The Specialist Committee on Hydrodynamics Modelling of Marine Renewable Energy Devices

Final Report and Recommendations to the 28 th ITTC

1 INTRODUCTION

This report summarises the work of the Specialist Committee on Hydrodynamic Modelling of Marine Renewable Energy Devices for the 28th ITTC.

1.1 Membership

The 28th ITTC Specialist Committee on Hydrodynamic Modelling of Marine Renewable Energy Devices (SC-HMMRED) consisted of:

- Assoc. Prof. Irene Penesis (Chair), Australian Maritime College (AMC), University of Tasmania, Australia
- Dr William Batten (Secretary), QinetiQ, UK
- Prof. Arnold Fontaine, Pennsylvania State University, USA
- Prof. Hyun Kyoung Shin, University of Ulsan, South Korea
- Prof. Ye Li, Shanghai Jiaotong University, China
- Dr Marek Kraskowski, Centrum Techniki Okrętowej (CTO), Poland
- Dr Petter Andreas Berthelsen, SINTEF Ocean (fmr. MARINTEK), Norway
- Prof. Motohiko Murai, Yokohama National University, Japan
- Dr Aurélien Babarit, École Centrale de Nantes, France

1.2 Meetings

The committee has met four times during the course of the three year mandate:

- Yokohama National University, Yokohama, Japan, from 11th to 12th February 2015;
- AMC, Launceston, Australia, from 1st to 3rd February 2016;
- SINTEF Ocean, Trondheim, Norway, from 4th to 6th July 2016;
- Centrum Techniki Okrętowej (CTO), Gdansk, Poland, from 7th to 9th February 2017.

In addition, Prof. Ye Li hosted the committee at Shanghai Jiaotong University (SJTU), China from 15th to 16th September 2017 prior to the full conference, showcasing SJTUs Multiple Functional Towing Tank—a newly developed word-leading marine fluid mechanics testing facility with top-class technology.

2 TASKS

The following lists the tasks given to the 28th Specialist Committee on Hydrodynamic Modelling of Marine Renewable Energy Devices.

Work relating to wave energy converters (WEC):

(1) Develop guidelines for uncertainty prediction for WECs.

(2) Monitor and report on developments in power take-off (PTO) modelling both for physical and numerical predictions of power capture.

(3) Review and report on the progress made on the modelling of WEC arrays.

(4) Review and report on challenges associated with the performance of WECs in irregular wave spectra, particularly when they relate to physical modelling.

(5) Check willingness of participants for the "round-robin" test campaign before starting work.

(6) Review and report on integrated WEC simulation tools based on multi-body solvers which are in development.

Work relating to current turbines:

(1) Develop specific uncertainty analysis guidelines / example for horizontal axis turbines.

(2) Report on developments in physical and numerical techniques for prediction of performance of current turbines, with particular emphasis on unsteady flows, off-axis conditions, and other phenomena which offer particular challenges to current devices.

(3) Report on the progress made on the modelling of arrays.

(4) Report on progress in testing at full-scale and moderate scale in-sea test sites.

Work relating to offshore wind:

(1) Report and review on wind field modelling including Froude/ Reynolds scaling challenges for the turbine in cooperation with the Specialist Committee on Modelling of Environmental Conditions.

(2) Report on the impact of control strategies and other features on full-scale devices on global response to allow improved understanding of the impact of simplifications adopted in model tests.

(3) Report on integrated tools for the simulation of floating wind turbines including platform, mooring, turbine and control system.

(4) Report on developments in full-scale demonstrators of floating wind turbines.

3 BACKGROUND

This report addresses a number of key issues in the physical and numerical testing of marine renewable energy systems, including wave energy devices, current turbines, and offshore wind turbines. The 27th ITTC Specialist Committee on Hydrodynamic Modelling of Marine Renewable Energy Devices Final Report and Recommendations, provides an overview of the types of devices considered, context of guidelines developed or under development by other international bodies as well as via research projects.

In the area of Marine Renewable Energy a key international body is the International Electrotechnical Commission (IEC) which addresses standards in all aspects of electricity generation, through an extensive series of technical committees. Of particular relevance here are IEC TC 88 (Wind Turbines) which includes issues related to Offshore Wind Turbines, and IEC TC 114 (Marine Energy - Wave, Tidal and Other Water Current Converters). Informal collaboration has resulted in cross-referencing of draft and existing ITTC guidelines and procedures, further assisting dissemination of ITTC Procedures and establishing best practice.

4 WAVE ENERGY CONVERTERS (WEC)

4.1 Overview: Developments in Wave Energy

Sea trials and Demonstrations. More

than 100 wave power pilot projects in the world have been launched over the past few years, including some deployed and tested at full-scale. Total installed capacity is about 4 MW, with 1.25 MW installed in Australia, 1 MW installed in the UK, about 0.76 MW in Canada and 0.4-0.5 MW in South Korea, China and Portugal. While Japan has only 0.15 MW installed, they are planning up to 350 MW of wave energy capacity in the near future, with the USA planning 40 MW (ARENA, 2016a). Some of these are outlined in Table 1 (adapted from Magagna et al., 2016).

The European Commission report (Magagna and Uihlein, 2015) highlighted a short list of 45 WEC developers that have reached open-sea deployment; 7 are U.S. based, 26 are EU based, 6 are Australian, and the rest are from other international developers. The most advanced device types are oscillating water column (OWC) and point absorbers, with some specific devices extensively tested at TRL 8. Oscillating wave surge converters (OWSC) and rotating mass devices have reached relatively high TRL, and are expected to follow through to higher TRL (Ocean Energy Status Report, 2016).

Full-Scale Array Testing. Carnegie Clean Energy, an Australian-based company installed the world's first commercial-scale grid connected array shown in Figure 1, comprising of three 11 m diameter 240 kW CETO5 units off Garden Island, Western Australia. More than 14,000 operational hours were logged by January 2016 (ARENAb, 2016), providing electricity and potable distilled water to Australia's largest naval base. Building on the successful deployment of the CETO5 array, CETO6 is planned, with an increase in generation capacity from 240 kW to 1 MW.

A number of additional array projects are moving forward including Wello in Scotland and AW-Energy in Portugal.

Figure 1 Array of three CETO5 heaving buoy converters off Garden Island, Western Australia

Government Funded Projects. Projects funded by governments are increasingly accelerating the wave energy industry through collaborations between research organisations and industry. Landmark projects are provided in Table 2.

The next iteration of MaRINET (called MaRINET2) aiming to address key objectives relevant to guideline development including:

- Standardisation of the testing implemented by the infrastructures along with an independent verification process for analysing and approving of the results generated by the wave, tidal, offshore wind and crosscutting systems under test in the TNA programme.
- Encourage interchange and dissemination of research results of tests through user meetings.
- Improve the quality, robustness and accuracy of physical modelling and testing practices operated by MaRINET2 infrastructures and develop new physical modelling practices for systems and subsystems under development for marine renewable energy systems where currently no standardisation exists.
- Deliver new and representative sets of standardised testing procedures to be adopted by MaRINET2 infrastructure within the TNA programme.

