The Specialist Committee on Hydrodynamic Modelling of Marine Renewable Energy Devices

Final Report and Recommendations to the 29th ITTC

1. INTRODUCTION

This report summarises the work of the Specialist Committee on Hydrodynamic Modelling of Marine Renewable Energy Devices for the 29th ITTC.

1.1 Membership

The 29th ITTC Specialist Committee on Hydrodynamic Modelling of Marine Renewable Energy Devices (SC-HMMRED) has been organized into three focus groups: Offshore wind turbines (OWT); current turbines (CT); and wave energy converters (WEC).

The committee consisted of the following members, divided into their respectively focus group:

Offshore Wind turbines:

- Dr. Petter Andreas Berthelsen (Committee Chair), SINTEF Ocean, Norway.
- Dr. Maurizio Collu (Committee Secretary), University of Strathclyde, UK.
- Prof. Hyun Kyoung Shin, University of Ulsan, South Korea.

Current turbines:

- Prof. Ye Li, Shanghai Jiaotong University, China.
- Dr. William M. Batten, QinetiQ, UK.
- Mr. Willam A. Straka, Pennsylvania State University, USA.

Wave energy converters:

- Dr. Giuseppina Colicchio, CNR, Italy.
- Dr. Keyyong Hong, Korea Research Institute of Ships and Ocean Engineering, South Korea.
- Dr. Jean-Roch Nader (replacing Assoc. Prof. Irene Penesis mid-term), Australian Maritime College, University of Tasmania, Australia.
- Dr. Sylvain Bourdier, LHEEA, Centrale Nantes, France.

1.2 Meetings

The Committee has met four times during the three-year mandate:

- SINTEF Ocean, Trondheim, Norway, 24-26 January 2018.
- AMC, UTAS, Launceston, Australia, 12-14 February 2019.
- University of Strathclyde, Glasgow, UK, 4-7 June 2019.
- University of Ulsan, Ulsan, South-Korea, 11-13 February 2020.

1.3 Acknowledgement

The Committee would also like to acknowledge the contributions from Maxime Thys (SINTEF Ocean) and Katarzyna Patryniak (University of Strathclyde) for the support provided in writing up this report.

2. TASKS

The following lists the tasks given to the 29th Specialist Committee on Hydrodynamic Modelling of Marine Renewable Energy Devices:

2.1 Report on Full Scale installations

a. Type of device
b. Problems in installation
c. Success of energy extraction
d. Survivability

2.2 Wave Energy Converters

a. Monitor and report on new concepts for WEC’s (focus on new WEC's with high TRL).
b. Develop guidelines for physical and numerical modelling of WEC’s.
c. Review and report on the progress made on the modelling of arrays.
d. Continue to monitor developments in PTO modelling both for physical and numerical prediction of power capture.

e. Investigate Survivability for WEC.

2.3 Current Turbines

a. Develop specifications for benchmark tests (EFD and CFD) for current turbines.
b. Investigate effects and reproduction at model scale of inflow turbulence and unsteadiness to the turbine.
c. Review and report on the progress made on the modelling of arrays elaborating on wake interactions and impact on performance.

2.4 Offshore Wind Turbines

a. Monitor and report on recent developments of testing methodology for offshore wind turbines.
b. Report on other existing regulations related to model tests of offshore wind turbines (e.g., IEC, classification societies, DoE) and draw on these regulations if considered relevant.
c. Develop a guideline for uncertainty analysis for model testing of offshore wind turbines.

3. PROCEDURES AND GUIDELINES

3.1 Existing guidelines

This committee is responsible for maintaining the following ITTC procedures and guidelines:

- 7.5-02-07-03.7 Wave Energy Converter Model Test Experiments

This procedure addresses designing and performing hydrodynamic model tests of wave energy converters. The guideline provides a careful consideration of the differences and complexities in testing a device at various TRLs where for example the power take-off (PTO) system should be representative of the full-scale PTO and survivability tests where extreme load fatigue analysis is required. No major revision has been performed during the 29^{th} ITTC.

- 7.5-02-07-03.8 Model tests for Offshore Wind Turbines

This procedure addresses designing and performing hydrodynamic model tests of offshore wind turbines. The guideline describes different methods for modelling of the wind loads on the wind turbine in a hydrodynamic testing facility as well as test procedures for offshore wind turbines. No major revision has been performed during the 29^{th} ITTC.

- 7.5-02-07-03.9 Model tests for Current Turbines

This procedure addresses designing and performing model tests of ocean and tidal current turbine devices at various scales in a reproducible environment at a hydrodynamic test facility and suitability for testing such devices. The procedure was revised to address current best practices. This included the addition of a section on noise measurements. Definitions and parameters were added as were additional relevant equations. The procedure was also updated to use current ITTC nomenclature and symbols.

- 7.5-02-07-03.12 Uncertainty Analysis for a Wave Energy Converter

The procedure addresses guidelines for the application of uncertainty analysis to the small-scale testing of wave energy converters provided by ITTC procedure 7.5-02-07-03.7, “Wave Energy Converter Model Test Experiments”. Details about the energy capture performance have been added to the procedure. Because of the relative importance of the PTO system in the different stages of development, three macro categories for the applications of the uncertainty have been identified: the concept validation stages (TRL 1-3), the design validation stages (TRL 4-5) and the system validation, prototype, and demonstration stage

(TRL 6-9). For each of these stages, the sources of uncertainty to consider are listed as well as guidelines for their reliable evaluation.

- 7.5-02-07-03.15 Uncertainty Analysis – Example for horizontal axis turbines

The procedure addresses guidelines for the application of uncertainty analysis to the small-scale testing of current turbines provided by ITTC procedure 7.5-02-07-03.9, “Model Tests for Current Turbines”. The guideline’s scaling discussion was combined, reduced, and simplified. The uncertainty example was updated to better align to Type A and B uncertainty nomenclature and ITTC standards. Errors in a few equations were corrected.

3.2 New guidelines

The following two new guidelines were developed during this term:

- 7.5-02-07-03.17 Uncertainty Analysis for Model Testing of Offshore Wind Turbines

The purpose of the guideline is to provide guidance on the application of uncertainty analysis to the model scale testing of offshore wind turbines following the ITTC Procedure 7.5-02-07-03.8, “Model Tests for Offshore Wind Turbines”. The model scale testing of offshore wind turbines focuses on the environmental loads and global response of the structure, similar to the testing of other offshore structures (floating or fixed).

See also Section 9.3 for more details.

- 7.5-02-07-03.18 Practical Guidelines for Numerical Modelling of Wave Energy Converters

The purpose of this guideline is to provide a methodology to assess the fidelity of the numerical simulation for Wave Energy Converters (WECs) at different stages of development, to set up numerical calculations and to analyse the obtained results. Therefore, they have been classified as a function of the objectives of the study, of the Technology Readiness level (TRL) of the WEC and the numerical facility on which they can be run has been detailed.

See also Section 7.2 for more details.

4. COOPERATION WITH OTHER COMMITTEES

The International Electrotechnical Commission (IEC) is a key international body which addresses standards in all field of electrotechnology. The work is organized through technical committees (TCs). The TC of particular relevance for this ITTC SC are IEC TC88 (Wind Turbines) and IEC TC114 (Marine Energy – Wave, tidal and other water current converters). Through the 28th ITTC term, there were informal collaboration that resulted in cross-referencing of draft and existing ITTC guidelines and procedures, further assisting dissemination of ITTC Procedures and establishing best practice. This collaboration is still ongoing for the 29th ITTC through direct contact with IEC TC88 (MT3-2 – FOWT and WG3 – OWT), IEA Wind Task 30 and an informal contact with IEC TC114.

In particular, committee members have been involved in IEC TC 88 MT 3-2 with the task to transform IEC TS 61400-3-2; 2019 into IEC IS 61400-3-2, a technical specification and guideline for floating offshore wind turbines (FOWTs) which all FOWT industry can refer to.

5. BENCHMARK DATA

The SC-HMMRED committee was tasked to report and identity benchmark datasets that are readily available for comparison for future experiments or to validate computational and performance models.

5.1 Wave Energy Converters

In the WECs field, the development of both numerical and experimental benchmark cases is still under development. Numerical and experimental test cases have been devised by IEA OES in its task 10 “Wave Energy Converters Modelling Verification and Validation” presenting the comparison among linear, weakly nonlinear, fully nonlinear codes and experimental data. The first experimental heave decay test data of a heaving floating sphere are available (Wendt et al., 2019). These tests aimed at providing rigorous benchmark dataset and were performed with high level of accuracy and precision as well as being supplemented with thorough uncertainty analysis. Some preliminary study of the numerical analysis of a heaving sphere are also available (Nielsen et al., 2019). For further update, this information can be found in: https://www.ocean-energy-systems.org/oes-projects/wave-energy-converters-modelling-verification-and-validation/.

The European H2020 project MARINET2 round robin is still ongoing. These tests focus on two kinds of WECs to identify the uncertainty deriving from the facility bias. However, no further updates on its progress have been publicised.

The same goes with the pan-European cost action WECANET with the planning of another round robin tests looking this time at different model scales. Once again, no further updates on its progress have been publicised.

On the other hand, in recently published article, (Orphin et al., 2021) have presented a comprehensive and detailed methodology to apply uncertainty analysis to the design and results of WEC model scale experiment using the Monte Carlos method. Example of the method is applied to a 1:30 scale experiment of a case study oscillating water column WEC in both regular and irregular waves.

At present, all the available databases are all relatively new and very few results have been published until now. However, they apply to different types of WEC technologies and address different features of uncertainties. This makes the different efforts even quite valuable for the numerical model validations. It is still to be seen if the published data are sufficiently detailed to be used by people not directly involved in the project.

5.2 Current turbines

There are a few benchmark studies currently available for verification of testing and simulations of current turbines. These include but are not limited to tow tank and water tunnel tests completed by Bahaj et al., (2007); a series round-robin experiments in multiple facilities conducted by Gaurier et al. (2015, 2018); and multiple-scale contra-rotating studies by Clarke, et al. (2007). Currently, the most complete benchmarking database for current turbines may be from the U.S. Department of Energy (USDOE) sponsored Reference Model (RM) project. Details of this project can be found at https://tethys-engineering.pnnl.gov/signature-projects/reference-model-project. This project included scaled turbine studies on a horizontal-axis and cross-flow hydrokinetic turbines (Neary et al. 2014). The largest database (relative to the types of available data) used a single three-blade horizontal-axis turbine (Fontaine, et al. (2013, 2020)). Other research included a dual rotor two-blade horizontal-axis (RM1) (Hill et al. (2020)) and a cross-flow turbine (RM2) (Bachant et al. (2014) and Wosnik et al. (2015)).

Each of these existing studies and many others provide a pool of data for comparison to other experiments or to verify other computational models. However, almost all published studies, to date, have limitations that hinder them from being considered a complete benchmark database. In most cases, details needed for validation and verification of modelling are not readily available. This includes open platform geometry definition of the turbine and test configuration within the facility; digital data files; and documented data uncertainty and hardware tolerances. An issue with current benchmark datasets in general is the range of turbine configurations that can exist including horizontal axis, vertical axis, kite and shrouded turbines to name a few. The proposed environment for each design is also often unique. Although similar, each configuration or application will have unique characteristics that may require different modelling and benchmark criteria.

Figure 1: Three-bladed "round-robin" horizontal instrumented turbine in water flume and tow tank (From Gaurier et al. (2015))

In many prior studies, performance parameters and turbine geometries used for experimental studies have been considered propriety or not readily available in the public domain. Often the data is presented in literature but not further. This is more evident with multi-scale studies or fielded installations. Multi-scale databases are important to confirm performance assessments and to validate scaling of performance of sub-scale models evaluated in experimental facilities and with computational predictions tools with fielded installations. A contra-rotating current tidal device (Clarke, et. al. (2007a, b)) was tested in tow tanks at 1/30th scale and in the Cylde estuary at 1/10th scale. However, detailed geometry information and digital measurement data for those designs do not appear to be available. Similarly, many current turbine experiments have been used to validate CFD predictions in literature. Very little of the data appears to be available in published online or accessible databases. The cavitation data of Bahaj et al. (2017) for instance has been successively used to validate computations predictions such as of Gharrere (2015) among others. Most of these data appears to be shared by personal communications.

A few databases are now or appear soon to be available online and publicly assessable. One of the first was a ''round robin'' study on three-bladed 0.7m diameter horizontal-axis turbine that was conducted in order to evaluate the impact of different experimental facilities on test results (Gaurier et al., 2015). This work tested the same model tidal turbine in two towing tanks, of very different size, and two circulating water channels. Performance assessments for TSR from 0 to 7 were conducted in each facility. Measurements included power, thrust/drag and inflow velocity. In general results in the various facilities were very similar. Due to the effect of inflow turbulence, the largest differences between the different facilities (circulating and towing) were observed in the fluctuations of torque and drag measurements. These tests highlighted the significant effect of blockage yielding high thrust coefficients, even at relatively small blockage ratios. The data from these tests can be found online (Gaurier et al., 2018a). To date, no uncertainty analysis has been present on these experiments. It also does not appear that the available data set include standard CAD files of the turbine or support structure. A second phase of this work comparing wave and current interactions is included in Gaurier et al. (2018b) so more data may be available in the near future.

The U.S. DOE Reference Model (RM) project created marine energy prototypes as reference models to benchmark performance and cost for the marine energy community. One objective stated for this project was to provide non-propriety turbine design for the marine energy community. For current turbines, this resulted in available studies for a single and dual rotor subscale horizontal-axis turbine and a subscale cross-flow turbine

(Neary et al. 2014). Some details of these benchmark experiments follow.

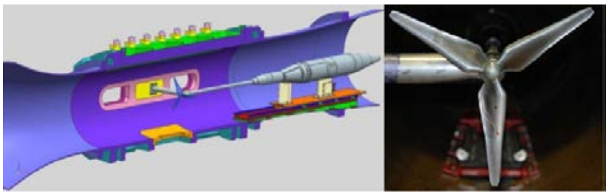

Figure 2: A 1:8.7 scale horizontal-axis current turbine (DOE-MHKF1) in cavitation tunnel (from Fontaine et al. (2013))

Fontaine et al. (2013, 2020) conducted a verification and validation study using a 1:8.7 single-rotor 0.575m diameter three-bladed horizontal-axis current turbine (Sandia turbine rotor, MHKF1, Figure 2) in a closed loop cavitation tunnel. The objective of this work was to generate a database that would provide a better understanding of the current turbine technology and means to validate analytical and numerical models. As such, this experiment provides one of the most detailed model-scale benchmark database to date for a horizontal-axis turbine. The measured data includes device power, steady and unsteady shaft loads, tower unsteady pressures, blade strain, device acoustic measurements, nacelle vibration levels, and oil paint flow visualization photographs. Flow mapping upstream and up to one rotor diameter downstream was measured using laser Doppler velocimetry (LDV) and stereo particle image velocimetry (SPIV). The flow measurements as well as much of the other data were synced with rotor blade position. The data and geometry files are reported to be provided on the USDOE Marine and Hydrokinetic Data Repository but do not seem to be available yet. The model scale turbine was tested for operating conditions for TSR from 2 to 6 for both cavitating and non-cavitating water conditions. This database will also include blade inspection data and general uncertainty estimates.

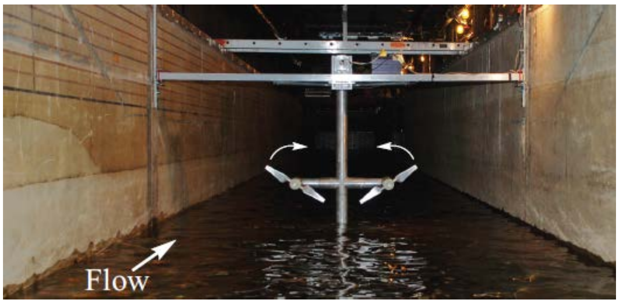

Figure 3: A 1:40 scale dual rotor horizontal-axis current turbine (DOE-RM1) channel facility (from Hill et al. (2020))

As part of the same U.S. DOE reference project, a dual rotor two-bladed horizontal-axis turbine was designed and tested at 1:40 scale in an open channel flume to evaluate power performance and wake flow recovery (Hill et al. (2020, Figure 3). Each rotor was 0.5m in diameter and evaluations completed for TSR from 1 to 9. Acoustic Doppler velocimeters were used to collect flow velocity up to 5 diameters upstream and downstream up to 10 diameters to record synchronized turbulent flow characteristics. This study included uncertainty estimates and should provide a robust dataset for numerical model validation.

