuned for the full-scale system would determine a coupling between rotor and platform modes different from the one achieved for the full-scale system. For this reason, instead of down-scaling the full-scale system gains, it is preferable to search new controller gains to achieve the target coupling between the different FOWT DOFs response. New pitch controller gains should be chosen to minimize the difference between the closed-loop poles of the floating system as simulated in HIL experiments and the down-scaled poles of the reference FOWT. Poles for the two system should be extracted from a linear, or conveniently linearized, model of the floating wind turbine. The model, and the resulting linear dynamics, should describe the rotor and platform DOFs, keeping into account rotor aerodynamics, the wind turbine controller action, mooring lines, hydrostatics and hydrodynamic radiation terms.

4.3.2.3 Instrumentation

The experimental setup should include the following measurements:

- Tower base loads. A 6-components force transducer should be mounted at tower-base, at the interface between the wind turbine scale model and the actuation system tool connection point (TCP). Measured tower base loads include gravitational and inertial loads associated with the wind turbine scale model, rotor loads and the tower aerodynamic drag;
- Tower top loads. A 6-components force transducer should be fitted at the interface between tower-top and the RNA connection flange;
- Platform motions as computed from the real-time integration of the floating system numerical model are the set-point for the actuation system. Effective platform motions could be either measured with appropriate sensor or reconstructed from the actuators actual position signals;
- The three-components scale model accelerations should be measured at tower-top and tower-base;
- Operating data from the wind turbine scale model control system are of fundamental importance. Generator speed, torque and blades-pitch angle should be acquired during experimental tests.

4.3.3 Carrying out the tests

During the tests, the reproduction of loads exerted by the wind turbine on the floating platform relies on the physical wind turbine scale model. In particular, wind turbine loads $\underline{F}_{wt}$ are extracted according to Equation 5 from the measurements of a 6-components load-cell. The sensor should be mounted at tower base and the loads reduction point should be coincident with the (ideal) point where the wind turbine tower is connected to the floating platform.

$$\underline{\boldsymbol{F}}_{\boldsymbol{wt}} = \underline{\boldsymbol{F}}_{lc} - \underline{\boldsymbol{F}}_{corr} \tag{5}$$

Wind turbine loads are obtained subtracting from the overall loads $\underline{F}_{lc}$ the inertial and gravitational load components associated with the wind turbine scale model $\underline{F}_{corr}$. The reproduction of the inertial and gravitational wind turbine loads is entirely demanded to the numerical model. Wind turbine loads computed according to Equation 5 are given by the superposition of different force contributions, as expressed by Equation 6.

$$\underline{\boldsymbol{F}}_{\boldsymbol{wt}} = \underline{\boldsymbol{F}}_{a,rot} + \underline{\boldsymbol{F}}_{a,twr} + \underline{\boldsymbol{F}}_{gyro} + \underline{\boldsymbol{F}}_{m,rot} \tag{6}$$

In particular, $\underline{F}_{wt}$ include the effect of aerodynamic rotor loads $\underline{F}_{a,rot}$, aerodynamic tower loads $\underline{F}_{a,twr}$, gyroscopic moments $\underline{F}_{gyro}$ and mechanical rotor loads $\underline{F}_{m,rot}$. The 6 components of $\underline{F}_{a,rot}$ are given by thrust and non-thrust aerodynamic loads. In presence of a non-null rotor tilt angle, the projection of thrust force according to the tower-base reference frame (where wind turbine loads are measured) results in a surge force, heave force and pitch moment. Aerodynamic tower loads $\underline{F}_{a,twr}$ are due to tower drag that results, when the wind turbine tilt is different from zero, in a surge force, heave force and pitch moment. Gyroscopic pitch and yaw moments $\underline{F}_{gyro}$ are caused by a variation of the wind turbine rotor rotation axis caused by platform yaw and pitch motion, respectively. Mechanical rotor loads $\underline{F}_{m,rot}$ are due to rotor inertia and unbalanced mass distribution.