Table 1 Operational and planned pre-commercial wave energy projects (Magagna et al., 2016)

Project	Location, Country	Max Capacity	Class	Devices	Status
WaveHub	Islay, UK	10 MW	Point absorber	Seatricity Oceanus 2	Currently two devices installed. No grid connection.
Sotenäs	Västra Götaland, SE	10 MW (modular)	Point absorber	Seabased	First devices deployed (1 MW)
Perth project	Perth, AUS	0.72 MW (modular)	Point absorber	Carnegie CETO5	Three CETO5 units were deployed in an small array
Portugal	Peniche, PT	60 MW	Pressure differential	Bombora mWAVE	Install 1.5 MW single device in 2018, planning for 6 MW and 60 MW farms.
Port Fairy Project	Victoria, AUS	250 kW	OWSC	BioPower Systems bioWAVE	Testing in 2017.
Wave Swell Energy	King Island, AUS	1 MW	OWC	WSE OWC	Scheduled to deploy in 2018.
WaveStar	Hanstholm, DK	0.6 MW	Point absorber	WaveStar	Grid connected since 2010, 1:2 scale (Project no longer operational) Applying for Horizon 2020 for 1 MW commercial demonstration.
Mutriku	Mutriku, ES	0.3 MW (modular)	OWC	16 OWC chambers rated 18.5 KW	Operational since 2011. One of the chamber is used for R&D testing.
Isle of Muck	Isle of Muck, UK	22 kW (modular)	Attenuator	Albatern	3 WaveNET unit installed
Westwave	IE	5 MW (modular)	t.b.d.	5 suppliers shortlisted	Project funder under NER 300 (34 mio. EUR), planned 2018.
Fred Olsen	Hawaii	23 kW	Point absorber	Fred Olsen Life Saver	Device grid connected, operating at 30% (6.7 kW)
Azura Wave	Hawaii	20 kW	Point absorber	Northwest Energy Innovations	Half scale prototype. Generating electricity since 2015
Oceantec	ES (Bimep)	30 kW	OWC	Oceantec Marmok-A5	Installed in October 2016
40SouthEnergy	Marina di Pisa, IT	100 kW	OWSC	H24 from 40Southenergy	Device installed at the end of 2015.
Eco Wave Power	Gibraltar, GI	100 kW (modular)	Point absorber	Wave clapper	Device installed and operative since June 2016.
Seapower	Galway Bay, IE	N/A	Attenuator	Seapower Platform	1:4 scale model to be tested in 2016 in Galway Bay
CEFOW	EMEC, UK	3 MW	Rotating Mass	3 X Wello Penguins 1 MW	Installation expected in 2017, 2018 and 2019. A device each year within H2020 project.
Corpower	EMEC, UK	25 kW	Point Absorber	1 x 25 KW Corpower	Device built in Portugal. Yo be tested in dry rig in Swe-den before deployment at EMEC
Swell	Peniche, PT	5.6 MW (modular)	OWSC	WaveRoller	Funded by NER 300 (9.1 mEUR), planned for 2018, 16 devices
CETO6	Garden Island, AUS	4 MW (modular)	Point absorber	Carnegie CETO6	1 MW device, 3 MW demo array planned
CETO6 Wave Hub	Cornwall, UK	15 MW (modular)	Point absorber	Carnegie CETO6	1 MW device in 2017, to be expanded to 15 MW by 2021
Camp Rilea	Oregon, US	40 kW	OWSC	Resolute Marine Energy	Small project with 2 devices (2017). Water will also be used onshore for desalination
Baby Penguin	Canaray Islands, ES	N/A	Rotating mass	Wello Penguin	Reliability for new "mild-climate" device
Wedge Global	Canary Island, ES	N/A	Point absorber	Wedge Global	Reliability testing new PA
NEDO	Port of Sakata, JAP	15 kW	OWC	MM Bridge OWC	Demonstration testing since 2011.
Ocean Power Tech	Kozu Island	100 kW	Point absorber	PB3	Deployed PB3 in ocean April, 2017.
Albany Wave Energy Project	WA, AUS	20 MW	Point absorber	CETO	Starting 2018.

Table 2 Landmark government projects

Project	Details	Status	Support
MaRINET2	Second iteration of the Marine Renewables Infrastructure Network project, coordinated and managed by Irish research centre MaREI in University College Cork and avail of the Lir National Ocean Test Facilities. 39 organisations from 13 countries, offering free of charge testing of MRE converters in facilities.	MaRINET1 finished 2016 MaRINET2 starts 2017	European Commission, Horizon 2020, €10.5m
DTOcean	Optimal design tools for ocean energy arrays to accelerate industrial development of ocean energy. 18 partners from 11 countries, coordinated by the University of Edinburgh.	Finished 2016	European Commission, 7th Framework, €6.2m
EquiMar	Delivered a suite of protocols for the equitable evaluation of MRE converters. Results create sound base for future standards (e.g. IEC TC 114)	Finished 2014	European Commission, 7th Framework, €5.5m
CORES	Developed new concepts and Components for Ocean Renewable Energy Systems. 13 partners from R&D centres and small-medium enterprises from across the EU.	Finished 2011	European Commission, 7th Framework
MERIKA	Marine Energy Research Innovation and Knowledge Accelerator through the creation of a European hub for MRE research. 7 partner organisations.	2014-ongoing	European Commission, 7th Framework, €4.4m
OCEANERA-NET	Coordinating funding programmes between EU countries and regions to support research and innovation in the ocean energy sector. 15 partner organisations from 8 EU countries.	2013-ongoing	European Commission, 7th Framework, €2.6m
PerAWaT	Establish and validate numerical models (WaveDyn) for the Performance Assessment of Wave and Tidal array systems.	Started 2009, launched WaveDyn in 2012	Energy Technologies Institute, €8m
Wave Energy Prize	18-month public design competition to increase the diversity of organisations involved in WEC technology development. 10 finalists tested low TRL WECs at U.S's most advanced wave basin at Carderock, Maryland. Data from all tests will be published in Nov 2017.	Finished 2016	U.S. Department of Energy, USD $6.5m
FORESEA	Funding Ocean Renewable Energy through Strategic European Action provides access to North-West Europe's ocean test centres.	2016 – 2019	Interreg North-West Europe programme, €11m
OPERA	Open sea operating experience to reduce wave energy cost, by open access to high-quality open-sea operating data (OWC WEC) to the wave energy development community. 12 partner organisations.	2016 – 2019	European Commission, Horizon 2020, €5.7m
NEDO	New Energy and Industrial Technology Development Organisation. Promoting the commercialisation of wave energy technology in Japan.	Ongoing	Japanese Government
CEFOW	The Clean Energy From Ocean Waves project aims to increase the speed of wave power development, reduce LCOE, and create supply chain for future wave energy projects	2015 – 2020	European Commission, Horizon 2020, €24.7m
Australian Wave Energy Atlas	Development of an open access online tool to asses Australia's wave energy resource, and best practice guidelines on physical impact assessments for wave energy developments in Australia's marine domain.	2014-ongoing	Australian Renewable Energy Agency (ARENA) AUD $1.3m

External Guidelines under Development. The IEC TC114 Technical Committee has referred to the following draft ITTC Recommended Procedures, Wave Energy Converter Model Test Experiments (7.5-02-07-03.7) and Uncertainty Analysis for a Wave Energy Converter (7.5-02-07-03.12) in development of the IEC Technical Standards for the Early Stage Development of Wave Energy Converters: Best Practices and Recommended Procedures for the Testing of Pre-prototype Scale Devices (TS 62600-103), due to be published in 2017.

4.2 Guidelines

The SC-HMMRED reviewed the procedures and guidelines under its responsibility related to WECs.

The following guideline was updated:

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

The procedure order in the guideline addressing model tests of WECs was revised to provide a consistent process enabling identification of the stage of development of a device (known as the technology readiness level (TRL)) and identification of suitable test procedures for evaluating device performance at a defined stage of development. This revision allowed for 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.

The following new guideline was developed:

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

The development of the guideline addressing uncertainty analysis for testing WECs is provided in the following section.

4.3 Uncertainty Analysis of a Wave Energy Converter

The ITTC Recommended Procedure, Uncertainty Analysis of a Wave Energy Converter (7.5-02-07-03.12) provides guidance to perform uncertainty analysis on WECs during the proof of concept stage (TRLs 1–4) where it is impractical to fully model the power take-off (PTO) system, but instead it is simulated by the use of orifices, mesh or damper. This guideline is complementary to the ITTC Recommended Procedure, Wave Energy Converter Model Test Experiments (7.5-02-07-03.7), and is developed based on ISO (1995) and in line with other ITTC uncertainty analysis procedures including ITTC Recommended Procedures, Guide to the Expression of Uncertainty in Experimental Hydrodynamics (7.5-02-01-01) and Uncertainty Analysis for Free Running Manoeuvring Model Tests (7.5-02-06-05).

An example of evaluating the experimental uncertainties when testing an offshore-stationary oscillating water column (OWC) device is provided. This includes uncertainties in the main parameters required to estimate the extracted pneumatic energy/power and assess device performance/efficiency such as incident wave elevation, wave elevation at different locations as waves propagate towards the device and behind it, OWC chamber's free surface elevation and differential air pressure.

4.4 Power Take-Off (PTO) Modelling: Physical and Numerical Predictions of Power Capture

Overview. WEC PTO systems can be classified into four categories according to their working principle: pressure differential (submerged point absorber, OWC), floating structures, overtopping devices, and impact devices (articulated or flexible structures positioned perpendicular to the wave direction). PTO systems for WECs include the use of air or hydro turbines, hydraulics, direct electrical or mechanical drive systems, or flexible electrical materials.