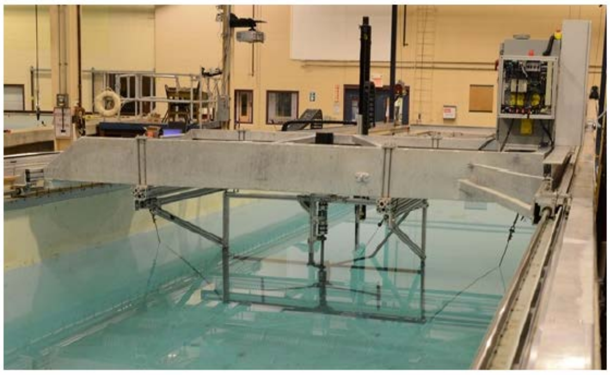

Figure 4: A 1:6 scale cross-flow turbine (DOE-RM2) setup up in tow tank (from Wosnik et al. (2015))

A 1:6 scale model of a cross-flow hydroturbine. RM2 (Barone et al. (2011)) was tested in a tow tank (Bachant et al. (2014) and Wosnik et al. (2015)). The scaled three-bladed turbine had a height of 0.807m and a diameter of 1.075m (Figure 4). Performance data such as turbine torque, drag and angular velocity were measured along with inflow speed and wake velocities at approximately one turbine diameter downstream. The data were obtained for Reynolds numbers, Re_D, from 0.4 to $1.3x10^6$. CAD STEP files for the 1:6 scale model geometry are available online (Bachant et al. (2015a)). A digital measurement database is also available for download ((Bachant et al. (2015b)).

5.3 Offshore Wind Turbines

The International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP) aims at advancing the accuracy of the coupled numerical modelling tools for offshore wind turbines. Tasks 23 and 30 include a few large-scale initiatives.

IEA OC3 - Offshore Code Comparison Collaboration (Jonkman and Musial, 2010) focused on testing the newly developed aero-hydro-servo-elastic codes for modelling the fixed-bottom and floating OWT. The main emphasis was given to the verification of the dynamics of different support structures including a monopile in shallow water, a tripod at an intermediate depth, and a floating spar buoy in deep water.

IEA OC4 - Offshore Code Comparison Collaboration Continuation (Musial et al., 2009) was established to verify OWT modelling codes through code-to-code comparisons. Phase I of the project analysed the complex hydrodynamics of a jacket foundation and its local vibration phenomena, while phase II investigated the implications of different hydrodynamic theories applied to a semi-submersible floating platform.

IEA OC5 - Offshore Code Comparison Collaboration, Continuation, with Correlation (U.S. Department of Energy, 2021) extended the previous two projects providing the validation of modelling tools through comparison of the numerical results to experimental response data from both scaled tank testing and full-scale, open-ocean testing. Phase I covered the dynamics of rigid and flexible cylinders, with no wind turbine present, while phase II focused on the DeepCwind floating semi-submersible with a 1:50 scale model of a 5-MW horizontal-axis turbine.

The most recent campaign, IEA OC6 - Offshore Code Comparison, Collaboration, Continued, with Correlation and unCertainty (IEA Wind, 2021) employs a three-way validation process where both the engineering-level modelling tools and higher-fidelity numerical models are compared to experimental results. The project involves validation of the nonlinear hydrodynamic and aerodynamic loading on FOWT undergoing large motion, as well as the development of an advanced pile/foundation interaction model and the development of a hybrid potential-viscous hydrodynamic solver for innovative floating OWT support structures.

Comprehensive information about the models and results of the OC3-OC6 projects are publicly available at IEA (2021) and at the webpages indicated in Table **1**.

Two experimental campaigns were conducted by the DeepCwind consortium at the MARIN offshore wave basin. The 1:50 scale models of a spar, a semi-submersible, and a tension-leg platform (TLP) were tested in the first campaign, followed by additional testing of the semi-submersible floater using different turbine and tower. The emphasis was given to capturing the coupling between the floating platform and the wind turbine dynamics in the operational, design, and survival seas states. Results were published in Goupee et. al (2013) and Goupee et. al (2014).

INNWIND.EU Task 4.2 partially financed by the MARINET project carried out several wave tank test campaigns. In the campaigns at the LHEEA and DHI facilities, a 1:45 model of DeepCwind semi-submersible and a 1:60 model of TLP with three different mooring lines configurations were tested with the same Froude-scaled 10MW rotor and individual pitch control. The effects of the directionally spread wave conditions, misaligned wind/

waves and extreme waves were studied. The final report and results were published in INNWIND.EU (2021) under deliverables 4.22-4.25.

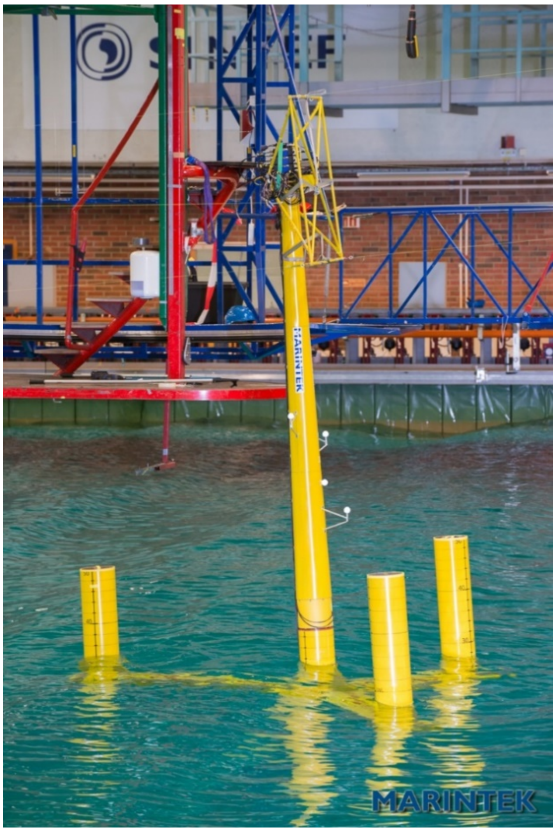

Figure 5: NOWITECH model test of a 5MW FWT (courtesy of SINTEF Ocean).

NOWITECH (Norwegian Research Centre for Offshore Wind Technology) carried out a test campaign for a 5MW semisubmersible floating wind turbine. The tests applied real-time hybrid model (ReaTHM) testing with a cable driven robot for modelling of the wind turbine (Sauder et al. 2016; Bachynski et al. 2016). The test results have been used as benchmark data for calibration of simulation models, e.g., Berthelsen et al. (2016) and Karimirad et al. (2017). The tests were performed at MARINTEK's (SINTEF Ocean) Ocean Basin in 2015 (see Figure 5).

A second NOWITECH test campaign was carried out in 2017 with a fully flexible bottom-fixed offshore wind turbine (Bachynski et al. 2019). The response of a monopile subject to irregular wave loads were investigated for a range of sea states during the tests (see Figure 6). The NOWITECH test data for benchmarking can be made available upon request.

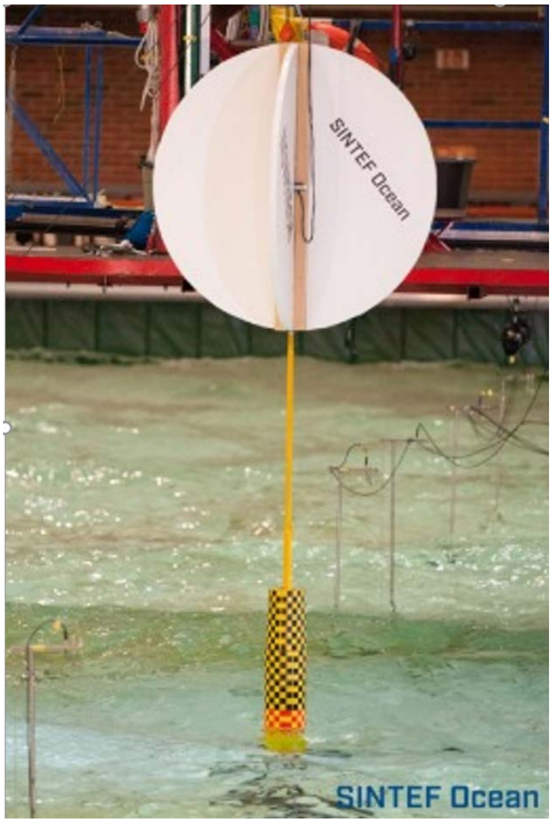

Figure 6: NOWITECH monopile test (courtesy of SINTEF Ocean).

Finally, a series of detailed aerodynamic and load measurements on a 4.5m diameter wind turbine model was conducted in the largest European wind tunnel DNW within the project 'Mexico' partly funded by the European Fifth Framework Programme. The campaign concerned a wide range of operational conditions, including multiple operational tip speed ratios, blade pitch angles, yaw misalignment angles and several unsteady cases. Information about the model and measurements was published in the report by Schepers and Snel (2007). The extensive results were subsequently analysed under the IEA Wind Task 29 and can be accessed at ECN (2021).

Table 1: Offshore Wind Turbines numerical and experimental test campaigns

INITIATIVE	LEADING ORGANISATION	YEARS	REPOSITORY WEBSITE/ REFERENCE
IEA OC3	International Energy Agency (IEA)	2004-2009	https://drive.google.com/drive/u/0/folders/0B0KGNSHvXXgCMmVsU3RkZ3FHVlE
IEA OC4	International Energy Agency (IEA)	2010-2013	https://drive.google.com/drive/u/0/folders/0B0KGNSHvXXgCSDBlREZLdDRxX2s
IEA OC5	International Energy Agency (IEA)	2014-2017	https://community.ieawind.org/task30/t30benchmarkproblems
IEA OC6	International Energy Agency (IEA)	2019-2023	Data will be made available upon completion of the project
Experimental Comparison of Three Floating Wind Turbine Concepts	DeepCwind consortium	2012-2014	https://doi.org/10.1115/OMAE2014-24172 https://www.nrel.gov/docs/fy13osti/58076.pdf https://doi.org/10.1115/1.4024711
INNWIND.EU Task 4.2	CENER	2014-2015	http://www.innwind.eu/publications/deliverable-reports
NOWITECH Semisubmersible	MARINTEK (SINTEF Ocean)/NTNU	2015	https://doi.org/10.1115/OMAE2016-54435 https://doi.org/10.1115/OMAE2016-54437 https://doi.org/10.1115/OMAE2016-54640
NOWITECH Monopile	SINTEF Ocean/NTNU	2017	https://doi.org/10.1016/j.apor.2019.05.002
Mexico	Energy Research Centre of the Netherlands (ECN)	2006-2007	http://iopscience.iop.org/1742-6596/75/1/012014
Mexnext (IEA Wind Task 29)	International Energy Agency (IEA)	2012-2018	https://www.mexnext.org/resultsstatus/

6. FULL SCALE INSTALLATIONS

6.1 Wave Energy Converters

For wave energy converters, only the Mutriku Wave Power Plant in Basque Country Spain, in operation since 2010, has demonstrated long term consistent power production (Magagna, 2019). Table 2 lists deployed or planned projects collected with information related of their type of technology, rated power, developer, and development status. Not all of those projects are full scale where the industry are still mostly at demonstration stages. Furthermore, very few data and information are available on these tests as well as virtually no information about installation issues, and survivability. The industry is still at early stage with very few commercial products meaning that they still rely heavily on investment and grant funds. Any issues or data obtained are therefore used sensitively and not publicised. Hopefully, more information on these tests will be available in the future especially in the lesson-learnt domain to help the development of the overall industry.

Table 2 Wave Energy Converter deployment worldwide (2017-2020).

PROJECT NAME	COUNTRY	YEAR ONLINE	DEVELOPMENT STATUS	DEVELOPER	Scale	RATED POWER [MW]	TYPE	REFERENCE
LAMWEC	Belgium	2020/2021	At Sea Prototype	Laminaria	1:7	0.2	Point Absorber	Lamaniria, 2021
Wavepiston	Denmark	2017-2019	Demonstration Scale	Wavepiston A/S	1:9	0.2	Oscillating Wave Surge Converter	WavePiston, 2021
mWave	Wales	2021	Development	Bombora	1:7	1.5	Gravity Based Pressure Differential	Bombora, 2021
King Island Project	Australia	2020	Installed Waiting Connection	Wave Swell Energy	Full Scale	0.2	Oscillating Water Column	WaveSwell, 2021
OE Buoy	Ireland/USA	2020	Arrived at Hawaii Test Site	Ocean Energy (Ireland)	Full Scale	0.5	Oscillating Water Column	Offshore Energy, 2019
PowerBuoy	North Sea	2020	Operational	Ocean Power Technologies	Full Scale	0.003	Point Absorber	Ocean Power Technologies, 2021
NEMOS Wave Energy Converter	Belgium	2019	At Sea Prototype	NEMOS	Large Scale	unknown	Point Absorber	NEMOS, 2021
Tordenskiold	Denmark	2019	Half-Scale Open Sea	Crestwing	1:2	unknown	Attenuator	Crestwing, 2021
WAVEGEM	France	2019	At Sea Prototype	GEPS Techno	Full Scale	0.15	Point Absorber	GEPS Techno, 2021
WaveSub	United Kingdom	2018	At Sea Prototype	Marine Power Systems	1:4	4.5 full scale (Prototype rated power unknown)	Submerged Point Absorber	Marine Power Systems, 2021
WaveRoller	Portugal	2018	At Sea Prototype	AW-Energy	unknown	0.25	Oscillating Wave Surge Converter	AW-Energy, 2019
C3	Sweden	2018	At Sea Prototype	CorPower	1:2	unknown	Point Absorber	CorPower Ocean, 2021
Oneka Buoy	Canada	2018	At Sea Prototype	Oneka	unknown	5/10 cubic meter of fresh water	Point Absorber	Oneka, 2021
Penguin	Finland	2017	Grid Connected Test	Wello Oy	unknown	1	Internal Rotating Mass	Wello, 2021

6.2 Current Turbines

6.2.1 Types of turbine

The type of tidal turbine still has not converged to a single type of system (Greaves & Iglesias, 2019). There are also developers investigating vertical axis devices and tidal fences. Both options may have advantages in shallower and restricted currents.

However, the majority of the devices are horizontal-axis turbines with either two or three blades. These can be mounted either on the seabed or floating with a tethered system.

One of the most successful turbines is the AR1500 turbine (SIMEC ATLANTIS ENERGY ,2020) as shown in Figure 7. This 1.5 MW turbine has a substantial tripod foundation.

Figure 7: AR1500 tidal turbine test fitting on the dock. (SIMEC ATLANTIS ENERGY, 2019).

As an example of a floating device, Orbital marine power devices is shown in Figure 8. This is 2MW device has two rotors with shared power electronics on one platform. This type of floating device allows for easier installation and maintenance.

Figure 8: Orbital marine power twin 2MW device. (Orbital marine power, 2021)

As an example of a different type of technology, a kite-based system has been developed by Miesto, (2021). This orbital path of this device shown in Figure 9. The additional motion increases the inflow speed but at increased complexity.

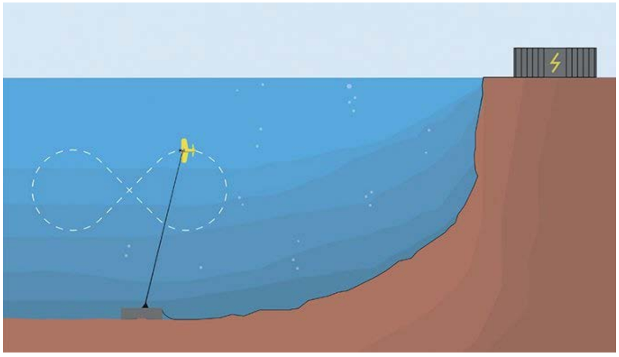

Figure 9: The orbital path of Deep Green device, Minesto (2021) turbine.

6.2.2 Success of energy extraction

From 2010 to 2019, almost 60 current turbines have been deployed in Europe. The total rated power is 27.7 MW of which 10.4 MW of this is currently operating. The remainder of 17.3 MW has now been decommissioned following the successful completion of testing programmes (Ocean Energy Europe 2019).

These installations have mainly been for medium and full-scale demonstrations to increase the technology readiness level. The most successful project is MeyGen Phase 1A which has installed four 1.5 MW turbines and had delivered 31GWH to the grid by the end of 2019. (SIMEC ATLANTIS ENERGY, 2019). After the demonstration phase, the total farm planed size is 86 MW.