4.3.3.1 Environmental calibration

The wind tunnel has the capability of reproducing air flows representative of natural wind found in any specific site. The natural wind on the wind turbine rotor is the combination of the approach flow (i.e. the flow approaching the site where the wind turbine is deployed) and near-field flow modifications. Floating wind turbines are generally intended to be deployed in open areas far from the coast, thus the airflow is not significantly dependent from topographic features. Near-field modifications inside any wind farm are mainly set by the upstream wind turbines. The approach flow is usually modelled to be representative of locally stationary atmospheric boundary layer (ABL) condition. Near-field modifications are worth being modeled whenever the goal of experiments is the investigation of the wind turbine performance in array configuration and can be neglected when the behavior of an isolated wind turbine is studied.

In wind tunnel experiments it is common to approximate the natural wind in particular weather conditions with a turbulent boundary-layer flow with locally stationary mean and turbulent speed properties. Wind is reproduced taking care of the variation of the mean speed with height from ground and its turbulence characteristics. Moreover, a correct representation of the ABL flow also requires the simulation of the energy of the three turbulent velocity components. The simulation of natural wind is achieved using passive turbulence generators placed at the beginning of the test section (spires) and roughness elements on the wind tunnel floor upstream the wind turbine model. The size and spacing of the above-mentioned devices are varied to generate different wind profiles.

Tests could also be performed considering a laminar flow, with a wind speed constant in time across the wind tunnel test section. In this case, turbulence components are as small as possible and mean wind speed is set to the wind turbine hub-height wind speed.

Wind tunnel walls could have a significative influence on the flow effectively acting on the wind turbine scale model. As the model size becomes significant with respect to the wind tunnel cross-section, the incoming flow is blocked and distorted. If the blockage ratio (defined as the ratio between the model frontal area and the wind tunnel cross-section) is less than 5%, flow distortion could be considered negligible.

Waves do not need to be calibrated since they are simulated by the numerical model. Wave kinematics could be reproduced in the experiment either starting from spectral parameters of the wave condition of interest or from wave elevation time series.

4.3.3.2 Open-loop and HIL configurations

The experimental setup should allow two operational configurations, identified as open-loop (OL) and hardware-in- the-loop (HIL). In the first case, the floating platform numerical model is integrated in real-time excluding the force feedback from the force transducer at tower base. In this way the wind turbine scale model is moved in feed-forward, according to the behavior of the numerical substructure only, neglecting the contribution of wind turbine loads. In the second case, the floating platform model is integrated taking into account the force feedback.

4.3.3.3 HIL system verification tests

Verification tests are performed to understand how the HIL force feedback and actuation chain affects the reproduction of the floating system rigid-body dynamics in still-air. The verification procedure is carried out by running the following tests:

- free-decay tests. An arbitrary initial condition is imposed to the surge or pitch DOF and the response of the directly excited platform mode is recorded. Time histories resulting from the same experiment run in open-loop and HIL configuration are compared as well as the dynamic properties of the interested modes;
- pink noise tests. Pink noise waves from 0° are run in still-air order to investigate the non-linear response of the floating platform rigid-body motion modes. The transfer function between wave height and the platform DOFs response can be computed to highlight how the HIL measurement and actuation chains affect the reproduction of floating system dynamics at different frequencies and, in particular, in the low-frequency range where platform modes are found.

4.3.3.4 Decay tests

Decay tests are performed by imposing to a single platform DOF a perturbation with respect to the static equilibrium position and allowing the system to move freely. For each run, only the response of the directly excited DOF is analyzed, disregarding the response induced by coupling on the other DOFs, being this of a lower order of magnitude.

The dynamic properties of the selected rigid-body motion mode are derived from the analysis of the dynamic response time history, obtained subtracting the steady-state value from the recorded time series. The initial part only of the decay time history is considered for computations (up to the fifth oscillations cycle was used for analysis of the LIFES50+ wind tunnel tests).

4.3.3.5 Pink noise

Pink noise tests are performed in order to assess the non-linear response of the floating system to broadband hydrodynamic loads. In particular the excitation provided by wave loads allows to identify the frequency response function for the platform DOFs in the low-frequency range, where platform rigid-body motion modes are found. Pink noise waves are also run for different laminar wind conditions in order to investigate how the floating system response is affected by rotor and control-induced loads.