Advances in Hydrodynamic Modelling of PTOs. Air turbines models include the representation of the interaction between the OWC air chamber and the water column motions (hydrodynamics). Recent studies have compared experimental test results with developed numerical models, finding that the models are capable of assessing the primary energy conversion for OWC devices (Sheng et al., 2014a, 2014b, Henriques et al., 2016, and Kamath et al., 2015). In order to predict the power production of an OWC, Bailey et al. (2016) developed a wave-to-wire model that incorporates all relevant kinematics, dynamics, and performance indicators. He and Huang (2017) carried out an experimental investigation into the characteristics of orifices for modelling a nonlinear PTO system for an OWC, finding absorbed power can be calculated using only pressure measurements.

Hydraulic converters transform the mechanical energy of a moving body into electrical energy. As similar hydraulic converters are used in many engineering fields, significant cross-over applications exist for their application in WEC PTO systems. Recent proposals of hydraulic PTO's include: a complete PTO system for the Wavestar WEC (Hansen et al., 2013), an inverse pendulum WEC (Zhang et al., 2014), a double-acting hydraulic cylinders array (Antolin-Urbaneja et al., 2015), and a system based on oil-hydraulic transformer units (Gaspar et al., 2016). A review of hydraulic PTOs for WECs has recently been published (Lin et al., 2015).

Direct electrical drive systems couple the WEC velocity and force to a generator using either magnetic fields or direct mechanical linkage (Elwood et al., 2009). These systems eliminate intermediate energy conversion processes. Developing these systems has been challenging due to difficulties in scaling the PTO for small-scale model tests (Taniguchi et al, 2017). Notable works include a large-scale ocean test to calibrate a numerical model (Elwood et al., 2009), along with wave emulation and hydrodynamic tests of proposed direct drive systems that validate and calibrate numerical models (Blanco et al., 2011, Cappelli et al., 2014, Henriques et al., 2011, Taniguchi, 2017, and Xiao et al., 2017). Rapid development of linear device technology is expected over the coming years, with new concepts using future linear PTO systems certain to appear.

Direct mechanical drive PTO systems use an extra mechanical system that drives a rotary electrical generator, a feature reported to reduce mechanical losses. Recent examples of research detailing direct drive PTO systems include a flywheel energy storage system which smooths out power variations (Binh et al., 2016, and Yoshida et al., 2012).

Hydro turbines used in overtopping WECs, which convert the potential energy of accumulated water in a raised basin into electricity via a low-head turbine and generator system (Kofoed et al., 2006). Kim et al. (2015) proposed a PTO system in which the pitching motion of the device causes a column of water to rise and fall periodically in a double-hull housed in a caisson, creating a bi-directional flow that spins a hydro turbine.

As new flexible electrical materials are developed alternative drive PTO systems are proposed. Tanaka et al. (2015) and Okada et al. (2012) independently proposed a PTO system using flexible materials such as piezoelectric devices, whereas Vertechy et al. (2015) and Moretti et al. (2015) proposed installing direct elastomers, rubberlike solids whose electrical and structural responses are highly nonlinear and strongly coupled, into the orifice of OWC.

Experimental Modelling of PTO Systems using Wave Emulators. Wave emulators capable of simulating realistic sea states are often used for scaled experiments to verify numerical models, to develop proof of concepts, and to validate parameters of interest. Testing WEC PTO systems in dry laboratory environments provides easy accessibility and controllable waves at a lower cost when compared to the difficulty and expense of testing in hydrodynamic facilities and at sea, enabling the rapid development of WEC PTO systems. A number of research institutions have developed wave emulators for the dry testing of WEC PTO systems (De Koker et al., 2017, Dießel et al., 2015, Henriques et al., 2016, Ramirez et al., 2015, Pedersen et al., 2016, and Ridge et al., 2014).

Numerical Tools for PTO System Modelling. The choice of numerical modelling techniques for PTO systems depends on the WEC operating principle. Modelling trends are leaning towards simulating not only the WEC system but also representing the PTO system in detail. Simulation accuracy is being improved by advancements in modelling techniques to represent the WEC and PTO subsystems as integrated systems. MATLAB/SIMULINK and DIgSILENT PowerFactory are suitable for PTO modelling in some instances, but no commercial software can currently examine the large number of multi-body problems required for the detailed examination of PTO systems. Rapid and continual development of software will enable the full simulation of all WEC and PTO parameters in the near future.

Point absorbers are usually modelled as a few elements. Li and Yu (2012) systematically reviewed different numerical methods theoretical, potential flow and viscous flow methods. Furthermore, Li and Yu (2013) developed a novel mesh matching method that allows using RANS to accurately describe the two body point absorber's behaviour under complicated sea condition, which was not possible in the past. They also demonstrated the significance of the nonlinear effects, including viscous damping and wave overtopping. The study showed that the nonlinear effects could significantly decrease the power output and the motion of the FPA system, particularly in larger waves.

4.5 Modelling of WEC Arrays

To date, most large scale deployments have been conducted with a single WEC. However, there is a necessity to expand these to 'arrays' or 'farms' in the future in order to reduce both installation and maintenance cost per unit as well as harnessing maximum energy at a given site (Penesis et al., 2016). This requires a thorough understanding of how WECs will interact with each other when part of a wave farm, which is essential to predicting the energy yield, the optimal configuration, and ultimately the cost of energy. Another important aspect is understanding how farms might impact the hydrodynamic environment of the site and their use in coastal defence (Folley, 2016).

Numerical Modelling of WEC Arrays. The majority of numerical models for WECs and WEC arrays are based on linear potential flow theory. With ever-increasing computing power other methods have been developed including wave propagation models, Computational Fluid Dynamics (CFD) models, spectral-domain models and model identification. Reviews of numerical models for WEC arrays can be found in Folley et al. (2012) and De Chowdhury et al. (2015). The following sections provide brief descriptions of state-of-the-art techniques for the numerical modelling of WEC arrays, summarised from the comprehensive book on this topic by Folley (2016).

Conventional Multiple Degrees-of-Freedom Array Models. One approach to modelling WEC arrays is extending the modelling of isolated WECs with multiple degrees-of-freedom using the same assumptions, capabilities and limitations. However, this adds complexity for modelling of WEC arrays due to the computational processing requirements. The most common numerical models for WEC array are frequency-domain models, with the application of boundary element method (BEM) codes (see Payne et al., 2008) provides a comprehensive review on the use of BEM codes). Recent developments in this area include a finite element method model of an array of OWC devices shown in Figure 2 (Nader et al., 2012 and 2014), and comparison of a BEM code with a semi-analytical technique for heaving WECs (De Chowdhury et al., 2016).

Time-domain WEC array models are significantly less common than frequency-domain models due to increased complexity, requiring additional analytical and computational resources. They are useful for assessing the performance of nonlinear PTO WECs in arrays (Forehand et al., 2016, Kara, 2016, and Nambiar et al., 2015). Spectral-domain models offer a more computationally efficient solution for predicting the performance of WECs such as heaving buoys in an array (Folley and Whittaker, 2013), further development of this approach is needed to improve simulation accuracy. Current CFD tools can model only a small number of WECs in an array (Agamloh et al., 2008, and Devolder et al., 2017). The use of nonlinear potential flow models and CFD models has been proposed for WEC array modelling (Folley et al., 2012), however they are still in early stages of development.