Although most of the installation has been in Europe, the Canadian province of Nova Scotia boasts the highest Feed-In Tariff which has attracted European developers. In the United States, various smaller commercial and demonstration projects have been ongoing since around 2012. These include but are not limited to the Roosevelt Island and Cobscook Bay tidal energy projects (https://openei.org/wiki/PRIMRE/Databases/Technology_Database/Projects). China has also been investing heavily in and now has a similar high feed-in tariff. (Ocean Energy Europe 2019). Other demonstration project examples include the Tasmania Turbo and Singapore Tidal demonstrations. Both were fielded for about a year each. One summary of the total installed capacity is shown in Figure 10.

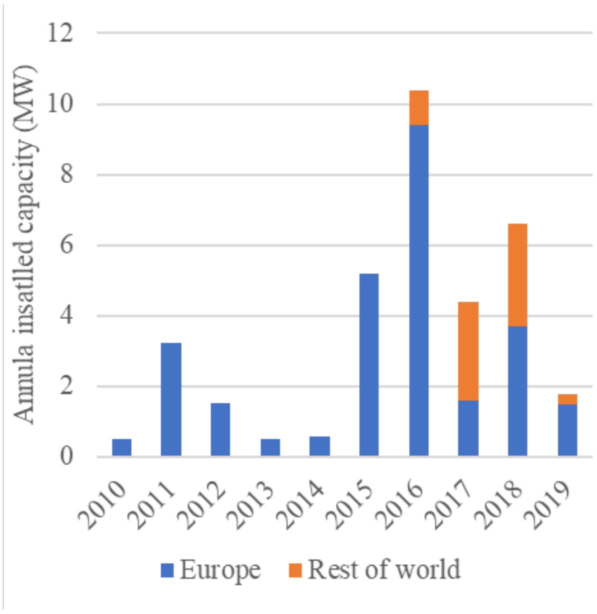

Figure 10: Global annual instated capacity (Ocean Energy Europe 2019)

There have been two main sources of failure with current turbine developers. Firstly, technical problems have been encountered. These have mainly been a fundamental structural or manufacturing issue of rotor blades or survivability issues causing rapid wearing or corrosion due to fatigue or inadequate designs/materials (EC, 2017).

Another source of failure has been due to financial problems. For example, producing the matching funds for public grants at demonstration scale or having to increase the shareholder contribution from private equity due to not meeting milestones (EC, 2017).

6.2.3 Installation issues

The installation of the current turbines support structure on the seabed has a lot of uncertainties in it due to the highly variable seabed morphologies. This remains a significant technological and, therefore, also a cost challenge. Each CT farm installation normally requires tailoring to adapt to the subsoil conditions. The techniques from the offshore oil and gas have also required a considerable amount of adaptation before they will provide viable solutions for tidal installations.

For example, fairings have had to be installed on jack-up barge legs as although the installation is done in slack water when the tide is changing the barge must go through a tidal cycle.

Lessons learned from marine operations in the Nova Scotia (FORCE, 2019) have highlighted issues with tugs requiring maximum thrust during turbine installs and limitations on towing in the tides. At Nova Scotia site the window for safe diving is approximately 20 minutes which limits the type of installation and mitigation options if automated installation systems fail.

In order to mitigate some of these installation issues of turbines firmly mounted to the seabed, there have been recent developments in floating moored systems. This also improves the ability to do maintenance. However, this increases the complexity of the device and in most cases the amount of fabrication.

6.2.4 Survivability

A significant number the early installation of turbines had issues with survivability. As of consequence, guidelines have been released to help developers EMEC (2009).

Also, over the last ten years, the understanding of the nature of the unsteadiness flow in tidal current test sites has improved. This has been mainly due to better quality measurements and analysis of tests sites which has improved the understanding of magnitude and frequency unsteadiness due to large scale turbulence structures and waves. (See for example McCaffrey et al. 2015 and Milne et al., 2016).

Some of the failures may also be due to not replicating enough of the environment in the test facility. This is further reviewed in Section 8.2 where the issues of the reproduction of inflow turbulence and unsteadiness in test facilities is discussed. As an example, recent experimental data, which has shown delayed separation and dynamic stall can result in blade root bending moments that exceeds the steady value by 25%, (Milne et al., 2016).

These additional loads have been the main cause of tidal turbine rotor blade fractures. This has resulted in the optimisation method to address these structural issues with increased blade thickness and improved fatigue life (Liu & Veitch 2012). This knowledge has led to improved predictions of the magnitude of unsteady hydrodynamic loading and there have been fewer failures.

The recent developments in floating current turbines have yet to become mature enough to show any patterns in survivability.

6.3 Offshore Wind Turbines

As the floating offshore wind turbine (FOWT) technology matures, the projects are starting to move from demonstration pilots to full commercial wind farms. Since the last (28th) ITTC report, in 2017, the number of operational floating wind turbines has more than doubled, quadrupling the total installed capacity (Table **3**). Spar and semisubmersible platforms remain the most widely applied concepts, however, new designs, such as the damping pool by Ideol, have gained some momentum. The major large-scale installations in Europe and Japan are described below and summarised in Table 3.

The world's first FOWT, Hywind Demo, remained operational in Norwegian waters for eight years. During that time, it produced more than 40 GWh, proving the survivability of the concept in a harsh environment (Equinor, 2021a). Taken over by Unitech, this wind turbine is still operational, and it is used for research purposes (UNITECH, 2021) at the test site of the Marine Energy Test Centre (MET Centre) off the coast of Karmøy, Norway.

The three FOWT of the Fukushima FORWARD project (2,5 and 7MW) were installed in the years 2013-2016 to assess their safety, reliability, and economic efficiency (Fukushima Offshore Wind Consortium, 2021). Although they provided a valuable early experience, the wind farm is currently being decommissioned; the project turned out not to be enough profitable due to its low availability, low output, and expensive maintenance of the two larger turbines (Randall-Smith, 2021). Having learned the lessons, Japan pursued another floating project (Kitakyushu Hibiki), successfully deploying a 3MW wind turbine supported by the Ideol's barge. Shortly after installation, the turbine survived three category 5 typhoons (Ideol, 2021b). Next, significantly larger wind farms are being developed in Pacific (e.g., Goto Sakiyama Oki Oki Huangdao Pilot A - 22MW, and Fukushima Phase 3 - 1GW).

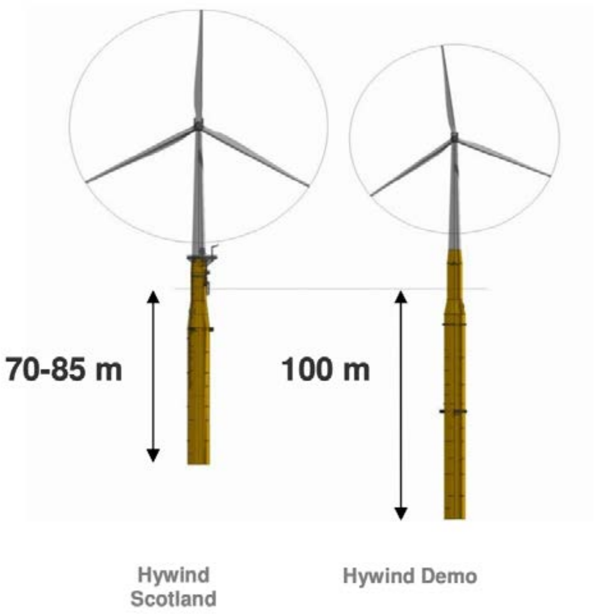

Figure 11: Hywind Scotland (2017) and Hywind Demo (2009) Spar floating offshore wind turbines (xodus group, 2013).

The world's first and largest floating wind farm, the Hywind Scotland Pilot Park, started producing power in 2017 (Equinor, 2021b). Five 6-MW turbines were mounted on the Equinor's spar platforms, achieving around 65% capacity factor in the first 3 months of operation. Importantly, according to Equinor, the cost reduction of 60 - 70% was reached as compared to the first Hywind project in Norway (Equinor, 2021b).

The second-largest floating wind farm was installed 20 kilometres away from the shore of Portugal within the WindFloat Atlantic project. Following the earlier 5-years trial of the Principal Power's semisubmersible, three world's largest floating wind turbines were connected to the grid, featuring the Vestas 8.4MW turbines with 164m diameter rotors (EDP, 2021).

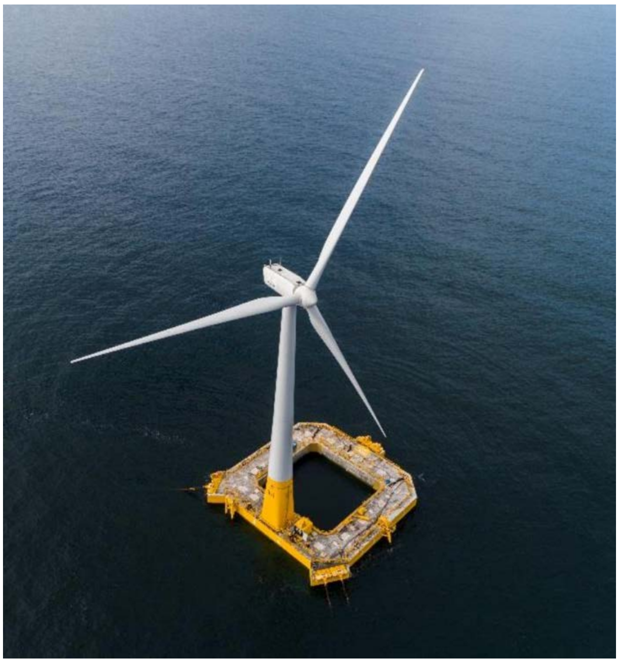

Figure 12: Floatgen by Ideol (Ideol, 2019).

The year of 2018 saw four major installations, with two semisubmersible platforms and two spar buoys. The project Floatgen installed one 2MW floating WT, allowing France and Ideol to join the floating wind industry (Ideol, 2021c). Following this success, French Eolink deployed a 1:10 scale prototype of a 12MW turbine which provided the basis for the future development of 10MW+ floating systems (Eolink, 2021). Finally, Kincardine Phase 1 project added another 2MW to the British offshore grid. This demonstrator of the Principal Power's semisubmersible is the first of 6 turbines to be installed. Ultimately, the wind farm's total capacity will reach almost 50MW (Group Cobra, 2021).

Another important project in the construction phase is the TetraSpar Demo at the MET Centre in Norway (Stiesdal, 2021). By focusing on the modularity of the design and its suitability for mass production, the project developers' goal is to switch from one-off foundation design, based on the oil and gas industry, to designs thought to be mass-produced, eventually lowering the CAPEX levels.

Another demo project planned at the MET Centre is the EU-financed H2020 project FLAGSHIP, a European collaboration led by Iberdrola. The consortium will design, build, install and operate a semisubmersible (OO-Star Wind Floater) type floating wind turbine with minimum a 10MW turbine. The project was established in 2020, and construction time is estimated to be 2 years with a test period of 2 years after that (Dr. Techn.Olav Olsen, 2021). The main objective of the project is to demonstrate cost-effective large floating wind turbines to ensure a reduction in LCOE to a range of 40-60€/MWh in 2030.

In 2021, the vast majority of the installations are planned to take place in France:

- EOLMed (30MW)
- Les éoliennes flottantes de Groix et Belle-Ile (28.5MW)
- Les éoliennes flottantes du Golfe du lion (30MW)
- Les éoliennes flottantes du Provence Grand Large (25.2MW)

All these projects have recently upgraded their choice of turbines to 8.4-10MW, taking the advantage of fast-developing wind technology and pushing the boundaries of the floating platforms' performance (EOLMed, 2021, EOLFI, 2021, EFGL, 2021 and PGL, 2021).

Hywind Tampen will be the largest floating wind farm when commissioned late 2022 (Equinor, 2021c). The project, consisting of 11 Hywind spar platforms, intends to provide electricity for the Snorre and Gullfaks offshore fields in the Norwegian North Sea. It is expected that the wind farm will reduce the annual emissions from the gas turbine power of the offshore fields by 200.000 tonnes CO_2 and 1000 tonnes NO_x. Each spar platform will be equipped with a Siemens Gamesa SG 8MW turbine providing a total capacity of 88MW. The Tampen wind farm will be the first to power oil and gas platforms, and due to the large size, it will be an essential step towards industrialization of floating wind technology and reducing costs for future projects.

Table 3: Completed installations of offshore floating wind turbines worldwide.

PROJECT NAME	COUNTRY	YEAR ONLINE	DEVELOPMENT STATUS	DEVELOPER	UNITS	RATED POWER [MW]	TYPE	REFERENCE
Hywind Demo (KARMØY)	Norway	2009	Operational	Equinor (sold to Unitech)	1	2.3	Spar	Equinor, 2021b
WindFloat Atlantic Phase 1	Portugal	2011	Decommissioned in 2016	Windplus Consortium	1	2	Semisub.	EDP, 2021
WindFloat Atlantic	Portugal	2020	Operational	Windplus Consortium	3	25.2	Semisub.	
Fukushima Demo 1 (Mirai)	Japan	2013	Operational	Mitsui	1	2	Semisub.	Fukushima Offshore Wind Consortium, 2021
Fukushima Demo 2 A (Shimpuu)	Japan	2015	Decommissioned in 2020	Mitsubishi	1	7	Semisub.	
Fukushima Demo 2 B (Hamakaze)	Japan	2016	Operational	JMU Corporation	1	5	Spar	
GOTO FOWT – Kabashima 2	Japan	2013	Operational	Toda	1	2	Spar	Utsunomiya et al., 2014
Hywind Scotland Pilot Park	UK	2017	Operational	Equinor/ Masdar	5	30	Spar	Equinor, 2021b
Floatgen	France	2018	Operational	Ideol	1	2	Barge (damping pool)	Ideol, 2021c
Kincardine Phase 1	UK	2018	Operational	Principle Power	1	2	Semisub.	Group Cobra, 2021
Kitakyushu Hibiki NEDO	Japan	2018	Operational	Ideol	1	3	Barge (damping pool)	Ideol, 2021b
Eolink (prototype)	France	2018	Decommissioned in 2019	Eolink	1	1.2	Semisub.	Eolink, 2021

7. WAVE ENERGY CONVERTERS

7.1 New concepts

There are many concepts of wave energy convertors. In fact, no technology convergence has been observed and every companies have developed their own technologies of devices and power take off systems: internal rotating mass from the Penguin (Wello, 2021), vertical plates attached to sea water pumps in the WavePiston (WavePiston, 2021), the uni-directional airflow system in the Uniwave (WaveSwell, 2021), the closed internal water circulation system in the WAVEGEM (GEPS Techno, 2021) or the pressure differential energy harvester through air-inflated rubber membranes as in the mWave (Bombora, 2021). A list of the most developed devices and their type of system can be found in Table 2.

7.2 Guideline for physical and numerical modelling of WEC's

The new guideline on numerical modelling of wave energy converters have been issued, the purpose is to provide a methodology to assess the fidelity of the numerical simulation for Wave Energy Converters (WECs) at different stages of development. Because of the WECs variety, it was impossible to draw a general procedure. Instead, the different numerical solvers that are available at the moment have been described and their range of applicability has been detailed as a function of: the TRL, the wave conditions, the non-hydrodynamic features that have to coupled and the numerical facility availability. More in particular, the numerical methods have been described and grouped in analytical, potential flow and computational fluid-dynamics models, eventually coupled with hybrid strategies.

In the fashion of the ITTC procedure 7.5–03 02–03 "Practical Guidelines for Ship CFD Applications", the main steps of the applications of all the numerical models have been detailed for the pre-processing stage (description of the body, setting of the boundary and environmental conditions), the computations (time and spatial discretization, device response to external loads as mooring, PTO and controls) and post-processing (collection and analysis of the data, verification and validation of the solution).

7.3 Physical and numerical modelling of arrays

WECs are reaching such a level of development to be appetible to electric utilities to replace fossil-fuel energy sources. To become truly commercial though, they have to be deployed in array or farms so that the cumulative production can be of the order of a few MW.

In these farm settings, the interactions between close by WECs (near field effects) will give rise to a complex wave field that affects the power extracted by each device and consequently the total power output of the farm. Moreover, at large distances behind WECs (far field effects), the farms alter the wave field affecting the coastal processes, such as: other users at sea, coastal ecosystems and the coastline.