4.3.3.6 Irregular wave tests

Irregular wave tests are performed to investigate the response of the floating system to irregular waves. Experiments are performed in still-air and under different laminar wind conditions. From these tests it is possible to evaluate how the platform DOFs response and wind turbine loads change for different wind turbine operating conditions.

4.3.4 Verification of Results

The HIL system is based on a reduced-order model of the floating system that is integrated in real-time to reproduce the platform response. This model should reproduce the floating system dynamics as measured in still-air ocean basin tests.

The HIL capability of reproducing platform dynamics in still air should be verified comparing experimental tests in no-wind conditions with equivalent simulations performed with numerical tools for the simulation of floating structure dynamics. The latter should be calibrated to match the still-air dynamics resulting from ocean basin tests. Differences between the output of numerical simulations and the outcome of HIL experiments are introduced by the simplifications in the HIL numerical model and uncertainties in the HIL force feedback. The direct comparison of HIL experiments and FAST[12] simulations highlights the sum of these differences, without the possibility of discerning single contributions. Errors due to modeling choices and due to the HIL measurement and actuation chains could be identified separately one from the others by performing a direct comparison between the stand-alone HIL model and a higher-order numerical model of the floating system.

During tests, it is possible to evaluate the effectiveness of the HIL methodology from some key parameters. The wind turbine loads extracted from tower-base measurements should be almost zero in still-air tests to confirm the correctness of the force subtraction procedure and the required parameters. The rising of unstable or limit cycle behavior in the platform response indicates large uncertainties in wind turbine loads.

Repeatability in wind and wave tests can be evaluated from repeated tests. This is advisable but obviously results in larger costs for the experimental campaign. It is therefore advisable to evaluate repeatability for the overall methodology in key tests and not for the simulation of specific load cases.

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[12] An aeroelastic computer-aided engineering (CAE) tool for horizontal axis wind turbines developed by the National Renewable Energy Laboratory: https://nwtc.nrel.gov/FAST

5 Comparison to existing guidelines

5.1 Introduction to general certification document structure

The standards and guidelines published by DNV GL follow a straight forward hierarchy characterised by three document levels. The three documents levels are specified as

- Service Specifications (SE),
- Standards (ST) and
- Recommended Practices (RP).

The intention of this split is to address different stakeholders with the specific information they need. In short, the service specifications describe the scope of work of a certification process in a technical field, list all available statements and certificates and provide contractual conditions related to the certification work. Thus, the SE‘s are primarily of interest for investors, developers and project managers.

DNV GL standards provides clear requirements for the design and the applicable methodologies. This includes e.g. the definition of design classes, load case tables, safety factors, etc. The ST’s are typically the main tools of designers and engineers when working on design approvals.

Additionally, the ST’s are supported by recommended practices which provides a broader insight to the calculation principals and methodologies and give practical recommendations for the design calculations based on recent experience and state-of-the-art technology.

This document structure enables DNV GL a faster revision cycle and to react efficiently on market trends, novel developments or on new technologies and experiences.

5.2 Certification of FOWT

This section provides a brief overview on the model test requirements for FOWT from the perspective of a certification body. DNV GL recently published three specific documents for the design of FOWT, namely a

- Floating wind turbine Service Specification DNVGL-SE-0422,
- Floating wind turbine Standard DNVGL-ST-0119 and
- Floating wind turbine Recommended Practice DNVGL-RP-0286.

Within these floating certification documents the topic model testing is clearly positioned and marks a significant element in the process of the certification of a FOWT.

Further guidance and recommended methods for testing in hydrodynamic facilities can typically be found in the ITTC (International Towing Tank Conference) Recommended Procedures and Guidelines[13], Recommended Procedures and the Recommended Practice DNV-RP-C205 "Environmental Conditions and Environmental Loads". The DNVGL-RP-C205, however, focus on the applications in the oil&gas and maritime industries. This is also valid for the guidelines published by ABS “Guide for Building and Classing Floating Offshore Wind Turbine Installations”, API RP 2T, and EN ISO 19904-1:2006. ITTC Procedure 7.5-02-07-03.8[14] can be used as guidance for model test for offshore wind turbines, with different solutions available for the modelling of the aerodynamic loads on the rotor but

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[13] https://ittc.info/media/8372/index.pdf
[14] https://www.ittc.info/media/8127/75-02-07-038.pdf

no information is given in the form of recommendations or guidance regarding the hybrid model tests. Guidance on hybrid testing is given in the procedure on active truncation of mooring systems (7.5-02-07-03.4[15]), which can be used to model deep water mooring systems in limited depth basins.