Semi-analytical Array Models. Semi-analytical WEC array models, based on linear wave theory, are analytical in that the solution can be written down explicitly in terms of mathematical formulae, but require further approximation or the truncation of an infinite series to allow computation in practice. These models lend themselves to ease of translation into computer code, allowing flexibility, extensions and coupling with other numerical techniques. Details on the theoretical development and general formation may be found in Child (2011) and De Chowdhury et al., (2015). The four semi-analytical techniques are as follows:

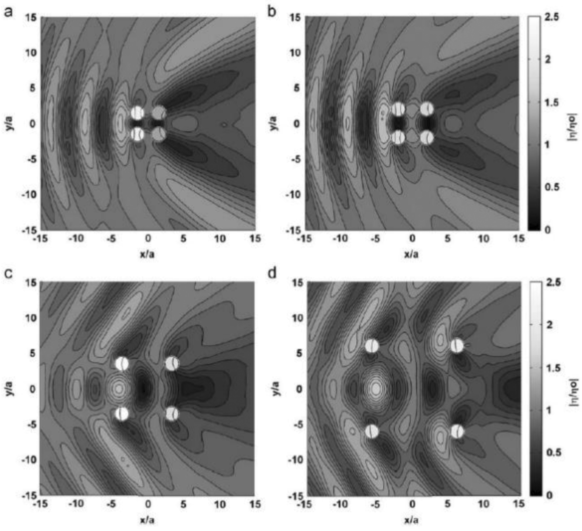


Figure 2 Total wave amplitude in and around four OWC device array for various spacings (Nader et al., 2012)

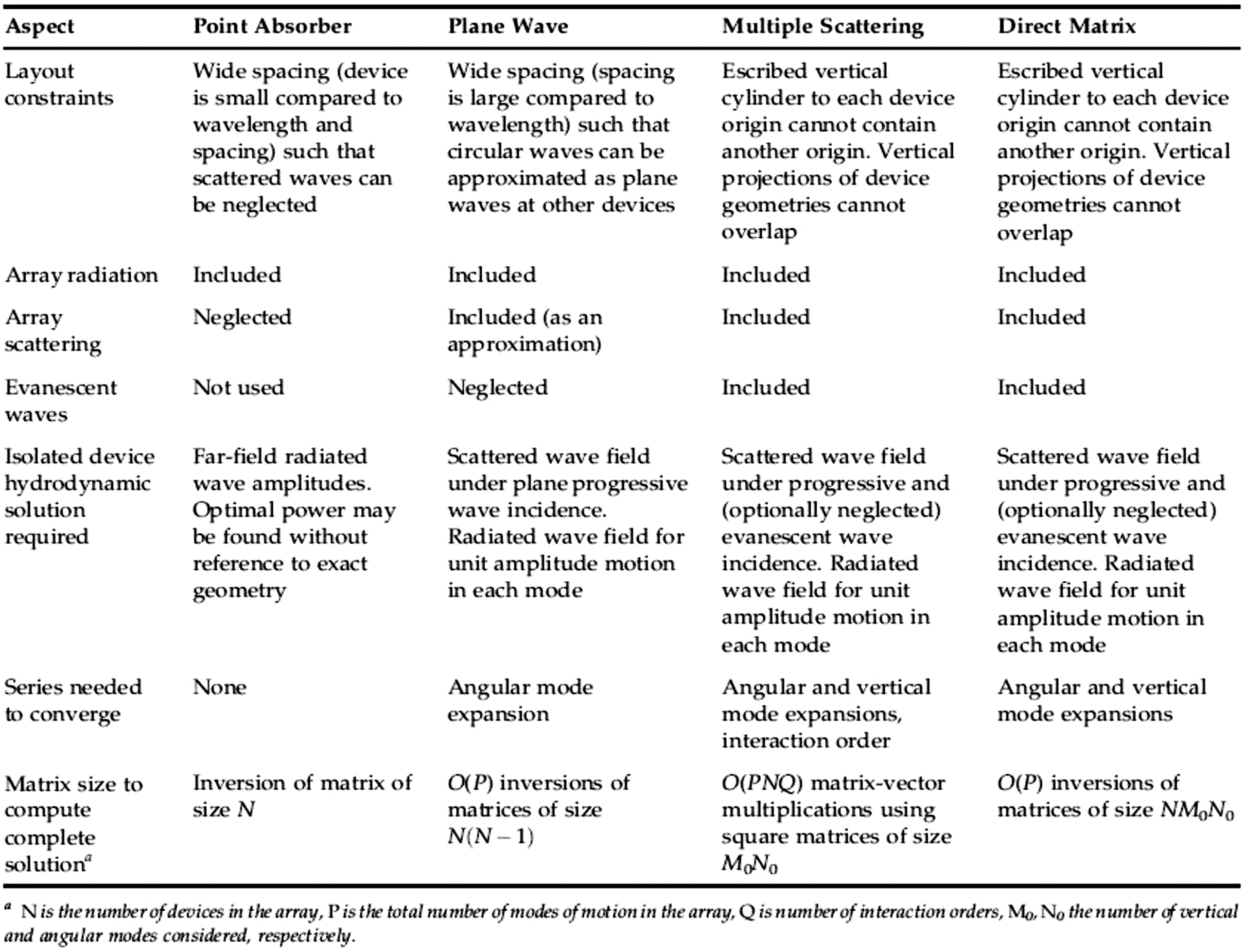
- The point absorber method: Array interactions involve only the waves radiated by each device (Wolgamot et al., 2012).
- The plane wave method: Scattered and radiated waves emanating from each device and acting on others in the array are approximated by plane waves (De Chowdhury et al., 2015).
- The multiple scattering technique: ‘Exact’ solution formed by considering a set of sequential interaction events at each device, the solution being reached via iteration (De Chowdhury and Mannasseh, 2017, Göteman et al., 2015a, b, Isberg et al., 2015, and Konispoliatis and Mavrakos, 2016).
- The direct matrix method: Solves the problem in largely the same way as the multiple scattering method, except that boundary conditions representing device interactions are applied to the entire wave field incident to each device simultaneously (Flavià et al., 2017, and McNatt et al., 2015).

Table 3 shows the comparison of the capabilities and limitations of all semi-analytical techniques (Folley, 2016).

Phase-Resolving Wave Propagation Array

Models. Phase-resolving wave propagation models use sponge layers and wave generation along a circle to simulate the physical process of energy absorption by WEC arrays, and the resulting wave transformation processes of reflection, diffraction, and radiation. This technique is based on the mild-slope equations, with MILDwave software typically used (Stratigaki et al., 2012). Folley (2016) presents a detailed example of implementing a WEC array in MILDwave. This technique can model large domains (in the order of tens of kilometers) with reasonable computational requirements; WEC array effects on coastal processes; and nested (or coupled) techniques for implementation into the wave propagation model. Detailed WEC interaction models to be nested in the wave propagation model can come from semi-empirical techniques (Beels et al., 2010), analytically derived (Babarit et al., 2013), or from numerical predicated wave fields from potential-flow or Navier-Stokes solvers (McNatt et al., 2013). Figure 3 shows a typical example of the application of this WEC array model for studying wake effects.

Table 3 Comparison of all semi-analytical techniques (Folley, 2016)



Aspect	Point Absorber	Plane Wave	Multiple Scattering	Direct Matrix
Layout constraints	Wide spacing (device is small compared to wavelength and spacing) such that scattered waves can be neglected	Wide spacing (spacing is large compared to wavelength) such that circular waves can be approximated as plane waves at other devices	Escribed vertical cylinder to each device origin cannot contain another origin. Vertical projections of device geometries cannot overlap	Escribed vertical cylinder to each device origin cannot contain another origin. Vertical projections of device geometries cannot overlap
Array radiation	Included	Included	Included	Included
Array scattering	Neglected	Included (as an approximation)	Included	Included
Evanescent waves	Not used	Neglected	Included	Included
Isolated device hydrodynamic solution required	Far-field radiated wave amplitudes. Optimal power may be found without reference to exact geometry	Scattered wave field under plane progressive wave incidence. Radiated wave field for unit amplitude motion in each mode	Scattered wave field under progressive and (optionally neglected) evanescent wave incidence. Radiated wave field for unit amplitude motion in each mode	Scattered wave field under progressive and (optionally neglected) evanescent wave incidence. Radiated wave field for unit amplitude motion in each mode
Series needed to converge	None	Angular mode expansion	Angular and vertical mode expansions, interaction order	Angular and vertical mode expansions
Matrix size to compute complete solution[a]	Inversion of matrix of size N	$O(P)$ inversions of matrices of size $N(N-1)$	$O(PNQ)$ matrix-vector multiplications using square matrices of size M_0N_0	$O(P)$ inversions of matrices of size NM_0N_0

[a] *N is the number of devices in the array, P is the total number of modes of motion in the array, Q is number of interaction orders, M_0, N_0 the number of vertical and angular modes considered, respectively.*

A key limitation of phase-resolving models is that the implementation of the reflection, transmission, and absorption characteristics of WECs in an array requires empirically fine-tuning of the absorption function using data from, for example, a BEM model or wave-tank model or sea trial data. Consequently, the accuracy of these models depends on the accuracy of the model used to tune WEC characteristics.