The numerical and experimental methods commonly used for the analysis of the array configuration were already thoroughly described in the former committee final report. The limits that were stated in that report have been only partially overcome. Below, just a few of the more outstanding examples of advancement from the experimental and numerical points of view are given.

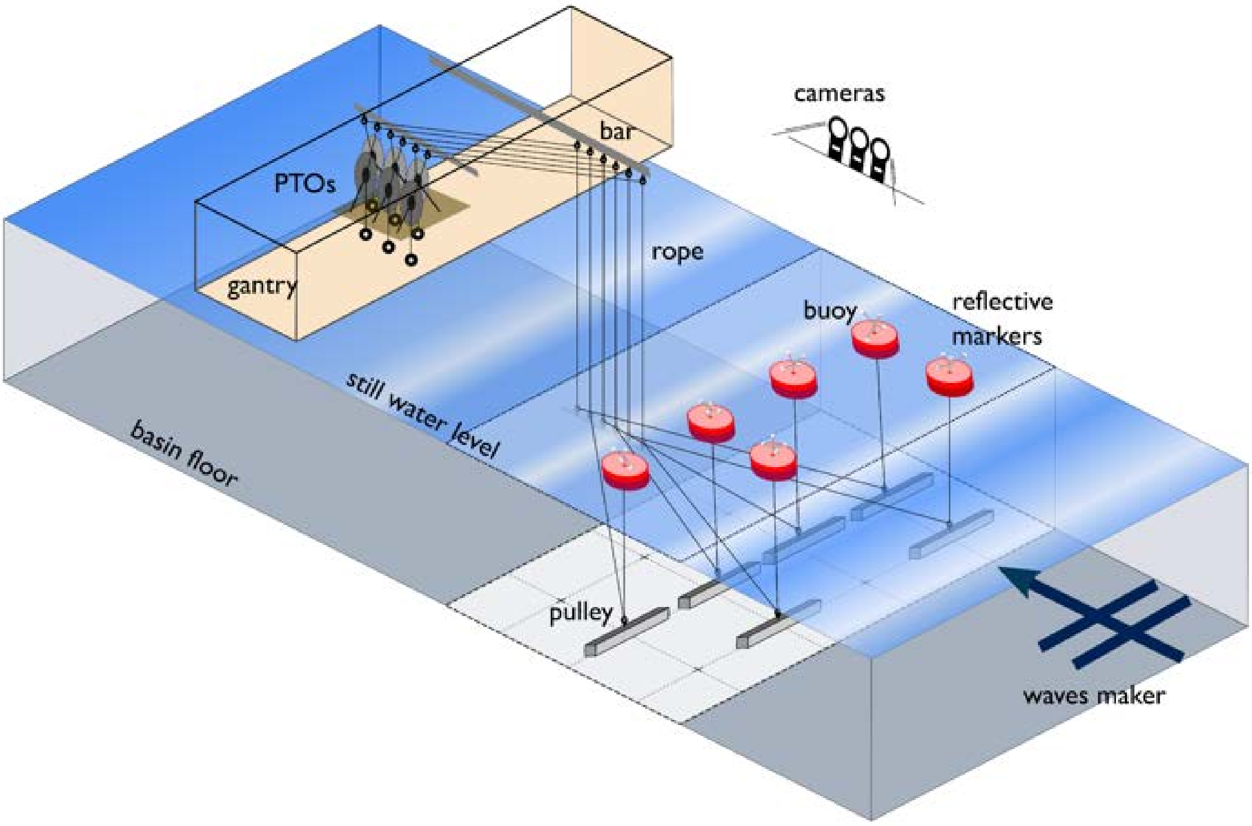

Figure 13: Layout of the array with each WEC moving in 6DOF (from Giassi et al., 2020)

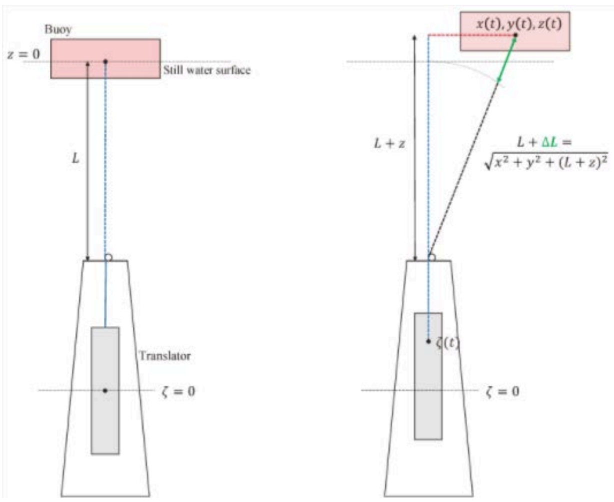

Figure 14: Relative displacement of the floater with respect to the PTO from Giassi et al., 2020.

Advancement in experimental analysis of the WECs farms can be found in Giassi et al., 2020; their work stands out because the analysed six point-absorbers can move in six DoFs. The array is tested both in regular and irregular waves in three different layouts. The full motion of the WECs highlighted that the floats moving also in sway cause the reduction of the shadowing effect. Moreover, as in the single WEC with multiple degree of freedom, the importance of non-linear behaviours is stressed for: 1) the two-body dynamics with different relative displacement of float and PTO due to slack and elasticity in the connection as shown in Figure 14 (mostly in irregular waves) and 2) Mathieu-type instability (mostly in regular waves) (Orszaghova et al., 2019).

From an experimental point of view, tests can be performed either in model test wave tanks or at sea. The two choices have opposite advantages and drawbacks. As for the single device, in the former case, facility biases are magnified (reflexion, incident wave field variations, blockage effects, etc.) and large uncertainties may occur when trying to quantify the relative interactions with the surrounding devices. In the latter case, full scale or large-scale tests can be performed limiting the errors induced by the different scaling laws relative to the different parts of WECs (hydrodynamic behaviour, viscosity, PTO system, mooring system) but it is very expensive, and the environment is difficult to control. For this reason, the recent work on arrays described in Yang et al., 2019, is noticeable because it is one of the few examples of quite well detailed large-scale experimental analysis of an array of WECs. The array is composed of point-raft WECs into three layouts with ten, six or two buoys deployed in real sea conditions in Taiwan Strait, China. Unfortunately, the importance of this paper is diminished by the lack of information about the PTO that is based on mechanical gear transmission of the rotation from the raft to the shaft to a permanent magnet generator (see Figure 15). However, neither the mechanical nor the electrical parts of the PTO are fully detailed and characterized.

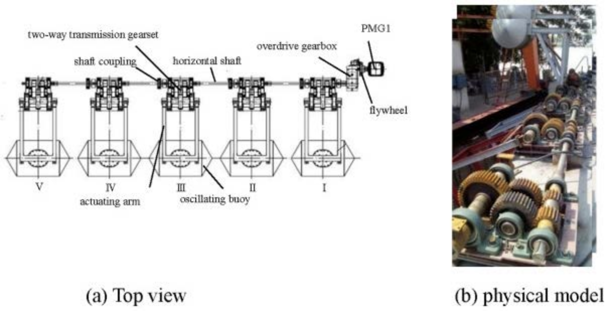

Figure 15: Array drive mode from Yang et al., 2019.

Advancement in numerical simulations of WECs arrays can be found in the full CFD simulations described in Devolder et. al., 2018. There, the numerical simulations of two, five and nine heaving Floating Point Absorbers (FPA) WECs arranged in a geometrical array configuration show the capability of state-of-the-art numerical models to predict the independent motion of closely-spaced WECs in regular waves. The results are compared to the WECwakes project experimental dataset. The paper presents also a percentage evaluation of the differences between numerical and experimental data for different sizes of array and for the heave motion, surge force and wave height in several location inside the array and around it.

7.3.1 Reliability of the results

As underlined in Göteman et al., 2020, the qualification of the reliability of both numerical and experimental data and models is fundamental to further proceed towards the optimization of farms.

In Devolder et. al., 2018., the CFD simulations are carried on with OpenFOAM that fully models the viscous and turbulent effect. There, the largest differences between numerical and experimental data are found in the case with the largest array (9 elements). They are respectively 18% on the surge force, 30% in the wave height and 64% in the heaving motion. Even though, the author claims that the largest difference in the heaving motion were due to different the frictional forces in the PTOs; this paper is one of the few examples where the comparison between numerical and experimental data are used to state the reliability of the adopted numerical models. Moreover, the authors give useful advices on the experimental procedures. For example, they state that fouling can alter the characteristics of sliding mechanism and they highlight the importance of their daily cleaning. They also recommend the validation of the numerical studies with the free decay tests for each individual WEC of the array to estimate the frictional forces due to the sliding mechanisms.

Another important step forward in the assessment of the numerical methods and, in particular, of the Phase-Averaging Wave Propagation Array Models is given in McNatt et al., 2020. There, the spectral wave action balance code SNL-SWAN is compared to the Boundary Element Methods code WAMIT. The comparisons are performed for three types of WECs (pitching flaps, points absorbers, and hinged rafts), for the single WECs or array layouts, in short, medium and long crested waves and with various amounts of directional spreading, Figure 16 compares the solutions for arrays of different types of WECs and WAMIT solutions is as assumed as reference.

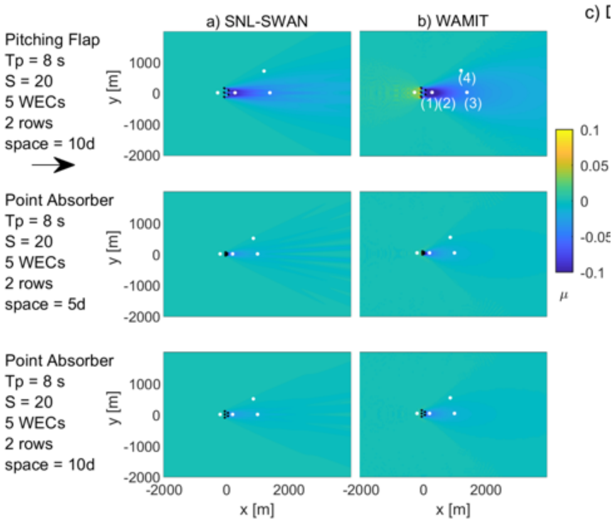

Figure 16: Example of wave field difference between SNL-SWAN and WAMIT from McNatt et al., 2020.

From their analysis, the authors draw the following guidelines for the use of SNL-SWAN:

1. For arrays, the impact of the park on the wave field differs from 20% to 60% between WAMIT and SNL-SWAN, the differences vanish 30 characteristic WEC dimensions away.

2. SNL-SWAN works better for larger spreading of the wave spectrum, consequently unidirectional waves are not well captured.

3. SNL-SWAN application has to be careful in shorter waves where it does not model wave reflection or scattering (including reflections in SNL-SWAN is underway).

7.3.2 Park optimization

The performance of a WECs-park depends on many parameters (layout, number of devices, mooring system, control strategies) that will have a deep influence on the LCOE, reliability of the installation, power production, electricity quality. For these reasons, the late development of the WEC-parks analysis is the introduction of optimization techniques (Sharp et al., 2018, McCarthy et al., 2019, Göteman et al., 2020).

The first studies related to the array optimization described the comparison among several configurations, but little explanations were given on the choices. It further evolved into a *parameter sweep* method, where one single parameter was regularly varied to find the optimal array layout as a function either of the power fluctuation or of the power output (Falvià et al. 2017, Lòpez-Ruiz et. al., 2018).

Because of the many parameters influencing the array performance, the simple sweep over single parameters is not suitable to find the optima, more complex solutions are needed.

The field of array optimization is quite new and there is no winning technique for it. Here we report the most used. One of them is the *nonlinear programming* (NLP) optimization, it is based on constraints and objective function that are nonlinear.

Another approach consists in the *Metaheuristic Algorithm* that looks for the solution space of sufficiently good solution. It is used when the optimization problem is too large to look for all the possible solutions and when the solution space is multi-peaked or when imperfect information is available. Among these methods there are the *genetic algorithms*, the *covariance matrix adaption*, the *differential evolution*, the *particle swarm algorithms* (for a complete description see Göteman et al., 2020).

Moreover, there is the *Bayesian Network approach for a Risk based optimization*, used in McCarthy et al., 2019, that is adopted to analyse the probability of a collision accident within the farm as well as the likelihood of meeting the desired level of power production. It is based on probabilistic techniques, that are well suited to take into account the many uncertainties associated with the WEC-farms analysis and enables to obtain the desired level of production while minimizing the risks associated with the proximity of several WECs.

7.4 Developments in PTO modelling both for physical and numerical prediction of power capture

The WEC PTO systems harvest wave energy through a series of hydrodynamic, mechanical, and electrical processes. In general, WEC devices are classified according to their primary energy conversion principles such as oscillating water column (OWC), overtopping, oscillating wave surge convertor (OWSC), point absorber, attenuator, submerged pressure differential (SPM). There are WECs based on flexible membrane and rotating mass as well. A primary energy conversion of OWC and overtopping type devices transforms wave energy into kinetic and potential energy of fluid respectively, while other WEC devices convert it into dynamic motion of submerged or floating body. The following process and composition of PTO systems varies depending on the characteristic of the primary energy conversion. A typical PTO composition includes appropriate generator and power control system in common and it is distinguished according to WEC devices such as OWC (air chamber, air turbine), overtopping (water reservoir, hydraulic turbine), OWSC (hydraulic pump, accumulator, hydraulic motor), point absorber (heaving buoy), etc.

The WEC PTO modelling is still far from a standardization mainly because of diverse WEC systems. The difference in PTO simulation results can be significant depending on modelling methods. Recent studies on PTO systems includes the nonlinear, unsteady, and viscous properties of the PTO components, which are critical for the accurate performance evaluation. A series of benchmark tests to compare the numerical tools for hydrodynamic modelling of WEC PTOs have been carried out by IEA-OES group since 2016 (Bingham et al, 2021). Research on coupling effects between integrated PTO components has increased as well. The optimal operation considering those interactions may increase wave energy extraction significantly, and it raises the need to develop an integrated WEC simulation tools (So et al., 2016, Penelba et al., 2018).

The OWC devices convert wave energy into oscillating water column in the pneumatic chamber and subsequently produces air flow in the connected duct that runs air turbine. Recent studies of pneumatic chamber include the CFD simulation of resonant sloshing with nonlinear PTO (Xu et al., 2019, Connell et al., 2018), the investigation of air compressibility effect inside chamber by Falcao et al. (2019) and Simonetti et al. (2018). A self-rectifying bi-radial air turbine was examined experimentally by Carrelhas et al. (2020), showing significant improvement of efficiency over a wide range of flow coefficients. An unsteady analysis of a bi-directional impulse turbine coupled with permanent magnet synchronous generator (PMSG) and its controller was carried out by Ezhilsabareesh et al. (2019), suggesting the maximum efficiency tracking for different axial velocities. Kim et al. (2020) analysed the hydrodynamic performance of pneumatic chamber interacting with air turbine based on 3-D potential flow in time domain, addressing that nonlinear flow characteristics depend on incident wave height.

The point absorbers transform wave energy into a moving body that is commonly connected to a direct electrical drive system, and the accurate estimation of its damping parameter is critical in the PTO design of point absorbers. Rodriguez et al. (2019) analysed the damping coefficient affected by wave conditions based on a hybrid method of numerical simulation and experimental measurement. Li et al. (2020) proposed a mechanical PTO using a ball screw and mechanical motion rectifier, converting wave energy into the unidirectional rotational of PMSG. Kong et al. (2019) developed a PTO control method for the optimization of an axisymmetric point absorber in irregular waves and compared the average capture width ratios obtained by time and frequency domain analyses. The latching control of direct mechanical derive PTO system may significantly increase the power extraction by point absorbers, while it raises practical challenges control caused by excessive peak-to-average power ratio (Shadman et al., 2021, Temiz et al., 2018).

The OWSC uses a hydraulic PTO system featured with lower flow rate and higher pressure, and it is commonly equipped with a breaking system to constrain an excessive motion of oscillating structural elements. Calvario et al. (2020) simulated the performance of OWSC concepts with different PTO layout configurations, and compared it to point absorbers, insisting that OWSC devices have less constraint in design optimization and advantage in operational wave condition. Senol et al. (2019) simulated the PTO model of bottom-hinged OWSC equipped with a braking system, proposing a PTO technique enhancing energy harvesting by minimizing engagement of the braking system.

7.5 Survivability for WEC

There are still a lot of unknown related to survivability for WECs. Very few companies who have deployed at full scale have shared any data or information related to the device survival response. There are essentially no publications comparing experimental and/or numerical model testing of survival conditions to full scale applications. And due to the complexity of WEC systems compared to other offshore structures, there is still a strong need to update guidelines, best-practices documents, and standards for the survivability testing of WECs.