Model tests of FOWT in terms of wind tunnel and/or basin tests are an integral part of the design verification according to DNV GL certification schemes. It is recommended to perform model tests already in the concept phase of a FOWT project. For FOWT the DNV GL certification scheme considers the phases “Concept”, “Prototype”, “Site Type”, and “Project” with a respective amount of verification activities. According to DNV GL standard, it is mandatory to perform a model test for novel prototype designs. As mentioned in Section 2, the background for this requirement is basically the lack of long-term experience with software simulations of FOWT and the few full-scale measurement campaigns available today. This results in a need for calibration and validation of existing simulation packages. The calibration of hydrodynamic coefficients and the validation of loads and stability simulations are explicitly mentioned in the scope of a floating prototype certification.

The DNV GL floating standard describes in detail how model tests may assist the design of FOWT. In section 2.6.2.1 it is stated „Model tests can be used to validate software, to check effects which are known not to be adequately covered by the software, and to check the structure if unforeseen phenomena could occur. The tests shall be as realistic as possible with respect to scaling of wind, wave and current loading, considering issues such as scaling laws and inadequate model test basins. Also, to make the tests as realistic as possible and obtain correct wind forces, it may be necessary to properly represent the effect that the wind turbine control system has on the wind forces. Also, a correct representation of the turbulence spectrum and spatial coherence of the wind will in most cases be important“.

Moreover, the Recommend Practice gives detailed information and guidance on „Real-time hybrid model tests“, see DNVGL-RP-0286, section 7.3.5.4. Herein is stated that “a challenge with real-time hybrid testing relates to the complexity of the control system used to connect the physical model to the numerical simulation. Time delays may for example cause additional damping or may put spurious energy into the system. Actuators may also have a physical limitation to emulate high frequency loads that may be important for some types of structures (e.g. TLP's). The capacity of the actuators to produce load variations at frequencies and in the range of amplitude that are important for the behaviour of the considered floater should be verified”. Documentation of the performance of the hybrid/HIL system is a necessary step in the model tests, as detailed in section 4.2.3.2 for the tests in an ocean basin and in Section 4.3.3.3 for the tests in a wind tunnel. Additionally, it is suggested to monitor performance of the system during and after testing, as explained in Sections 4.2.4 and 4.3.4 for ocean basin and wind tunnel tests, respectively.

The DNV GL standard do not give any preference for a specific testing methodology, but the coupled dynamics of wind wave and controller impacts, as mentioned above, shall be covered. This means that the presented approach of this deliverable which introduces a combination of wind tunnel and basin tests coupled by means of Hybrid/HIL technology would be a suitable test setup for a certification purpose of a novel FOWT design.

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[15] https://www.ittc.info/media/8119/75-02-07-034.pdf

5.3 Certification recommendations for FOWT model tests

Regarding the overall level of confidence and uncertainties of model tests the DNVGL-RP-0268 provides the following check list of influencing parameters:

- The accuracy of the RNA modelling (geometry, elasticity, mass distribution)
- Sensitivity to the dynamic response of the instrument cables
- Sensitivity to additional loading on instrument cables (wind, current and waves if submerged)
- The accuracy of the spatial and temporal variations of the wind field generated. To reduce uncertainties, the applied time series of the wind field should be repeatable.
- The accuracy of the actual installation of the FOWTs including the mooring and anchor system
- The accuracy of the model used for redesigning the scaled rotor blades (performance scaling) if physical wind turbine model is applied
- The decreased accuracy caused by large horizontal motions (including yaw rotation)
- For hybrid model testing the results are sensitive to time delays and limited frequency range of the actuating system, as well as the accuracy and correctness of the simulation models applied for real-time aerodynamic load calculations.
- The dynamic response of the actuator applying the wind loads (e.g. eigenfrequencies of cables, bandwidth of winches, fans or propeller engines if these are used in hybrid models)
- The accuracy of actuators (e.g. rotational speed of fans, if these are used in hybrid methods).
- Possible inaccuracies for low wind velocities (i.e. loads with small magnitude).