Phase-Averaging Wave Propagation Array Models. Phase-averaged wave propagation models, also called third generation spectral wave models, model how the sea-state varies both spatially and temporally based on linear wave theory. They can efficiently model very large WEC arrays with hundreds of WECs distributed over of tens of kilometers.

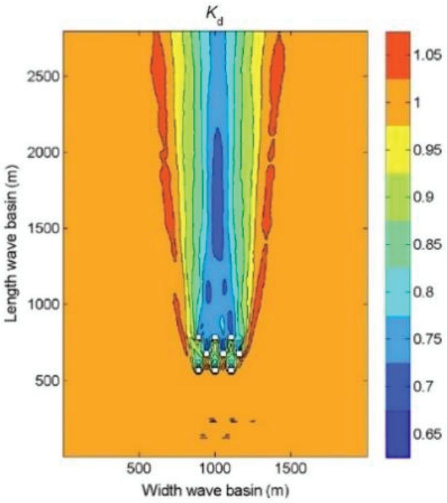


Figure 3 A typical example of wave interaction with a farm of 3 × 3 overtopping WECs, and the resulting wake, visualised using the disturbance coefficient Kd, for irregular long-crested head-on waves with Tp = 5.2s

Software include SWAN, TOMAWAC, and Mike21SW, which take into account all dominant natural processes. This technique can estimate what impact the WEC array may have in surrounding wave conditions, or to calculate WEC array interactions, but not how the WEC changes wave action or the WEC itself. WECs can be included in these spectral wave models in two ways, represented as either supragrid elements (Carballo and Iglesias, 2013), or subgrid elements (Venugopal et al., 2017). Folley (2016) provides a detailed description of their implementation and differences. Greenwood et al. (2016) compare spectral and Boussinesq models for small arrays of WECs using MIKE, highlighting the specific conditions where each model thrives and regions of reduced performance.

Advantages of these models is that they are computationally efficient as WECs may be represented using any structure, from a look-up table to a complex set of governing equations. Limitations include that they: (1) contain only the magnitude of each spectral wave component and do not contain any information about the phase of the wave, hence ‘phase-averaging’, (2) require another model to calculate the response of single WECs that is then used in the WEC array model, and (3) are relatively undeveloped and lack validation. Further development in the representation of WECs in phase-averaged wave propagation models is required (Folley, 2016).

Comparisons of WEC Array Models. Evidently, there is no single best numerical modelling technique for WEC arrays. The most appropriate numerical modelling technique depends on the required characteristics of the particular modelling task, which is not always clear because each approach has strengths and weaknesses. Folley (2016) attempts to address this ambiguity by comprehensively reviewing and comparing state-of-the-art techniques, thus making clear which method is most suitable to which application. A key concern raised by Folley et al. (2012) and reinforced by Folley (2016) is the urgent need to address the empirical validation of these models. Some works have attempted to address this issue (Folley and Whittaker, 2013, Troch et al., 2014, and Mercadé Ruiz et al., 2017). It is noteworthy to mention DNV GL have released the industry’s first commercial software tool for WEC farm array planning, called WaveFarmer (2017).

Physical Modelling of WEC Arrays. While the physical development process for single WECs is reasonably well established, WEC array performance and environmental impact is undeveloped in the physical domain. Limited experimental investigations have been performed due to the cost and size related to testing facilities as well as the complexity of the experiment and related instrumentation (Penesis et al., 2016). WEC array experiments are more complex compared to single WEC investigations due to the requirements of measuring the; interactions between waves and WECs to determine the q factor (ratio between WEC array power and the sum of the power of non-interacting devices that would make up the array); measurements of far-field WEC effects, and measurement on the moorings over a large space. Results from testing various WEC array geometric configurations will lead to the optimisation of array lay-outs for real applications, and enable urgently needed experimental validation for numerical tools.

Array effects and performance. The majority of WEC array experiments have focused on the hydrodynamic response and power output of WECs in an array and the array sea-state modification. These investigations include the use of point absorbers/heaving buoys (Folley & Whittaker, 2013, Mercade Ruiz et al., 2017, Nader et al., 2017, Penesis et al., 2016, Stratigaki et al., 2014,2015, Troch et al., 2014, and Zanuttigh and Angelelli, 2013), OWC devices (da Fonseca et al., 2016), and overtopping devices (Magagna et al., 2011). Each of these studies show intra-array effects to be significant, constructive and destructive, and that they depend on incident waves, array configuration and PTO settings.

Recently, a novel approach was applied to study the radiation and diffraction response from an array of generic resonant type WEC, with a focus on determining the q-factor (Nader et al., 2017). The same submerged spherical buoy WEC was used to represent both monopolar (heave only) and bipolar (surge only) behaviour. In light of previous works' concerns of measuring wave climate with point measurements (O'Boyle et al., 2011), stereo videogrammetry was applied to accurately measure the spatial and temporal wave climate throughout and downstream of the array.

Experimental investigations on large arrays (Figure 4) have shown that the influence of arrays of WECs on coastal processes is important to consider, with wave height decreases of up to 18% observed downwave (Stratigaki et al., 2014,2015, and Troch et al., 2013,2014).

Uncertainties in WEC array tests have been identified, including issues with the spatial-temporal variation in wave climates, and repeatability and reproducibility of model responses (O'Boyle et al., 2011, and Lamont-Kane et al., 2013). These studies highlight the importance of qualifying, if not quantifying, the uncertainties that influence test results and validation of numerical models. The later study provided a set of draft protocols which may assist in WEC array tests.

Figure 4 WEC array with 25 heaving buoys from the WECwakes project (taken from Troch et al., 2014)

As with single WEC model tests, scale effects and the influence of the test facility on results are important to consider. These effects are likely to be exacerbated for WEC array testing because there are more WECs, with more instrumentation and a large footprint in the basin, leading to issues with boundary effects and basin homogeneity. Therefore, uncertainty analysis of WEC array experiments will be crucial to understanding how test results can be extrapolated to full-scale. This area in physical modelling of WEC arrays has not yet been subject to investigation.

Array Moorings. Few examples in the literature focus on measuring the mooring loads of an array of floating WECs, but the importance of the mooring system design on the performance and survivability is far-reaching and should not be overlooked. The dynamic response of the moorings is crucial to the mooring system design since it enables the attenuation of non-vertical movements that affect performance (da Fonseca et al., 2016). When testing for survivability, this study found that closing the air chamber for turbine protection purposes induced amplification of peak mooring loads by a factor of five in irregular waves.

Validation of WEC Array Modelling Tools. There has been a renewed effort in the development of numerical tools for modelling WEC arrays (Folley, 2016). However, for these models to be useful they require experimental validation and uncertainty assessment. Research projects and studies on this topic include the WECwakes project (Troch et al., 2014), the PerAWaT project (Cruz et al., 2013), Folley & Whittaker (2013), and DTOcean (DTOcean, 2017).

4.6 Performance of WECs in Irregular Wave Spectra

Assessing the performance of a WEC in irregular wave spectra is essential to understanding how the system will produce power in the ocean. Estimating WEC power requires an accurate characterisation of the wave climate at a given oceanic site. Performance assessment therefore involves two tasks: wave resource characterisation at the site, and computing WEC power performance.

Wave resource characterisation is commonly achieved using local hindcast data from *in situ* buoy measurements or wave prediction models (SWAN, MIKE 21 SW, WAM, etc. see Carballo and Iglesias (2012) for methodology example and Saulnier et al. (2013) and Perignon (2017) for uncertainties related in using such models related to irregular wave spectra). Wave climates are typically described using a scatter table of sea states according to the significant wave height (H_s) and peak or energy period (T_p, T_e,) and possibly peak or mean direction (θ_p, θ_m), as described by spectral distribution of energy densities (JONSWAP, Pierson-Moskowitz, Bretschneider). Testing a WEC across the H_s and T_e elements of the scatter table produces a power matrix (Figure 5), which when multiplied with the scatter diagram elements consisting of the probability of occurrence of a sea state enables the estimation of a long-term WEC power performance, known as the mean annual energy production (MAEP).