The guidelines for Wave Energy Converter Model Test Experiments, the survivability section, has been further extended. Advices have been added regarding the full design framework to obtain the load characteristic of the WEC (fatigue and extreme response statistics) prior to the tests. Once the environmental conditions are identified depending on the type of state conditions (Ultimate Limit States or Accidental Limit States), the details of specific test conditions, the relevant parameters to be included and the quantities to be measured are listed.

8. CURRENT TURBINES

8.1 Benchmark Specifications

To date, much of the data and design geometries for marine renewable devices including current or tidal turbines have been considered propriety or not readily available in the public domain. More recently, for current turbines, a few experimental programs have been conducted for the purpose of validation of CFD predictions or to evaluate the impact of different facilities on test results and turbine performances. The databases for some of these studies are currently or will soon be available online in the public domain. A few of these were summarized in section 5.2. Although each of these databases provide valuable resources, specification for more complete future benchmark studies are needed. Planning for a benchmark should follow guidelines addressed in ITTC 4.0-0.

8.1.1 Objectives

The three key objectives for current turbine benchmarking evaluation would be to

- Understand the bias between experimental testing facilities
- Provide geometry configuration, boundary conditions and performance data for CFD validation and verification
- Provide data to assess performance scaling and predictions tools of full-scale devices.

8.1.2 Facility and turbine configuration

The choice of experimental facility or facilities for current turbines is anticipated to have a more significant effect than for standard open water propellers. This is a result of a higher influence of blockage and the effect of inlet turbulence due to the shorter blade chords. The type of facility used would be dependent on the type of turbine that is needed for the benchmark data. It is also recommended that multi-scale data been considered for any benchmark database in order to develop and confirm scaling both for computational models and for facility performance scaling. The benchmark turbine needs to be non-proprietary and ideally be or already been fielded in order to obtain full-scale data to compare.

The choice of a turbine for any benchmark test will depend on the range of test facility or facilities that would be used. ITTC Procedure and Guideline 7.5-02-07-03.9 has good advice that must be used and followed when planning a current turbine benchmark evaluation. The range of configuration of tidal and current devices can include horizontal-axis, vertical-axis, kite, and shrouded turbines. Although similar, each configuration will have unique characteristics that may need different modelling criteria and hardware and measurement requirements. Benchmarking can and should be accomplished for single rotors, multiple rotors and arrays as flow and wake interactions are important. The horizontal-axis turbine configuration appears to be one of the more popular fielded configurations. The U.S. DOE RM project used two horizontal-axis turbine designs. Given its detailed database, RM turbine (MHKF1) would provide a good candidate to be used for further benchmark studies as the turbine design and details should be soon in the public domain. Other existing turbines databases such as used in round-robin testing (such as Gaurier et al. (2015)) would also provide a good candidate provided further geometry, facility/setup details and data uncertainty were provided.

As tidal/current rotors usually consist of two to three blades with short chord lengths and small amounts of skew or rake, the Reynolds number (Re) based on chord length can be low. Consequently, a section profile with predictable transition is necessary. Some tests have specificity used low Re glider sections (Stallard et al. (2012)) or specially tailored MHK design sections (Shui et al. (2012)). The material choice for the benchmark rotor should be stiff and must exhibit similar deflections at all scales of proposed tests. Inspection and QA measurements of the rotor should be made to ensure that the sections are built to within ITTC propeller model accuracy (ITTC 7.5-01-01-02). For instance, the section form tolerance of 0.05 mm is recommended for the entire blade given these short chord lengths. If tests are performed in facilities of different sizes (“round-robin” style) it would be preferable to also test rotors of different scales to help provide data to access performance scaling assessments and tool validation.

The support structures on which the turbine is attached are usually device dependent. The benchmark testing and any computational evaluations must properly consider and represent faithfully as possible the intended superstructures including the nacelle, PTO housings, supports, and towers of the turbine configuration. The benchmark experiment needs to minimize any hardware needed to support the turbine and measurements as documented those items for digital reproduction. The computational benchmarking should “model-the-model” including all support structures and facility boundary.

8.1.3 Boundary and inflow condition

Turbines typically operate in areas of strong velocity gradients with moderate to extreme turbulence levels and at times oscillating flow patterns. In most facilities, it is difficult to replicate these conditions and by design free stream turbulence levels can be small in most test facilities. Very small-scale turbines have been tested in facilities with roughness elements on the floor of the tank or tunnel but this is difficult to replicate between EFD facilities and to model in CFD so it might not be feasible for in any round-robin benchmarking tests. Removable turbulence generating grids (symmetric and/or asymmetric) or similar devices should be considered in a closed-loop flume or tunnel benchmark test to quantify the sensitivity of turbulent inflow variations on device performance parameters including wake structures and blade forces. These issues are further discussed Section 8.2.

This data would be used to verify CFD tool development. Inflow condition measurements are of upmost importance for the benchmark database. It is recommended that upstream measurements of velocity, velocity profiles and gradients (if applicable) and turbulence quantities be completed as part of the benchmark experiment. This should be accomplished at multiple locations upstream of the turbine. CFD modelling needs to use these measurements as boundary conditions during the evaluation along with all facility boundaries. If the benchmark includes a large-scale fielded device, site surveys need to be completed or collected to provide adequate comparisons to facility configurations and computational model boundary conditions.

8.1.4 Data measurements

It is key for a successful benchmark test that the inflow conditions of all EFD and CFD tests are measured / predicted correctly. In order to confirm data needs the test planning team must include some CFD end users. These end users need to review the test plan and be actively involved with any test readiness review to confirm adequate data quantity and locations. The key components for performance are measurements will be rotor torque, thrust and RPM. Measurements of the direct power generation is highly recommended as is inflow quantities as discussed in prior section. The following measurements should be considered for any benchmark database. These include

- Oil paint visualization of blades and key components to show limiting streamlines to highlight flow structures and separations
- Wake measurements behind the turbine and support structures using PIV, LDV or ADV. These measurements should if possible be synced with rotor position.
- Steady and unsteady loads on single blades using multi-component forces cells or strain gages
- Steady and unsteady loads on support structures such as the tower
- Dynamic pressure measurements on tower to provide load fluctuation data
- Dynamic loads included unsteady rotor torque, thrust and hub side forces. These data will be especially important during any turbulence inflow sensitivity studies
- Flow visualization including mini-tuft
- Cavitation measurements (if applicable for configuration or facility)
- Broadband noise measurements.

8.1.5 Operating conditions

Measurements in unsteady flow are strongly dependent on the PTO system. Most experiment setups use a constant RPM control as it is easier to setup. However, full-scale device will be power or torque controlled. It is recommended that care be taken in datum methodology. The tests should be conducted over a range of TSR achievable for the turbine design and facility. In most cases, this will be done by setting the inlet flow or carriage speed and varying the motor-generator RPM systematically. For closed-loop facilities with pressure control, it is recommended that the pressure be set to at minimum to suppress cavitation and reduce its effect on blade loading during some data runs.

8.1.6 Database

A key to any benchmark database is a well-documented and accessible digital record. This database must include standard neutral format CAD representative (e.g., STEP) of the turbine, support structure and testing facility to allow the computational modelling of the entire configuration. The key data should be processed to provide averages, standard deviations and have uncertainty estimates. The experimental data results should combine Type A and B uncertainties to aid in comparisons. In order to compare the data among different facilities, blockage corrections (e.g., Bahaj et al., 2007) should be applied and documented. The blockage correction can be tested as part of the CFD benchmarking. All data must be provided in a neutral data format.

8.1.7 Evaluation criteria and teaming

It is important for consistent and useful benchmarking that the process includes input from all parties including experimental staff from each facility and computational analysts and tool developers that will use data. This will start with the downselect of turbine design and configurations; baseline data needs and measurement locations. Guidelines for benchmarking are provided in ITTC 4.0-01 (2002). To succeed a set of definitions, evaluation criteria and items like document standard, design and test reviews and data storage need to be agreed upon early in the process. It would be overwhelming to attempt to summarize all the benchmark criteria for both facility and computational efforts in this document. Good practices in QA, data uncertainty analysis, and thorough documentation of the experiment and data is needed from the test team(s). Similarly, the computational and tool end-users must define and use standard criteria such as mesh, grid, convergence and exercising turbulence models (Oberkampf & Trucano, 2002)

8.2 Reproduction at Model Scale of Inflow Turbulence and Unsteadiness

8.2.1 Requirements and constraints

For current turbines to become a commercially viable technology, they must maintain high levels of reliability in the hostile ocean environment as discussed at full scale in Section 6.2.4. Consequently, the turbines must be designed to withstand large unsteady hydrodynamic loads introduced by the presence of waves, turbulence and velocity shear and flow misalignment (e.g., Milne et al., 2017; MacEnri et al., 2013 and Payne et al. 2018).

Of these, the peak loads induced by waves has been suggested to be most significant and can be several orders of magnitude larger than ambient turbulence (Lust et al., 2013). This is however strongly dependent on the type of tidal site. For fatigue both the high cycles due to turbulence and low cycles due to waves and velocity profile need to be understood. The higher frequency associated with turbulence also cause flicker in the output from the generator (MaxEnri at al., 2012).

These key causes of unsteady loads are shown in Figure 17. Unsteady loads result from turbulence, shear flows, waves, surge and flow directionality changes. There are also unsteadiness due flow misalignment (yawed condition) and due to interactions between current turbines within an array.

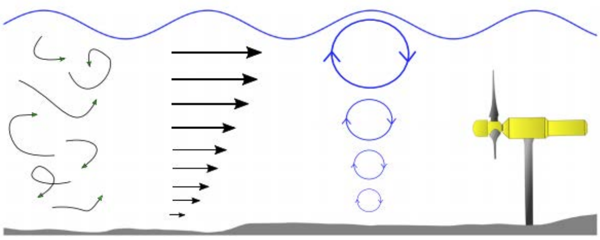

Figure 17: Diagram of the key causes of unsteady loads on tidal turbines (Draycott et al. 2019).

Fully replicating all the unsteady flow features is not considered a realistic option for a single test facility. Consequently, tests are done with simplifications of the environment to produce unsteady flows for validation data.

Experiments with unsteady inflow are typically done to develop and validate the numerical methods than cover a full set of conditions. As an example, Galloway et al. (2014) performed a set of experiments in order to validate Blade Element Momentum Theory (BEMT) code in the presence of waves and yawed flow.

When performing these types of experiments in model test facilities, the most significant considerations, due to operating at lower flow velocities, is the reduced Reynolds number. This is particularly important when reproducing combined current and wave tests that are also Froude number dependent. It, therefore, may be necessary to modify the blade geometry to obtain the correct power and thrust coefficients in the reduced Re regime (Whelan & Stallard 2011).

The other key consideration when performing these experiments is the control strategy. It is typical to use speed control (e.g., Guo et al. 2018), however, implementation of torque control could significantly alter the expected peak thrust, Ordonez-Sanchez et al. (2019). These uncertainties are further discussed in the ITTC Horizontal Axis Turbine Uncertainty Analysis Recommended Procedure and Guideline (7.5-02-07-03.15).

8.2.2 Replicating velocity profile

The use of surface roughness on the bed of long flumes. This produces some non-isotropic turbulence, but these facilities are generally limited to tests with small model scale turbines or turbine simulators. These tests are generally done to help validate simulation tools for modelling CT wakes for array modelling and validation.

8.2.3 Replicating flow misalignment

Several developers have investigating cost saving by design devices that are bi-directional in design and not requiring a yaw mechanism. This has been successfully achieved by pitching the blades 180 degrees and running in reverse. However, most tidal sites have some bias due to the bathymetry and consequently, the flow is not truly bi-directional. This unsteady effect can be readily replicated in the test facility by changing the angle of the model is to the flow direction (E.g., Galloway et al., 2014).

8.2.4 Replicating turbulence

When developing a velocity profile in a circulating water channel or tunnel with bed roughness the background turbulence in the facility will also increase. This may resemble some parts of the turbulence spectrum.

The use of screens and grids to generate turbulence has been used (E.g., Blackmore et al., 2016). However, the turbulence generated may have intensity values at the turbine location close to real conditions but isotropic in nature and with different length scales. The non-isotropic nature of tidal flow is particularly dominant in shallow water.

The inverse of the normal configuration is done at IFREMER's circulating water channel where the flow conditioning units are removed. This increased the level of streamwise turbulence intensity from 3% to 12%. Payne et al. (2018) experiments using this facility found that for frequencies below the rotational frequency, load spectra are correlated to spectral density of the onset flow velocity. Above the rotational frequency, loads are mainly affected by turbine operation phenomena. The tower shadowing effect is clearly identified through frequency and angular analysis.

8.2.5 Replicating combined waves and current

The use of circulating water channels with combined with currents. This is limited to very few facilities such as the FlowWave tank at the University of Edinburgh. In this facility an experimental assessment was conducted on tidal turbine loading from irregular waves over a tidal cycle (Draycott et al., 2019b). During this experiment, the standard deviations of measured turbine parameters for the opposing condition range between 215 and 260% of the following case, and between 340 and 565% of the current-only measurements. An example set of results is shown in Figure 18. This confirms that greater fatigue damage will be accumulated during one-half of the tidal cycle. The mean values, however, appear to be unaffected by the presence of waves suggesting that the overall turbine performance is unaltered.

Similar effects were also demonstrated in Guo et al. (2018) experiments in a towing tank. Although the range of standard deviations in torque and thrust were noticeability less. This may be due towing tank tests not replicating the interaction between the current and wave that is only possible in circulating water facilities.

This is also evident in the experiments of Ordonez-Sanchez et al. (2019) performed in a towing tank with waves where the effect of two different power control strategies were included.

The influence of combined turbulence and opposing waves has also been studied as an example of an extreme case (Fernandez-Rodriguez et al., 2014). Wave kinematics are not strictly sinusoidal due to interaction between waves and large-scale turbulence of the opposing flow, but linear theory provides velocity at hub height to within 77%. Applying this force prediction method with a thrust coefficient of 2.0 provides extreme thrust forces.

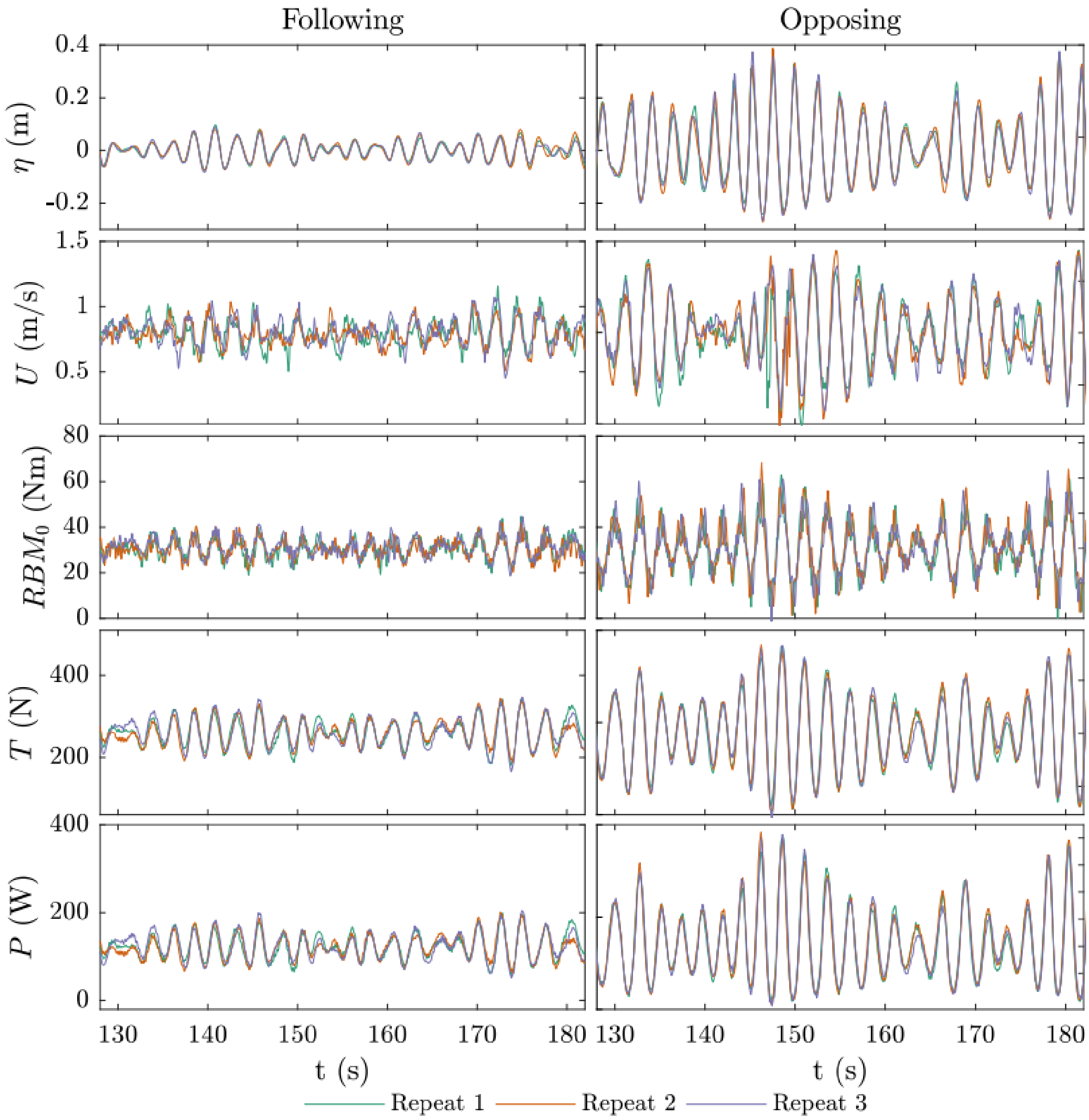

Figure 18: Time-domain results of key environmental and turbine parameters for the opposing and following wave conditions. The three repeats of each conditions are shown for each parameter; H is the surface elevation; U is the streamwise velocity, 0.4 m beneath the surface;. RBM_0 is streamwise blade root bending moment sensors; T is rotor-based thrust measurement; P is rotor power.