With respect to the LIFES50+ model test campaigns, and especially the testing of the Hybrid/HIL approach presented in this report, the relevant influence parameters have been taken into account in the planning of model tests and during the execution of the LIFES50+ measurement campaigns, see for instance Sections 4.2 and 4.3. The comparison of the measurement results with simulation calculations are another essential part of the certification scope, e.g. in prototype certification. This analysis is documented in LIFES50+ report D4.6 "Model validation against experiments and map of model accuracy across load cases."

6 Conclusion

Model testing is an important step in the design process of floating offshore wind turbines and is used for global and partial system verification and characterisation, validation of numerical models, and estimation of extreme loads and responses.

Model testing in hydrodynamic facilities with focus on hydrodynamics only can be used for component testing, marine operations, and partial system identification where simplifications have to be assessed carefully. Model tests in wind tunnels have traditionally been used for understanding complex aerodynamic phenomena at the wind turbine level like dynamic stall and 3D rotational effects, but also at a larger scale like the wake interference for wind turbines operating in array configurations typical of wind farms or for the development of advanced control logics at the level of the wind farms.

For global system verification, validation of numerical codes, system characterisation and estimation of extreme loads and responses, it is advised to model the FOWT as closely as possible. Due to the challenges related to generation of high-quality wind and waves, scaling incompatibility and model construction limitations, the real-time hybrid or HIL approach for performing true-to-scale model testing with FOWT is appealing. Two alternatives are possible: 1) Performing HIL model tests in a wind tunnel with a physical wind turbine connected to a 6DOF actuators controlled by real-time simulations of the floater subject to hydrodynamic loads, or 2) performing real-time hybrid model tests in an ocean basin with a physical model of the FOWT, without the rotor geometry, coupled to a force actuator controlled by the simulated aerodynamic loads. The terms HIL testing, as used by Politecnico di Milano, and Real-Time Hybrid Model testing, as used by SINTEF Ocean, refer to the same testing method coupling experiments and simulations in real-time, see Section 1.1 on terminology.

The main advantages of performing HIL model tests in a wind tunnel over full physical model tests in an ocean basin is the increased control over the wind field. HIL model test in a wind tunnel can be used in open-loop (i.e. forced motion) for calibration and validation of aerodynamic models, and in closed-loop mode (measured aerodynamic loads are used as input to the numerical model) for preliminary tuning of the wind turbine controller if performed before ocean basin tests. Advanced tuning of the wind turbine controller can be performed if the numerical model for simulating the platform dynamics has been calibrated previously. A redesign of the model scale wind turbine controller is required due to the differences between the wind turbine characteristics (mass and aerodynamic) at model and prototype scale. Generation of turbulent wind can be required for advanced tuning of the controller due to its influence on the behaviour of the FOWT, see Goupee et al. (2014).

Real-Time Hybrid Model tests in an Ocean Basin enables testing of FOWT. The limitations of classical physical tests due to scaling issues, model construction, and wind generation are removed allowing to test with a true-to-scale model, under realistic environmental conditions (irregular waves with turbulent wind). Real-Time Hybrid Model tests of FOWT in an ocean basin can be used for final system verification, which requires modelling of the complete system, as well as system development such as controller tuning. Validated numerical models for the calculation of the aerodynamic loads are required. Additionally, the tests can be used for calibration of hydrodynamic models.

The following procedure is recommended when performing hybrid/HIL model tests with a FOWT in a wind tunnel and an ocean basin.

1) Perform HIL wind tunnel tests for the validation of the aerodynamic model that will be used in the ocean basin tests. For the verification, wind tunnel tests with realistic platform motions are necessary.
2) The second step consists of using the previously validated aerodynamic model and use it for hybrid model tests in an ocean basin. The tests are used for calibration of the platform and hydrodynamic model as well as for final verification.

Ideally, additional iterations of the process would be preferred but could be difficult to realise since costly and time taking. Note that the recommended approach described above is close to the approach followed in the Lifes50+ project.

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