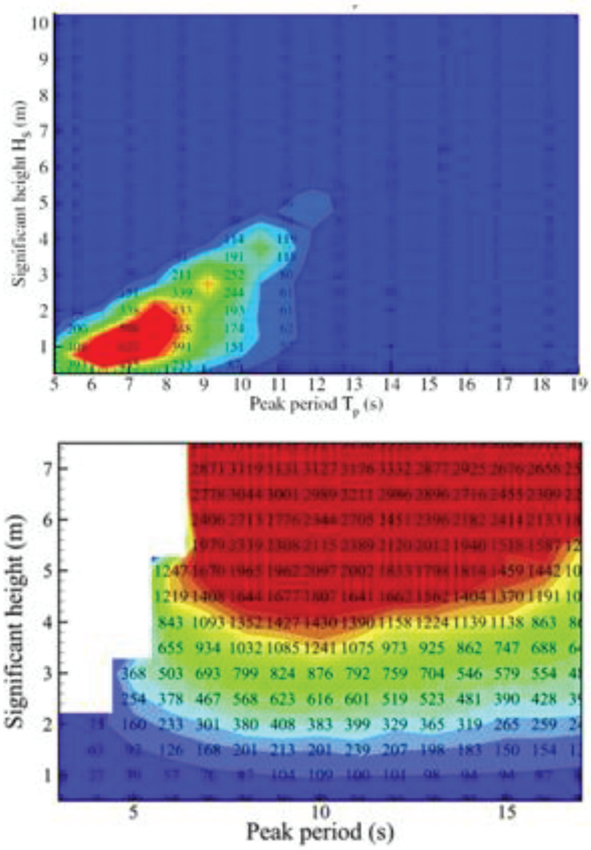


Figure 5 (Top) Power matrix and (bottom) scatter diagram of flap type device (taken from Babarit et al., 2012)

A number of studies have questioned the

two-parameter (H_s, T_e/T_p) dimensionality of the performance matrix (Clabby et al., 2012, de Andres et al., 2013, 2015, Hiles et al., 2015, 2016, Kerbiriou et al., 2007, Pascal et al, 2012, Portilla et al., 2009, and Saulnier et al., 2011a, 2011b). These studies show that additional spectral parameters are required to accurately assess the performance of a WEC, both at the time-scales of sea state and long-term power prediction. Limitations of the classical approach to assess WEC performance include: resolution, linear interpolation between elements, standard spectral shapes, constant bin size, more dimensions relevant (direction, water level), and limited data sets. Spectral representation of sea states may result in a large variety of shapes, including unimodel (JONSWAP, etc.) and multimodel (two or more peaks). Therefore, depending on the type of WEC the performance may be significantly influenced by temporal or spatial changes in frequency distribution (spectral distribution) and also wave directionality (directional spreading) for direction sensitive devices.

WEC performance has been found to be sensitive to spectral distribution through numerical and analytical studies of spectral bandwidth, peakedness, and wave groupiness (Hiles, et al., 2015, and Saulnier et al, 2013), as well as through experimental studies (Clabby et al. 2012). Figure 6, taken from Clabby et al. (2012), shows that if the response of a device is particularly frequency sensitive, its performance will vary significantly depending on the formulation of the energy density. These investigations highlight that the spectral bandwidth parameter adequately completes the H_s and T_e/T_p sea state description for characterising the performance of these WEC types. It is noteworthy to mention that wave groupiness is also an important parameter to consider in the design of PTO systems.

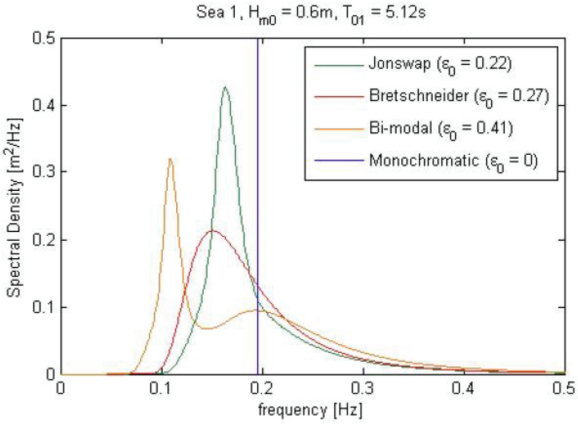


Figure 6 Spectral energy distributions for a selected sea state (taken from Clabby et al., 2012)

Often, sea-states are not unimodal since they are the result of various wave systems (superimposed remotely originated swells and local wind-seas) leading to complex multimodal spectral shapes. The classical method of power production assessment has been shown to be inaccurate in those areas with high percentage of multimodal spectra (De Andres et al., 2015, Hiles, et al., 2015, Kerbiriou et al., 2007, and Kpogo-Nuwoklo et al., 2014). These studies infer the importance of considering a multi-set description of sea states for assessing available power and WEC performance.

Refinements for wave climate descriptions have been made through the use of buoy measurements (Saulnier et al., 2011a, and Saulnier and Le Crom, 2013). These studies find that each wave system should be identified and characterised properly so that its influence upon the device may be better identified. With respect to directional spreading, neglecting the multimodel nature of sea states when assessing the response of a direction-sensitive WEC may lead to very erroneous results (Saulnier, 2009). In such cases the multi-system description should be used (Kerbiriou et al., 2007, and Portilla et al., 2009). Pascal et al., (2012) carried out an experimental investigation into the performance of three types of WECs (floating OWC, two fixed OWCs, and Edinburgh Duck model) with different directionality properties, finding that for the WEC types studied directional spreading showed insignificant influence.

To avoid the challenges associated with irregular wave spectra, assessing the performance of early-stage WECs can be achieved using polychromatic waves, which have properties of both regular and irregular waves (Mitchell Ferguson, 2015). This intermediate wave option offers more realistic sea states than regular waves, leaving irregular wave spectra assessment for a later stage of device development.

When applying the aforementioned methods to calculate the MAEP, uncertainties arise from a variety of contributing factors, and there is currently no accepted method for quantifying the uncertainty in MAEP calculations. Hiles et al. (2016) attempted to address this problem by propagating the uncertainty from numerically generated WEC power production data and historic metocean data, identifying that variability in the wave climate contributed to most of the uncertainty in MAEP.

For a list of physical experiments in which WEC performance was assessed in irregular wave spectra see Ozkop and Atlas (2017). The revised ITTC Recommended Procedure, Wave Energy Converter Model Test Experiments (7.5-02-07-03.7) discusses some of the issues of irregular wave spectra and provide guidance for irregular wave tests.