8.2.6 Interactions within an array

Within an array of current turbine there can be both flow acceleration due to blockage and unsteady wakes. This interactions with the background turbulence have recently been studied for an arrangement of three turbines (Gaurier et al. 2020). For the configuration tested the analysis of the power spectral density functions of the downstream turbine torque and thrust showed no signature of the upstream turbines. Numerical modelling of this interaction is discussed in Section 8.3.

8.2.7 Numerical modelling turbulence

The key point in inflow turbulence is more on the real spectrum of the site data. How to recreate the inflow in the numerical tool. For example, Ebdon et al. (2021), analysed inflow turbulence extensively by conducting a wake flume experimental test and then introducing them into a RANS code. Ahmed et al. (2017) tried to implement the EMEC site data into RANS and LES code to analyse the inflow impact. Stevens (2017) presented an overall analysis on Cook Straight in New Zealand. Du et al. (2016) presented a site survey on the turbulence impact in Zhoushan Site, China). They all concluded that the site measurement with ADCP is not sufficient for detailed analysis for turbulence load on rotor blades.

Several papers have reported numerical investigations on inflow turbulence that site data might not cover. For example, Togneri et al. (2021) compared a few different numerical methods for modelling inflow turbulence. Arini et al. (2018) proposed a 2D numerical method to analyse inflow turbulence impact on vertical axis tidal current turbine. Hu et al. (2017) conducted a comprehensive analysis of the relationship between inflow turbulence condition and array performance by utilizing LES method. This research provides important support for modelling tidal current turbine array.

8.3 Current Turbine Array Modelling

With the improvement of tidal current turbine technology, there have been extensive studies on tidal current turbine modelling (Nachtane et al., 2020). A number of researchers still focused on improving the standard array modelling approaches. They extend these approaches by introducing new descriptions of physics or trying to combine different sub-categories methods together. For example, Gajardo et al.(2019) developed an approach combining BEM and DES to study tidal current turbine wake. Ma et al. (2018) proposed both a theoretical and CFD combined methods for vertical axis tidal current turbine array performance evaluation. Bonar et al. (2017) developed a theoretical method to analyse the performance of a non-uniform array in a uniform inflow. Hu et al. (2017) improved the LES-ALM methods to study tidal turbine array with different inflow conditions. Nuernberg & Tao (2017) demonstrate the utilization of the dynamic mesh with RANS to simulate tidal current turbine array.

Some researchers have also started to work on the free surface impact on the array performance. This is a particularly important physics, which was only evaluated theoretically in the past. Li et al. (2021) presented a recently developed high efficiency RANS code that can evaluate the wave impact on tidal current turbine array wake and quantified the wave impact. Kolekar et al. (2019) improved an existing theoretical assessment method on free surface effect on turbine array performance. Draycott et al. (2019) presented their recent experimental investigation on wave effect's impact on array performance. Sufian et al. (2017) have shown numerical simulation on the wave impact by introducing wave induced velocity into the CFD model.

Furthermore, researchers have begun to also introduce turbine control algorithm within array modelling. These are implemented either numerically or experimentally. For example, Delafin et al. (2021) discussed the array performance with variable active pitch control. Zhao et al. (2020) introduced a torque control algorithm into actuator line method. Gu et al (2018) demonstration a blade pitch control algorithm with field test. Wang et al. (2018) developed a new approach combining the vortex method and geometrically exact beam theory to study the dynamic response on turbine blades in an array. Mannion et al. (2018) showed a numerical simulation result on a vertical axis turbine array with variable pitch control.

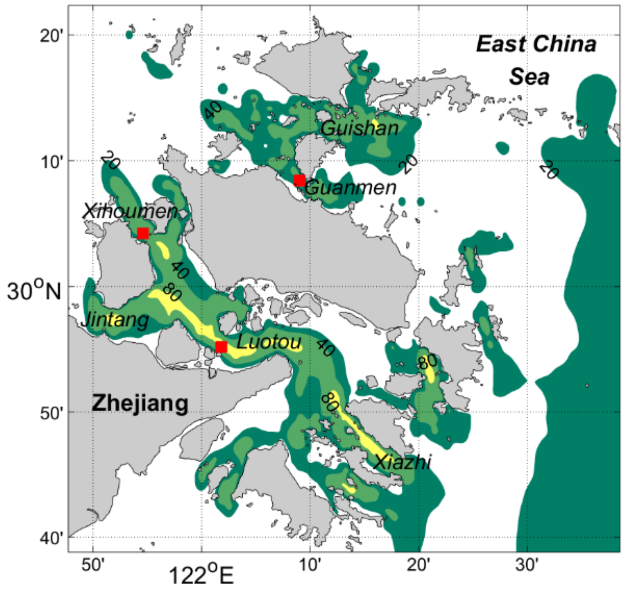

Figure 19: Tidal Power and Local Flow:A-Zhoushan Site-China(Deng et al 2019).

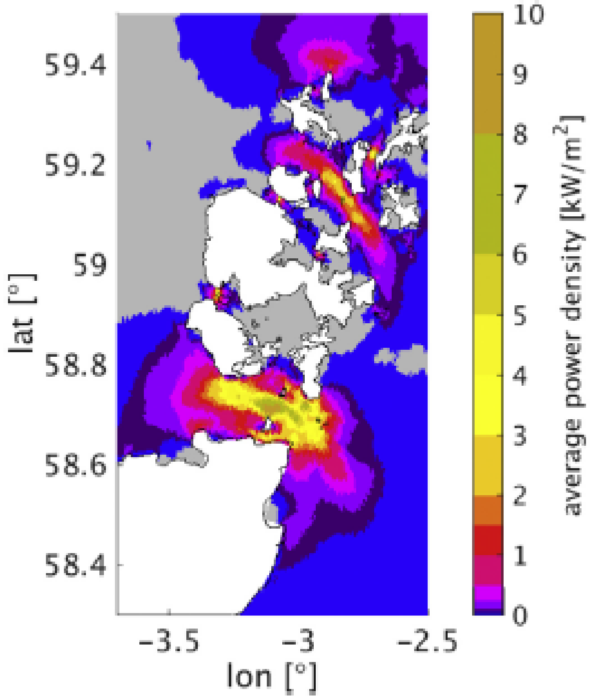

Figure 20: Tidal Power and Local Flow: Pentland Firth,UK(De Dominicis et al. 2017).

Interaction between ambient flow and tidal current turbine array also becomes a hot topic. Tidal current turbine array may affect the local channel flow and even regional ocean current. For example, Deng et al. (2019) discussed a tidal array performance in Zhoushan area China with realistic local ocean flow by utilizing (Regional Ocean Modelling System). They found that when the scale of the tidal current turbine farm is large enough, the array will pose noticeable impacts on the local environment. Musa et al. (2018) conducted a large eddy simulation to investigate the array performance in a channel with large migrating fluvial bedforms. Du Feu et al. (2017) introduced a new approach for investigating trade-offs different objectives of developing tidal current turbine array with a focus on impact on the local flow. In this study, they developed a numerical tool. De Dominicis et al. (2017) utilized Finite Volume Community Ocean Modelling to simulate the performance of UK tidal current turbine farm Pentland Firth and its environmental impact.

9. OFFSHORE WIND TURBINES

9.1 Development of testing methodology for offshore wind turbines

Offshore Wind Turbines are complex dynamical systems, exposed to both hydrodynamic and aerodynamic loads, and their global response is also strongly influenced by the wind turbine controller (Goupee et al. 2014; Goupee, Kimball, and Dagher 2017).

There are two major challenges related to wave tank testing of offshore wind turbines (Sauder 2018):

- Generation of high-quality wind in tank facilities.
- Incompatibility between Froude and Reynolds scaling laws.

The wind field in hydrodynamic facilities is generally of poorer quality than what can be obtained in wind tunnels (Wendt, Robertson, and Jonkman 2017; Allen and Goupee 2017). Although efforts are being made to increase the capacity of wind generation in such facilities (e.g., Wind-Wave basin at the University of Maine), there is still a quality imbalance between the waves/current and the wind generation. Wind tunnel facilities with towing tank below exist but the size of the basin and the capacity to generate waves are significantly reduced compared to state-of-the-art ocean basins.

As for the latter, the similitude relationships (through scaling laws) are essential for interpretation of experimental data and for scaling up results for the prediction of how the prototype will behave. Hydrodynamic tests are usually governed by Froude scaling due to the dominant gravity and inertia loads, but viscous loads are important for the modelling of aerodynamic loads on a wind turbine. For practical purposes, however, it is not possible to satisfy all scaling laws simultaneously and there will be a mismatch of flow conditions between the prototype and the model. This difference is referred to as scale effects and is mostly related to difference in Reynolds number in model and full scale.

Until recently, these two challenges have been addressed by improving the capacity of wind generation in hydrodynamic laboratories, and by re-designing the rotors models with the aim to model full-scale aerodynamic loads (Borg 2018; Courbois 2013; de Ridder et al. 2014). Allen and Goupee (2017) noted that large uncertainties remain regarding the aerodynamic loads generated with such approaches, in particular the representation of rotor torque and gyroscopic effects. In addition, a performance scaled rotor will require a redesign of the model scale wind turbine controller to provide the same control characteristics as the prototype due to the differences in the rotor performances and inertial characteristics (Fontanella et al. 2019; Yu et al. 2017)

The two challenges can also be addressed by using Hardware-In-the-Loop (HIL) testing, also known as Real-Time Hybrid Model testing. The problem is then broken down into several physical and numerical substructures, which are interconnected in real-time. For model testing of offshore wind turbines, the structure is broken into one substructure for hydrodynamic loads and one for aerodynamic loads. Depending on the testing facility (hydrodynamic laboratory or wind tunnel), one substructure is physically represented and the other represented by a numerical model.

In the following subsections, the most common approaches of modelling the wind turbine in scaled model tests are further discussed, namely using physical rotors or hybrid methods. Simplified and passive methods such as simulating the steady wind load by weights connected via wires or drag discs are discussed in e.g., ITTC Recommended Guidelines 7.5-02-07-03.8.

9.1.1 Geometrically scaled rotors

The need to model the wind turbine controller has been the motivation for including a physical rotor in hydrodynamic experiments. Other advantages with a physical rotor are the inclusion of 3p excitation, as well as better modelling of aerodynamic damping and the influence of the platform motions on the aerodynamic rotor loads. Initially, these tests used geometrical and Froude scaling of the rotor, (e.g., Molin, Remy and Facon 2004, Nielsen, Hanson, and Skaare 2006, Robertson et al. 2013).

The DeepCwind consortium studied three different floaters (spar, semi, and TLP) in their test campaign (Robertson et al. 2013). Detailed analysis of the aerodynamic performance of the scaled rotor is given in (Martin 2011; Martin et al. 2014) and is summarised below.

The main parameters characterising the performance of a rotor are the thrust coefficient $C_T=T/(½\rho_a U^2 A)$ and the power coefficient $C_P=Q\Omega/(½\rho_a U^3 A)$, where U is the wind speed, A is the swept rotor area, ρ_a is air density, T is the rotor thrust force, Q is the rotor torque and Ω is the rotational speed. These characteristics are usually given as function of the tip speed ratio TSR=Ω*R/U* where *R* is the rotor radius. Maintaining the TSR ensures the correct rotor rotational speed as well as any system excitations related to the rotor rotation. Using Froude scaling, where ratio between inertial and gravitational forces are preserved between prototype and model scale, will scale wind speed to maintain the ratio between wind speed and wave celerity.

For aerodynamic performance testing of a wind turbine, the scaling is aimed at preserving the Reynolds number, which is the ratio between inertial and viscous loads. A large difference in Reynolds number was found when performing model tests in a hydrodynamic facility based on Froude scaling. Initially, it was expected that the difference in Reynolds number between model and prototype scale would only have a minor effect on the aerodynamic performances of the rotor due to the potential nature of the lift at small angles of attack. However, the wind turbine profiles that were originally designed for high Reynolds numbers operated now at low Reynolds number, where the blade lift and drag coefficient were found to be much smaller. Since the blade lift is nearly perpendicular to the rotor plane, reduction of the lift force causes a reduction in rotor thrust. Since blade drag is nearly in the rotor-plane, increase in the blade drag will cause a significant reduction in the rotor torque and therefore a lower power coefficient.

To overcome this scaling incompatibility, three different solution were proposed by Martin et al. (2014): adjustment of the thrust by increasing wind speed, addition of roughness on the blade profile, or redesign of the wind turbine blade, where combinations can be considered.

In the first phase of the DeepCwind model tests they adjusted the wind speed to match the thrust force on the rotor (Robertson et al. 2013). The main load components transmitted from the wind turbine to the supporting structure are the gyroscopic moment, the rotor torque, and the rotor thrust. The gyroscopic moment is conserved as long as the mass of the rotor is correctly modelled, and the rotational speed is Froude scaled. To match the rotor thrust, the wind speed was increased by approximately a factor of two. The rotor torque was accepted to be much smaller than specified since it is considered to be less important than the thrust.

Although it is possible to achieve proper mean thrust by increasing mean wind speed, it does not necessarily preserve the same change in thrust due to platform motions, inflow wind speed, and blade pitch angle, as the prototype. The influence of the increased wind speed on the aerodynamic damping due to the platform pitch motions close to the natural frequency was described as representative by Martin et al. (2014). On the contrary, Hall and Goupee (2017) reported a reduced damping due to relatively smaller changes in the relative wind speed due to the pitch motions. The TSR could no longer be maintained when the wind speed was increased. The excitations increased for tests with dynamic winds due to the increased mean wind speed (Kimball et al. 2014).

Adding roughness to the rotor blades to trigger a transition from laminar to turbulent boundary layer flow was tested by Martin et al. (2014) and Courbois (2013). It was found to have a positive, but not sufficient, influence on the rotor thrust at high TSR. Use of artificial roughness should be done with care due to the sudden nature of the transition away from laminar stall.

9.1.2 Performance scaled rotor

Redesign the model blade profile was the third approach proposed by Martin et al. (2014). In this case, low-Reynolds number profile with lift and drag coefficients equivalent to the prototype blade profile is used for the model tests. This type of scaling is called performance scaling. More details about the performance scaling method are given in Martin (2011) and Fowler et al. (2013). It was also used by de Ridder et al. (2014) for the building of the MARIN Stock Wind Turbine (MSWT) model which was used for the DeepCwind phase 2 model tests (Goupee et al. 2014).

Redesigning the blades according to performance scaling will allow for Froude-scaled wind and will give realistic modelling of variations in thrust due to platform motions, variations in wind speed, and blade pitch angle. In the scaling process, the blade mass, blade length and rotor rpm are scaled according to Froude scaling preserving gyroscopic loads. The blade profiles, cord length and twist angle are then modified to achieve the Froude scaled rotor thrust over the range of TSR of interest.