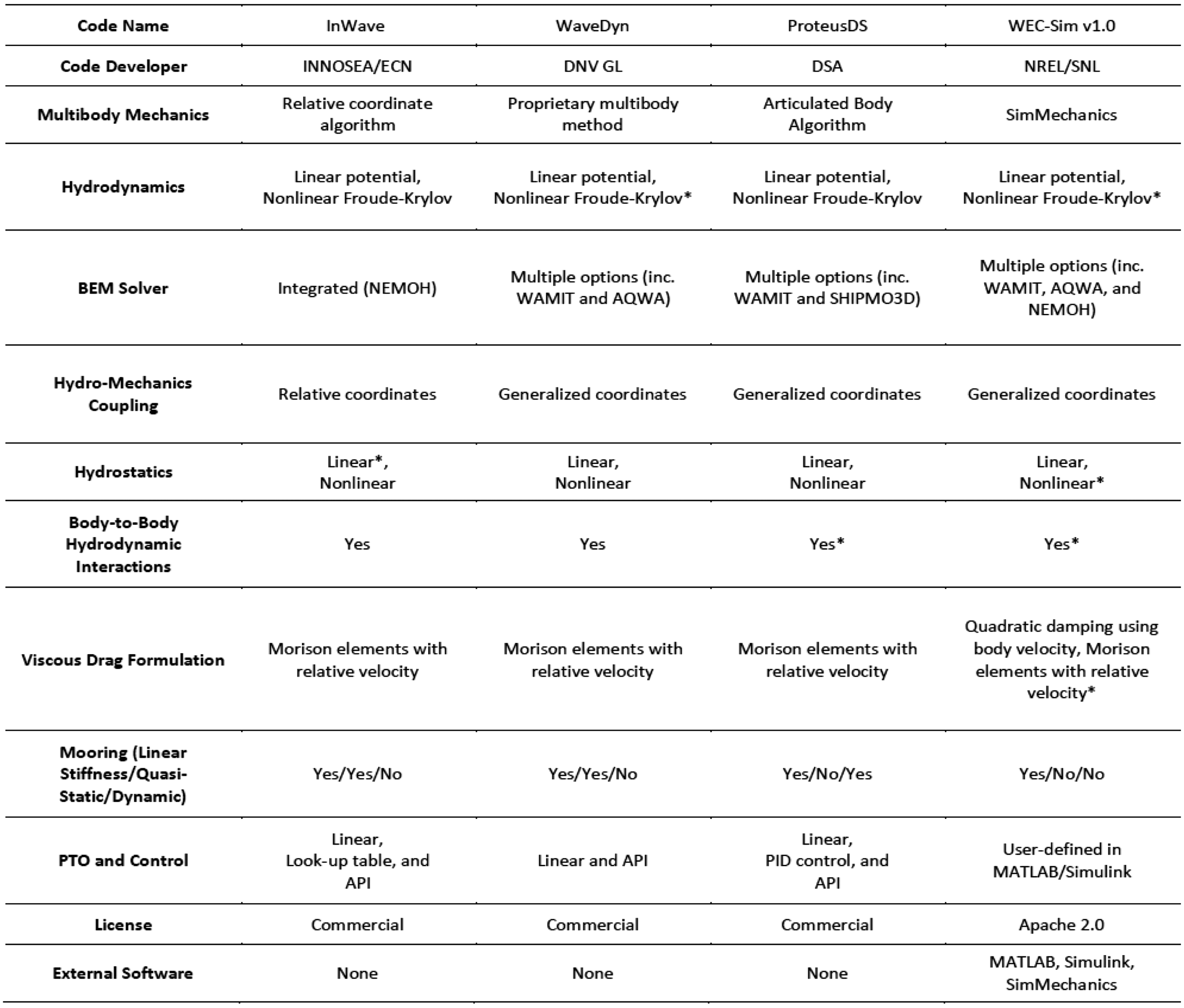
Challenges in Survivability Tests. In design studies it is necessary to simulate WEC response to extreme wave conditions. An accurate assessment of the highest possible wave power is a major issue when considering the survivability of devices. The spectral shape, peakedness and bandwidth, as well as directionality are important parameters to consider (Saulnier, 2013, and Saulnier and Le Crom., 2013). Extreme loads are often caused by complex nonlinear wave-structure interaction. The prediction of those loads is a critical step in the design process, and the application of mid- and high-fidelity numerical methods and experimental wave tank tests are often needed (Quon et al., 2016).

The issue of WEC extreme condition modelling (ECM) was recently addressed in a workshop hosted by Sandia National Laboratories and the National Renewable Energy Laboratory (Yu et al., 2015, and Coe et al., 2014). From this workshop a review was carried out of the numerical and experimental modelling methods for predicting WEC loads, motions and performance in extreme conditions. Key findings and recommendations from Coe et al., (2014) include:

- Numerical and experimental ECM developed by offshore oil and gas and shipping industries are useful, albeit limited due to WECs maximising motions where the other structures minimise.
- It is not always the largest wave that causes the largest load, rather series of specific wave trains.
- The occurrence of extreme loads can be studied as a stochastic event.
- Open-source experimental data sets are needed to validate WEC design and analysis methods, and the development of a set of guidelines and best practices that describe how to numerically model WECs in extreme conditions.

Considering these findings, the development and application of a design process for predicting WEC extreme loads was undertaken and later improved (Quon et al., 2016). The methodology used searches the extreme wave events that are likely to result in the maximum load through Monte-Carlo-type simulations (Figure 7). The work recommends further analysis and development of WEC-specific ECM methods are needed because of unique WEC system designs, complex nonlinear waves, and WEC body interaction and mooring. Additionally, extreme wave conditions can be predicted by applying an extrapolation method to hindcast data from a spectral wave model calibrated with in situ measurements at a wave energy site (Le Crom, et al., 2013, and Prevosto, 2011).

Table 4 Integrated WEC simulation tools (* under development as of 2015)



Code Name	InWave	WaveDyn	ProteusDS	WEC-Sim v1.0
Code Developer	INNOSEA/ECN	DNV GL	DSA	NREL/SNL
Multibody Mechanics	Relative coordinate algorithm	Proprietary multibody method	Articulated Body Algorithm	SimMechanics
Hydrodynamics	Linear potential, Nonlinear Froude-Krylov	Linear potential, Nonlinear Froude-Krylov*	Linear potential, Nonlinear Froude-Krylov	Linear potential, Nonlinear Froude-Krylov*
BEM Solver	Integrated (NEMOH)	Multiple options (inc. WAMIT and AQWA)	Multiple options (inc. WAMIT and SHIPMO3D)	Multiple options (inc. WAMIT, AQWA, and NEMOH)
Hydro-Mechanics Coupling	Relative coordinates	Generalized coordinates	Generalized coordinates	Generalized coordinates
Hydrostatics	Linear*, Nonlinear	Linear, Nonlinear	Linear, Nonlinear	Linear, Nonlinear*
Body-to-Body Hydrodynamic Interactions	Yes	Yes	Yes*	Yes*
Viscous Drag Formulation	Morison elements with relative velocity	Morison elements with relative velocity	Morison elements with relative velocity	Quadratic damping using body velocity, Morison elements with relative velocity*
Mooring (Linear Stiffness/Quasi-Static/Dynamic)	Yes/Yes/No	Yes/Yes/No	Yes/No/Yes	Yes/No/No
PTO and Control	Linear, Look-up table, and API	Linear and API	Linear, PID control, and API	User-defined in MATLAB/Simulink
License	Commercial	Commercial	Commercial	Apache 2.0
External Software	None	None	None	MATLAB, Simulink, SimMechanics

4.7 Integrated WEC Simulation Tools Based on Multi-Body Solvers

Over the past decade a number of integrated simulation tools for simulating WECs based on multi-body solvers have been developed to address the needs of industry and research. These numerical mid-fidelity codes simulate WECs using time domain multi-body dynamics methods to model device motions, and hydrodynamic coefficients to model hydrodynamic forces. They are capable of modelling complex interactions between multi-body dynamics, hydrodynamics, hydrostatics, and PTO and control systems in a coupled simulation environment.

The overarching aims of these numerical tools are: to reduce WEC design uncertainty, improve power performance, improve survivability in extreme conditions; and to accelerate WEC technology development by reducing investment risk (Yu, 2017).

The Wave Energy Converter Code Comparison (WEC3) project attempted to verify and validate four numerical tools, as well as inform the upcoming IEA OES Annex VI wave energy modelling project (Combourieu et al., 2015). The Annex IV project will deliver code-to-code verification and code-to-experiment validation. General details of the four codes are given in the study, with their capabilities compared in Table 4. Figure 8 shows the floating three-body oscillating flap type device (F3OF).

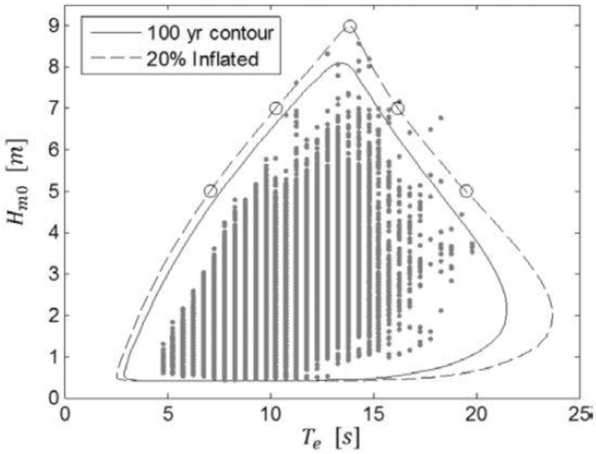


Figure 7 100-year contour for a data buoy on the west coast of USA. Open circles were the 5 sea states that were used to search for the extreme events (Quon et al., 2016)

The main conclusions from this code-to-code comparison study are:

- Good overall agreement in the numerical predictions from the four codes.