The rotor torque is only a secondary target in the blade redesigning step as it is considered less important for the overall dynamics. For instance, the overturning moment due to the turbine torque is approximately 5% of that due to rotor thrust at rated wind speed for the 5MW NREL turbine (Fowler et al. 2013). On the other hand, approximate modelling of the power coefficient is required to study the controller performance on the power production. The power coefficient is smaller at model scale due to the larger drag observed at model scale, which affect the torque and therefore the power.

A combination of increasing the wind speed and redesigning the rotor was used by Courbois (2013) to model the correct wind turbine thrust. The blade profile was similar to the prototype, but the blade twist was adapted to better replicate the rotor thrust. The wind speed was higher than Froude-scaled values, and consequently, the TSR was not correctly modelled.

Borg (2018) presented a different approach for performance scaling where the goal was to maintain the slope of the thrust as function of TSR, not only the thrust. This ensures better modelling of the unsteady aerodynamic loads that comes from the platform motions, wind fluctuations, and blade pitch control.

9.1.3 Challenges and limitations with physical rotors

In addition to the Froude and Reynolds scaling law incompatibility described above, there are a few other challenges and limitations related to using a physical rotor for wave tank testing of offshore wind turbines. These includes:

- Mass of the model RNA (Rotor-Nacelle Assembly).
- Interference from the instrumentation cable.
- Model scale wind turbine controller.
- Generation of high-quality wind field.

A fully instrumented physical rotor in model scale is likely to be heavier than the down-scaled mass of the prototype RNA (Gueydon 2016, DNV 2019). This is a larger challenge for smaller model scales. To overcome this problem, masses in the support structure can be shifted around to maintain the global moments of inertia and CoG. Also, elements from the RNA model such as motor, transducer and encoder can be moved to the base of the tower with the rotor connected via a shaft in the tower in order to meet target design mass (Ward et al. 2018). Deviations from the target mass distribution can be of importance for the structural modes and force measurements of the tower if an elastic model of the tower is applied. The influence of this deviation can be investigated numerically to determine which results from the model tests that will be inaccurate due to the mass deviation (DNV 2019).

The instrumentation and power cables can influence the motion response of a floating wind turbine model. A free-hanging cable will contribute with additional weight and aerodynamic drag forces in the experiments. Cable influence on the platform response has been reported for the first phase of the DeepCwind model tests (Robertson et al. 2013). It is recommended to use a thin, flexible, and light cable instead. Else, the cables influence on the floater motion should be evaluated in the model set-up, e.g., by comparing free decay tests with and without the cables present (DNV 2019).

The model scale wind turbine controller must be re-designed to account for the differences between model scale and prototype rotor aerodynamic behaviour and inertial characteristics (Fontanella et al. 2019). A reduced order model can be used to tune the model scale wind turbine controller to achieve the same operating behaviour between the model scale and prototype wind turbine (Fontanella, Bayati, and Belloli 2018; Yu et al. 2017).

Wind generation in hydrodynamic facilities are not as consistent as can be expected in a wind tunnel. As reported from the DeepCwind model tests (Robertson et al. 2013), drop-offs in the wind velocity, increased turbulence at the edges of the rotor plane, and low-level swirling behaviour induced unwanted excitation in the system.

Molin, Remy, and Facon (2004) investigated the importance of the quality of the wind generation in hydrodynamic facilities. Their main concern was that unwanted turbulences and spatial-temporal in-homogeneities in the wind field could give rise to parasitic excitations triggering resonant modes. They compared tests with fans setup in an offshore basin with tests in a wind tunnel-wave basin facility at IRPHE , based in Luminy (France). Unfortunately, the experiments were inconclusive because the results were affected by an imbalanced rotor.

Courbois (2013) developed a wind generating system based on centrifugal pumps at the testing facilities of the Ecole Centrale de Nantes (ECN) to avoid twisted flows caused by axial fans. The system was developed to operate at higher wind speeds than typically Froude-scaled wind speeds. Due to the weight of the centrifugal fans, they had to be mounted on land and attached to the diffuser in front of the model via a flexible tube.

More advanced systems use a set of screens and honeycomb to enhance the quality of the wind field. Screens have the same effect as a section reduction, by minimizing longitudinal turbulence and spatial homogenisation of the mean velocity. The honeycomb reduces the lateral turbulence components. For the DeepCwind tests (Robertson et al., 2013) the wind was generated by a set of 35 fans with a honeycomb front plate to reduce swirl and a nozzle to reduce turbulence. Counter rotating fans were used to reduce swirls generated by the fans.

Hall and Goupee (2017), Goupee et al. (2017) and Thys et al. (2018) demonstrated the significance of turbulent wind in tank testing of floating wind turbines. The wind turbulence was observed to introduce substantial low-frequency excitation. The behaviour of the wind turbine and its controller is also sensitive to the type of wind field (steady vs turbulent) as shown by Goupee et al. (2014). The blade pitch controllers tended to increase the platform's pitch response in steady wind cases compared to similar tests with no blade pitch controller. On the other hand, for tests in dynamic wind the damping levels were found to be similar for cases with and without controller.

Advanced fan-based wind systems can produce wind spectrums by adapting the power input frequencies. As indicated by Goupee et al (2017), the current state-of-the-art of open-jet wind generation machines is limited to temporal variations with no spatial variations. The NPD spectrums are well suited for this, since only the temporal variations in the longitudinal direction are prescribed and no realistic spatial variations in the wind characteristics are given. Allen and Goupee (2017) observed from numerical and experimental studies that using the NPD spectrum gave lower responses than a more realistic Kaimal spectrum for very low frequencies. They indicated that it could be wise to develop better means of generating full-field, turbulent winds in model testing of floating wind turbines. Wind turbulence may also excite responses at higher frequencies. Significant blade-root and tower-top bending excitation at 1p and 3p frequencies, respectively, reflect the spatial wind speed variations in the turbulent wind field (Hall and Goupee, 2017).

The use of a combined wind-wave testing facility, such as LHRI (France), NMRI (Japan), Newcastle University (UK), and the Harbin Institute of Technology (China), presents an alternative to installing the wind-generating system in an existing hydrodynamic testing facility. While these facilities represent the advantage of high-quality wind production, the small size, and the limited capacity to generate waves are significant disadvantages.

9.1.4 Hybrid testing

The limitations and challenges mentioned above have led to alternative methods for model testing of floating offshore wind turbines in the form of hardware-in-the-loop or real-time hybrid model testing. For consistency, these types of tests will be referred to as hybrid testing.

As summarised by Chabaud et al. (2013), early interest in hybrid testing, and the possibility to combine experiments with numerical simulations, goes back to the 1970's for testing of buildings under seismic loads. Other applications can be found in the automotive industry but also within renewable energy. The earliest reference to hybrid testing in marine technology is made in Buchner (1999) and Cao and Tahchiev (2013) where hybrid testing is proposed as a solution to overcome the wave tank depth limitations when testing moored structures in ultra-deep water.

The Ecole Centrale de Nantes performed in 2013 a hybrid tests with a floating wind turbine where the rotor thrust was modelled by use of a ducted fan (Azcona et al., 2014). Numerical simulations computed the aerodynamic thrust in real-time which then was applied to the model using a ducted fan. The thrust from the fan was controlled using an open-loop system where the relation between fan speed and thrust was obtained from static tests. Figure 21 shows the ducted fan from the EU FP7 INNWIND tests (Aszcona et al. 2016).

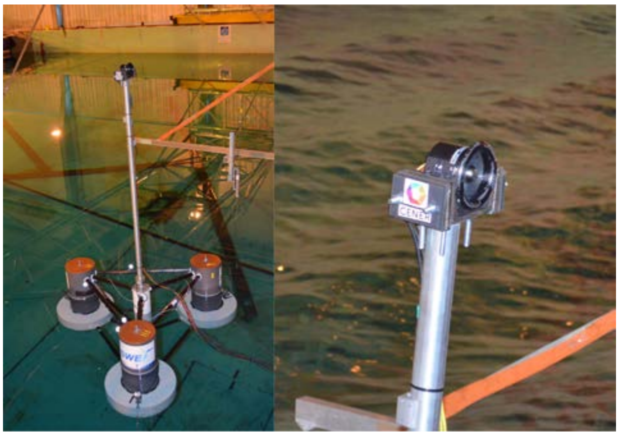

Figure 21: Hybrid testing with a single ducted fan used in the EU INNWIND-project (courtesy of CENER).

A sensitivity study showed that other rotor loads than the thrust could have a significant impact on the tower loads, motions, and mooring line tensions of a semi-submersible FOWT (Bachynski et al., 2015). To include additional rotor loads, Sauder et al. (2016) used a cable driven parallel robot connected to a frame at the tower top of the FOWT model. The robot was controlled based on a closed loop system, and all the rotor loads except for the vertical rotor loads, were applied on the model. The performance of the hybrid method, referred to as ReaTHM (Real-Time Hybrid Model) testing, is verified by means of calm water decay tests with the hybrid system in following mode (i.e. connected to the model with zero net load applied), by repetition tests and by comparison of requested and measured rotor loads. The system was found to work for the main frequencies of interest (up to 2Hz model scale). Furthermore, fault conditions including blade failure and emergency shutdown were tested.

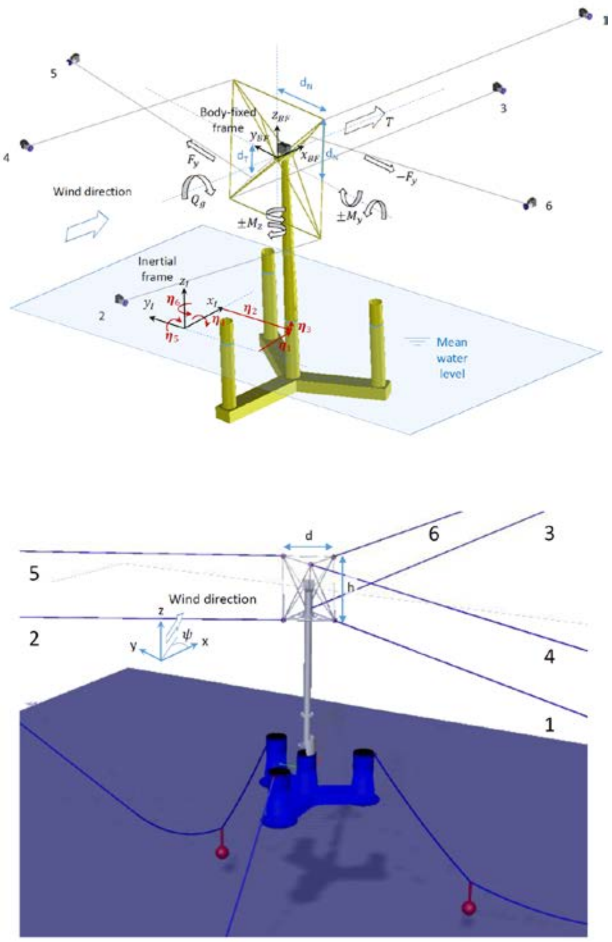

Figure 22: Real-Time Hybrid Model (ReaTHM) testing setup with cable driven parallel robots: NOWITECH (top); LIFES50+ (bottom). From Chabaud et al. 2018.

The hybrid testing with cable driven robots, initially developed for the NOWITECH CSC FOWT tests, was further improved for the EU H2020 LIFES50+ ocean basin tests (Chabaud et al., 2018; Thys et al., 2018). The frame for the cable attachment points on the wind turbine tower was reshaped into a square pyramid frame, which allowed for more flexible multidirectional modelling of the wind loads, including the effect of rapid changes of wind direction during the tests (see Figure 22). The bandwidth of the LIFES50+ tests was increased to blade sweeping (3p) frequency or up to 3-4Hz in model scale, while the bandwidth of the NOWITECH tests were set to wave frequency or up to 1-2Hz in model scale. The cable driven parallel robot setup was also applied in the WINDMOOR project for testing a 12MW floating wind turbine, see Figure 23 (Thys et al., 2021).

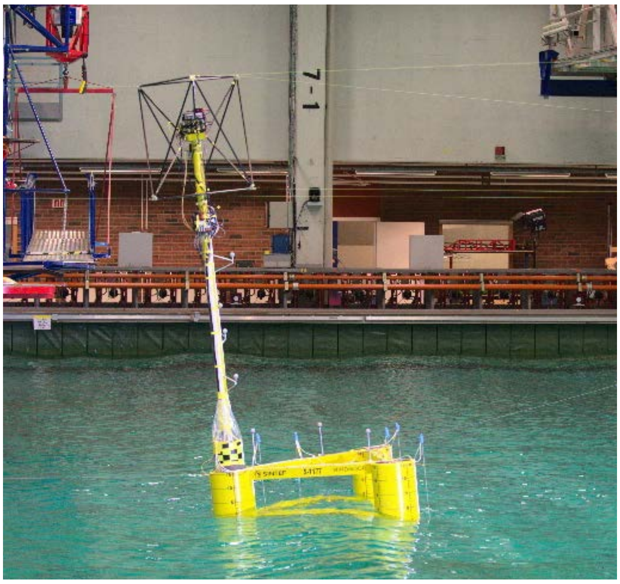

Figure 23: Real-Time Hybrid Model (ReaTHM) tests of the INO WINDMOOR 12MW FOWT (courtesy of SINTEF Ocean).

As an alternative to cable driven robots, a multi-fan or multi-prop actuator can be applied for emulation of multiple degrees of rotor loads. The idea is an extension of the single ducted fan actuator, which is limited to the modelling of thrust force only. By applying multiple propellers spread out in a similar configuration as a drone it is possible to include out-of-plane rotor moments (see Figure 24). Such system has been developed and tested for a four-propeller actuator (e.g., Pires et al., 2020; Fontanella et al., 2020; Vittori et al., 2021) and for a six-propeller actuator (e.g., Urbán and Guanche, 2019, Jurado et al., 2017).

Hall et al. (2017) validated the hybrid testing technique by comparing model tests with a semisubmersible FOWT using two different rotor thrust modelling techniques: 1) hybrid testing with a single cable driven robot and 2) physical wind-driven performance scaled rotor. The agreement between both methods was found to be good, but the importance of true-to-scale turbulent wind demonstrated the value of hybrid testing.

Figure 24: MARINET2 tests with CENER's multi-fan actuator system tested at MARIN (courtesy of CENER).

The hybrid testing technology for hydrodynamic tank tests has a clear advantage over conventional methods when it comes to modelling of a realistic three-dimensional turbulent wind field. Together with the improved rotor loads emulation, hybrid testing methodology offers an effective tool for the development and validation of control strategies for floating offshore wind turbines (Fontanella et al., 2020). Hybrid testing is also very suitable for calibration of hydrodynamic coefficients in numerical simulations models since the aerodynamics loads can be controlled and documented from the tests with high accuracy. It does also have the flexibility to model various load cases with fault conditions.

Hybrid testing of FOWT in wind tunnel facilities has been developed in parallel with hybrid wave tank testing (Bayati et al., 2013). In these tests the wind turbine aerodynamic rotor loads are reproduced by a scaled rotor model exposed to physical wind combined with a numerical hydrodynamic model of the platform providing real-time rigid-body motion. The computed platform displacements are imposed to the wind turbine model using a parallel kinematic robot (see Figure 23). The hybrid wind tunnel tests were initially performed for 2DOF floater motion but was later expanded to 6DOF (Bayati et al., 2014; Belloli et al., 2020). The wind field in a wind tunnel is of higher quality than what can be achieved by an open-jet wind generating system normally used in a hydrodynamic test facility. Thus, hybrid testing in a wind tunnel is a good alternative way of investigating unsteady aerodynamic loads and wind turbine controller actions on the overall dynamics of the floating wind turbine.

Figure 25: 6DOF hybrid setup of a floating wind turbine in a wind tunnel (from Belloli et al., 2020; courtesy of Politecnico di Milano).

Hybrid testing opens new opportunities, but it should also be applied with care. Documentation and verification of the setup should be carried out prior to testing, and the performance of the hybrid system should be closely monitored during testing. Time delays from simulations, data transfer and actuator response may cause additional damping or introduce spurious energy into the system. The capacity of the actuators must be carefully considered for relevant ranges of frequencies and magnitudes of load components when designing the experimental setup. As demonstrated by Gueydon et al. (2018), the use of a hybrid system outside its bandwidth may lead to unwanted responses in the system. Also, the accuracy of the wind loads is limited by the accuracy and correctness of the numerical simulation model.

9.2 Existing regulations related to model tests of offshore wind turbines

This status report presents the existing guidelines and standards addressing the model tests of offshore wind turbines published by classification societies, including ABS, BUREAU VERITAS, DNV, and Class NK as well as IEC IS 61400-3-1, IEC TS 61400-3-2 and ISO 29400.

These regulations are as follows:

- IEC TS 61400-3-2, Design requirements for floating offshore wind turbines, April 2019;
- IEC IS 61400-3-1, Design requirements for offshore wind turbines, April 2019;
- ISO 29400, Ships and marine technology - Offshore wind energy - Port and marine operations, May 2020;
- ABS, Guide for Building and Classing Bottom-Founded Offshore Wind Turbine Installations, July 2020;
- ABS, Guide for Building and Classing Floating Offshore Wind Turbine Installations, July 2020;
- BUREAU VERITAS NI 572, Classification and Certification of Floating Offshore Wind Turbines, January 2019;
- Class NK, Guidelines for Offshore Floating Wind Turbine Structures, July 2012;
- Class NK, Guidelines for Certification of Wind Turbines and Wind Farms, May 2014;
- DNV, DNVGL-RU-OU-0512, Floating offshore wind turbine installations, October 2020;
- DNV, DNVGL-ST-0126, Support Structures for Wind Turbines, July 2018;
- DNV, DNVGL-ST-0119, Floating Wind Turbine Structures, July 2018;
- DNV, DNVGL-SE-0422, Certification of Floating Wind Turbines, July 2018;
- DNV, DNVGL-RP-0286, Coupled analysis of floating wind turbines, May 2019;

Societies have acted in competition with one another and in concert with the national and international standards agencies to provide sets of rules and design appraisals for the offshore wind turbine (floating or fixed) industry. A more nebulous, but nevertheless crucial, role has been as a central 'repository' of knowledge and experience. (Garrad, 2012) The development of the standards and rules and their application to offshore wind turbines (floating or fixed) have allowed the offshore wind turbine industry to gain confidence in the designs. Also, the standards and certification on offshore wind turbines (floating and fixed) address how they are about to change from addressing prototype installations with a few unit to large scale floating offshore wind farms consisting of many identical units.

Utilizing the experience and lessons learned from certifying based on standards can make the offshore wind turbine (floating or fixed) industry to know where the largest cost savings can be found and how standards and certification can be used to eliminate risk from the project while maintaining the same level of confidence.

It has been found that the other regulations do not include the guidelines or procedures for the model tests, but they referred to the need of model tests for specific topics like air gap, verification of coupled analysis codes, etc. Model tests may be carried out to assess a wide range of issues. The items listed in DNVGL-RP-C205, Environmental conditions and environmental loads, December 2020 are also relevant for offshore wind turbines:

- Hydrodynamic load characteristics
- Global system concept and design verification
- Individual structure component testing
- Marine operations, demonstration of functionality
- Validation of numerical models
- Estimation of extreme loads and response.

In addition to these, model tests of FOWTs are carried out to understand the loading mechanisms and relative importance of and coupling between different environmental loads. A good control of the loading conditions makes it possible to investigate rare but critical conditions. Also, control of the relative importance of different environmental loadings is a desirable benefit provided in a model basin.

9.3 Guideline for uncertainty analysis for model testing of offshore wind turbines

The following new guideline was developed during this term:

- 7.5-02-07-03.17 Uncertainty Analysis for Model Testing of Offshore Wind Turbines

The purpose of the guideline is to provide guidance on the application of uncertainty analysis to the model scale testing of offshore wind turbines.

A first step in uncertainty analysis is to identify all significant sources of uncertainty. The sources of uncertainty related to model testing of offshore wind turbines can be grouped into these main blocks: model, installation, control system and actuators, measurement and data processing, environmental condition modelling, and initial test conditions. Additional sources of uncertainties due to the scaling can be grouped into the mismatch of Reynolds number and viscous effects on the hull and mooring lines (Bachynski et al., 2019).

In this guideline, an example of the uncertainty analysis to offshore wind turbine model test is shown and it suggests Type B uncertainties (estimated through a simplified analytical uncertainty propagation) for the estimation of RAOs were found to be of importance compared to Type A uncertainties (estimated through repetition tests).

10. CLOSING SUMMARY

10.1 Wave energy converters

At the present level of development, the commercial exploitation of wave energy is only economically viable if WECs are used in other multi-use costal structure such as coastal protection, off-grid applications or if they are deployed in large arrays. In these farm settings, the interactions between close by WECs (near field effects) will give rise to a complex wave field that affects the power extracted by each device and consequently the total power output of the farm. Moreover, at large distances behind WECs (far field effects), the farms alter the wave field affecting the coastal processes: other users at sea, coastal ecosystems, and the coastline. Advancement in the numerical and experimental modelling of arrays have been done and summarized in the report. The most significant advancement is the introduction of park optimization techniques that allow a multi-criteria choice of the WECs position in the array.

In the WEC PTO system modelling, more efforts have been made to identify nonlinear effects, unsteady characteristics and viscous effects in recent years. Understanding on coupling effects between components of a PTO system is critical to improve the performance evaluation and more attention is being given to develop the integrated simulation tools that can include interactions between PTO components. A series of benchmark tests on various WEC PTO models have been carried out by the WEC modelling group of IEA-OES and it may identify the capability and potential improvement of the current WEC PTO modelling.

However, wave energy technology is certainly one of the most diverse in terms of ocean renewable energy systems. In fact, most companies possess very unique and different ways to harnessing ocean wave energy. This can arguably explain the slow development of the sector where lessons learn from failures or successes, supply chain, component manufacturing etc. cannot be easily transfer from one device to another. To date, no company has reached the full commercial stage and only the Mutriku Wave Power Plant has demonstrated consistent power production with commercial implications. In order to increase their competitiveness, companies are slowly moving towards niche markets, off-grid applications and integration in current or future ocean structures (breakwaters, multipurpose platforms, harbours etc.).

It is therefore important to ensure thorough guidelines and procedures to help developers through the TRLs. There are still many unknowns around accounting for scale effects, hydrodynamic PTO impacts or survivability tests and much of the data available are very new. As further information slowly become available, continuing improvement of these guidelines and procedures will be important if not necessary.

10.2 Current turbines

General specifications for both experimental and computational benchmarks for current turbine have been laid out and outlined for current turbine. To date, much of the data and design geometries for marine renewable devices including current or tidal turbines has been considered propriety or not readily available in the public domain. In the past few years, for current turbines, there are a few experimental programs that have been conducted for the purpose of validation of CFD predictions or to evaluate the impact of different facilities on test results and turbine performances. The databases for a few of these studies are currently available online. Each of these databases appear to provide valuable resources for future studies. However, in most cases the available data is not adequate as a benchmark for validation of CFD or verification and confirmation of experimental processes. Generally, there is a lack of needed information available with published databases such as detailed geometry definitions needed for CFD to model the experiment; documented digital data files or uncertainty analysis. The U.S. DOE had developed a reference turbine project in which included three current/tidal turbine designs and subscale evaluation. One was a 1:8.7 scale a three-bladed horizontal-axis turbine. A design report was completed and electronic database for this design should soon be available online.

Large- and full-scale CT are being deployed throughout the world with increasing success. Between 2010 and 2018 almost 60 CT has been deployed in the sea around Europe. These have mainly been for medium and full scale tests. The most successful project is MeyGen Phase 1A which has installed four 1.5 MW turbines and had delivered 17GWH to the grid by mid-2019. After the demonstration phase the total farm planed size is 86 MW.

Over the last ten years the understanding of the nature of the unsteadiness flow in tidal current test sites has improved. This has been mainly due to better quality measurements and analysis of tests sites which has improved the understanding of magnitude and frequency unsteadiness due to large scale turbulence structures and waves. This has led to improved predictions of the magnitude of unsteady hydrodynamic loading. With this knowledge, the survivability has improved and there has been a reduction in the occurrence of blade and drive train failures. The improved understanding of the tidal sites has also led to a reduction in the installation time combined with experience gained through learning-by-doing.

Replicating all the unsteady flow features is not realistic for a single test facility. Consequently, tests are done with simplifications of the environment to produce unsteady flows for validation data. The following techniques have been reviewed in the literature:

- The use of a towing tank with waves. Due to matching Froude similarities the carriage speed is often low, so consequently the blade Re numbers are low which may cause large regions of laminar flow and separation.
- The use of planner motion type mechanisms in towing tanks. This is generally limited to generic simulation of key vibration magnitudes and frequencies.
- The use of screens and grids to generate turbulence in circulating water channels and cavitation tunnels. The turbulence generated may have intensity values at the turbine location close to real conditions but

isotropic in nature and with different length scales.
- The use of circulating water channels with combined with currents. This is limited to very few facilities and the range of quality of the waves can be limited.
- The use of surface roughness on the bed of long flumes. This produces some non-isotropic turbulence, but these facilities are generally limited to tests with small model scale turbines or turbine simulators. These tests are generally done to help validate simulation tools for modelling CT wakes for array modelling and validation.

Regarding the numerical simulation on turbine array, some researchers still focus on improving existing method to tune the accuracy of the wake structure, but a good number start to develop method to study other aspects of array such as free surface effect and control algorithm. It can be understood that the accuracy of the wake under free surface effect is in the same level of that of the traditional methods while that of the control study is less. Nevertheless, they require further experimental test for validation. Additionally, like wind energy, tidal energy's potential impact on environment receives attention lately while they are conducted in small regions. Further investigations are expected to be conducted to understand this impact clearly with a greater scale and higher accuracy.

10.3 Offshore Wind turbines

Due to the scarcity of publicly available experimental results, especially relative to full-scale fixed and floating offshore wind turbines, a number of initiatives have been carried out by the research community to fulfil this gap, including numerical code-to-code comparisons and physical experiments at scaled model level.

A series of important initiatives, organised under the IEA Task 23 and Task 30, have been the OC3 (Offshore Code Comparison Collaboration), focusing on the code-to-code comparison of a number of aero-hydro-servo-elastic codes, considering a monopile, a tripod, and a Spar, the OC4 (Offshore Code Comparison Collaboration Continuation), focused on the complex hydrodynamics of a jacket foundation and of semisubmersibles, the OC5 (Offshore Code Comparison Collaboration Continuation, with Correlation), which extended the previous OCx initiatives by validating the numerical tools considered against experimental data (fixed flexible cylinder and semisubmersible), and the currently ongoing OC6, which expanded the verification and validation adopting a three ways approach: engineering level modelling tools, higher-fidelity numerical tools, and experimental data, analysing more complex problems such as aerodynamics and hydrodynamics of FOW undergoing large motion, hybrid potential-viscous approaches, and advanced pile/foundation interactions.

In addition to the above, a series of experimental campaigns have been conducted on scale models of FOWT, typically at a scale around 1:50, modelling the three main FOWT substructure types: spar, semi-submersible, and TLPs (DeepCwind, INNWIND.EU), and also adopting real-time hybrid model approaches (NOWITECH) to address the fundamental conflict between Reynolds scaling of aerodynamic forces and Froude scaling of hydrodynamic forces.

As far as full-scale installations are concerned, the focus has been on floating offshore wind farms. Since the last (28th) ITTC report, in 2017, the number of operational floating wind turbines has more than doubled, quadrupling the total installed capacity.

The most adopted configurations, so far, have been the spar and the semisubmersible configurations, but new ones (e.g., the damping pool barge by Ideol, the ballast-stabilised "pendulum" Tetraspar, by Stiesdal) are also emerging. After a number of demonstrators, with rated power around 2 MW, the first floating wind farms, with 3-5 wind turbines, for a total of 25-30MW rated power, have been commissioned, with many more in the pipeline.

The survivability and the success of energy extraction has been fully proven for the spar and semi-submersible configurations, with two demonstrators having operated for a number of years in harsh conditions and delivering to the electric utility grid tens of GWh (e.g., Hywind demo in Norway, and WindFloat Atlantic Phase I), and two floating wind farms with rated power 25-30 MW successfully delivering electricity (Hywind Scotland pilot Park – spar, and WindFloat Atlantic – semi-submersible). Also, the 3MW demonstrator by Ideol, installed in Japan, managed to survive three category 5 typhoon shortly after its installation. To date, there are still no MW-scale Tension Leg Platform (TLP) demonstrators tested in an offshore environment. Between 2009, when the first demonstrator was installed by Statoil (now Equinor), and now, the most active countries have been Norway, Portugal, Japan, the UK, and France.

Significant challenges still remain in terms of scaled aero-hydrodynamic model testing of floating wind turbines due to the scaling challenges associated with the Reynolds number dissimilitude. Real-time hybrid testing techniques have been further developed and applied in more tank tests, i.e. platform responses are measured experimentally and passed into numerical simulations, whereas actuators, or other means, apply the appropriate aerodynamic loads according to simultaneous simulations of the wind turbine. Performance scaling is still widely used where the main objective of the scaling procedure is the representative modelling of the aerodynamic thrust. Some of the challenges related to the aerodynamic modelling of wind turbines loads include:

- Assessing and documenting the accuracy and uncertainty related to modelling of the aerodynamic wind turbine loads in hydrodynamic model testing of floating wind turbines, both for tests with physical modelling of the wind turbine and for hybrid testing.
- Generating high quality physical wind fields in open air in a wave tank and measure/document the spatial and temporal variations.

As the turbines become bigger, the design of the support structures has become relatively slender, and the significance of structural elasticity may be more important in future model testing.

During this term ITTC developed the new guideline 7.5-02-07-03.17 ‘Uncertainty Analysis for Model Testing of Offshore Wind Turbines’. Generally, the development of the standards, rules, and guidelines known as regulations and their application to offshore wind turbines (floating or fixed) have allowed the industry to gain confidence in designs. Also, the standards, guidelines and certifications address how they are about to change from addressing prototype installations with a few unit to large scale (floating or fixed) offshore wind farms consisting of many identical units. As a central ‘repository’ of knowledge and experience in the field of offshore wind turbine, IEC published both IEC IS 61400-3-1 ‘Design requirements for offshore wind turbines’ and IEC TS 61400-3-2 ‘Design requirements for floating offshore wind turbines’ in April 2019. Also ISO published ISO 29400 ‘Ships and marine technology - Offshore wind energy - Port and marine operations’ in May 2020.

11. RECOMMENDATIONS

The 29th Specialist Committee on Hydrodynamic Modelling of Marine Renewable Energy Devices has the following recommendations for future work:

11.1 General recommendations

1. Continue interactions with IEC.
2. Review interactions between model scale and moderate/full scale test sites.

3. Review of testing of deployment (transportation, installation) and O&M for marine renewable devices.
4. Review testing of multipurpose platforms (e.g., combined WEC/OWT/ Solar/Aquaculture platforms).

11.2 Recommendations for wave energy converters (WECs):

1. Continue to monitor development of new concepts of WECs.
2. Continue to monitor developments in PTO modelling both for physical and numerical prediction of power capture.
3. Assess the feasibility of developing specific guidelines for numerical and experimental survival testing of WECs.
4. Assess support to using the benchmark round robin data for numerical comparison and/or for evaluating facility biases and scale related uncertainties.
5. Update the uncertainty analysis of WEC testing to include the uncertainties of the power capture and potentially of a different type of device technology.
6. Update and extend array section of the guidelines for numerical modelling of WECs.
7. Review and report on the different PTO control strategies for power optimisation and survivability modes.
8. Review and report on comparisons between full scale data and numerical work/experimental model testing.

11.3 Recommendations for current turbines (CTs):

1. Continue to monitor development in physical and numerical techniques for prediction of performance of current turbines.
2. Assess the support for round robin test of a 3-blade horizontal axis turbine (such as the DoE turbine). If there are enough willing participants develop a technical delivery plan.
3. Review and report the techniques use for CFD modelling current turbines. This should include the use of combined EFD/CFD techniques for scaling and blockage corrections and methodologies for replicating environmental conditions.

11.4 Recommendations for offshore wind turbines (OWTs):

1. Continue monitoring and report on the development in full-scale installation of floating offshore wind turbines.
2. Report on possible full-scale measurement data available and address how these data can be utilized for validation of simulation tools and evaluation of scaling effects from model scale tests.
3. Continue monitoring and report on the development in model testing methodology for offshore wind turbines.
4. Review and report on recent development of physical wind field modelling in open space with application for wave tank testing of floating offshore wind turbines, including modelling of turbulence and measuring and documentation of the wind field.
5. Review and report on the development of numerical offshore wind farm modelling.

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