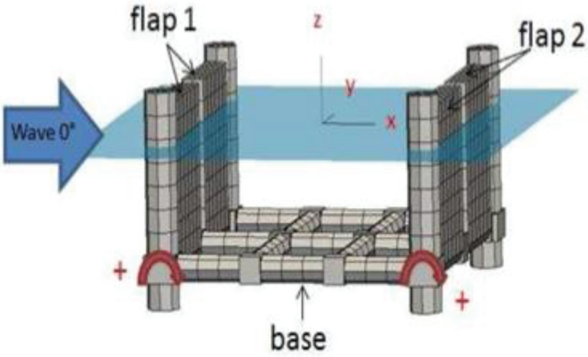


Figure 8 Schematic of the F3OF inspired by the Langlee device

- Without viscous corrections, largest differences were observed between codes that take into account hydrodynamic body-to-body interactions and those that don’t.
- Participants have different approach for taking into account viscous effects through corrective terms. It is observed that it leads to differences in numerical predictions that can be significant.

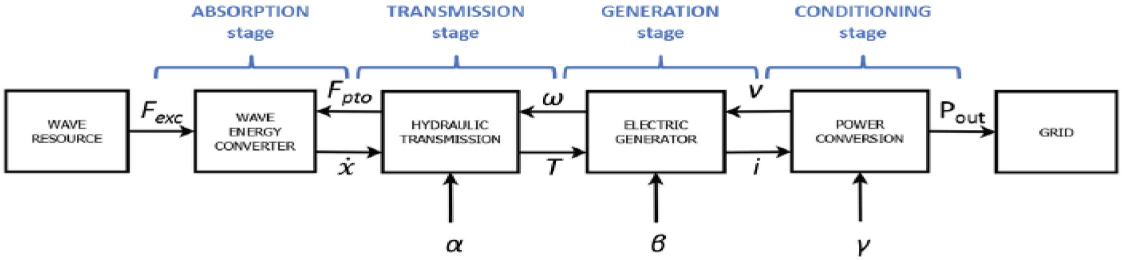


Figure 9 Diagram of a WEC with a hydraulic PTO (Penalba & Ringwood, 2016)

The next phase of this project will include validation against experimental data sets. While these codes are continually being developed to increase their capabilities, at present there are limitations in the type of device that can be modelled. For example, these numerical tools are unable or not proven for modelling OWC, overtopping devices, or WECs with flexible/elastic materials. There are other options however for these device types, with examples in literature an OWC (Amundarain et al., 2011), an overtopping device (Igic et al., 2011), and a flexible material WEC (Algie et al., 2016).

Wave-to-wire Modelling. Essentially, the integrated simulation tools described above are commercial software (except WEC-SIM) that incorporate the concept of wave-to-wire (W2W) modelling (see Nielsen et al., 2014 and Pecher & Kofoed (2017) for an overview of W2W models, and Penalba & Ringwood (2016) for a review). W2W modelling can be done without using these tools by modelling stages that comprise the entire chain of energy conversion from waves to the grid as shown in Figure 9. A W2W model can typically offer the following options (Nielsen et al., 2014):

- Time series of the power output.
- Details concerning the efficiency of the PTO system.
- Implementation of different (optimal) control strategies.
- Time series of structure motions and mooring line forces.
- Fatigue loads on structural components which are exposed to high cyclic loading
- Dynamical prediction of the response of a wave energy converter in moderate sea states.

4.8 Round-Robin Test Campaign

A key aspect of developing guidelines for WEC testing is that results from independent tests will be compatible between different facilities. In order to determine uncertainties regarding facility biases, a series of comparative tests must be undertaken across a considerable number of test facilities. These tests generate benchmark data for identifying biases and enables the determination of how these effect model scale test results. A round-robin test campaign has therefore been proposed for investigating facility bias in WEC model test experiments. This campaign would run similar to the structure of the world wide campaign which has occupied the resistance committee since the 24th ITTC. The inter-facility comparison involves testing two geosim models in analogous test conditions across many ITTC member facilities (41 institutions in the 26th ITTC). A technical procedure for identifying facility biases pertinent to WEC model tests should include: model definition, test definition, uncertainty analysis, and data submission. Brief discussion on each of these sections follows. Noting that the MaRINET2 project has planned a second attempt at a round-robin campaign, due to start late 2018.

Model Definition. To minimise the influence of the model geometry in facility biases identification the institutions participating should test the same model. Because scale factors are not well-characterised for WEC tests, only one model at one scale should be considered. As there is still yet to be design convergence for WEC technology, consensus shall be sought between participating institutions to decide which type of WEC would be most beneficial to the wave energy community. Due to the extensive research and development of OWC type WECs is well-suited.

Test Definition. Each institution will do the tests following their usual procedures with the best possible care in order to obtain good quality results. Thus, all measurement equipment and systems have to be properly calibrated and prepared. Each institution should test the model on four different days in order to change the test conditions and obtain better uncertainty analysis results. All measurement systems have to be described, including conditioners, calibration curves, and data acquisition frequency rate. Prior to tests, the WEC model and PTO components should be inspected thoroughly for damage or wear that could introduce uncertainty into the findings. Tests should be carried out in regular and irregular waves, with constant PTO control settings and damping characteristics. Regular wave test should include at least three sets of tests with the same wave steepness. For irregular wave tests, 10−20 representative sea states across a bivariate scatter diagram (Hs, Te/Tp) could be used. The selected sea states chosen may be based on constant significant wave height and average/peak period to enable extrapolation graphs to be drawn up such that, if required, all elements of a bivariate table can be computed. Facility biases may be analysed for the following tests that are common in WEC investigations. Proposed tests are outlined in Table 5.

Uncertainty Analysis Procedure. The goal of the comparison is to obtain for each test type, each performance indicator, and each institution the percentages of the precision limit (P), bias limit (B) and uncertainty (U) as defined in ITTC Recommended Procedure, Guide to the Expression of Uncertainty in Experimental Hydrodynamics (7.5-02-01-01) and The ITTC Recommended Procedure, Uncertainty Analysis of a Wave Energy Converter (7.5-02-07-03.12). The procedure to analyse the data is explained in "IIHR technical report T442, Statistical Approach for Estimating Intervals of Certification or Biases of Facilities or Measurement Systems Including Uncertainties" (Stern et al., 2005). Each institution is encouraged to estimate their own precision limits, biases limits and uncertainty, and send it to the 29th ITTC Specialist Committee on Hydrodynamic Testing of Marine Renewable Energy Devices. When all data is collected, a Reference Value for Certification, obtained from all the institutions results will be calculated, with the final uncertainty analysis completed by the SC-HMMRED.

Table 5 Proposed tests for the round robin campaign

Test	Objective	Measurement Technique and Reporting
Motion response	Determine the response amplitude operators (RAOs) of relevant performance indicators (e.g. kinematic and dynamics)	• Free decay tests for relevant DoF's (free-floating body and full system) • RAO curves for regular and irregular waves
Absorbed power	Determine the WEC absorbed power	• Based on the measurements of kinematics and dynamics (e.g. velocity/force, flow/pressure) • Reported as capture width for regular waves • Power matrix for irregular waves
Wave tank characterisation	Characterisation of the wave field at the location of the device	• Characterisation carried out following either three methodologies: • Calibration of incident waves without WEC • From suitable wave specifications • Measuring wave field during tests, separating into incident, reflected and radiated components in post-processing • Performance indicators to report for regular waves: height and period • Performance indicators to report for irregular waves: significant wave height, zero up-crossing period, energy period, peak period, repeat time, and spectral shape.

Data Submission. While it is important in a round-robin campaign that an appropriate procedure is adopted in order to preserve the confidentiality of the data, and to avoid the possibility that the evaluation of the data could be affected by a knowledge of facility from which it originated, experience from the resistance committee has shown that this is challenging and can restrict the data sets available for analysis. As previously mentioned, perhaps an open approach could be adopted, provided an appropriate procedure is developed through consensus by participating institutions to ensure the collective community of expertise can guarantee data collected is always to a high standard. On the other hand, in this day and age a double blind approach might be feasible. Each institution could upload data to a DropBox which can only be accessed by a moderator outside of this ITTC committee.

This moderator can simply name each uploaded data set as Institution 1, Institution 2… Institution N, and send all data sets to the Evaluators for processing. If there are ambiguities in the data, the moderator can be notified of the problematic data set and thereby contact the relevant institution for clarification. If there are concerns about the institution and mediator identities being known to one another, the data file could be encrypted and uploaded to an anonymous file sharing site, and the encryption key only given to the Evaluators. Communication could be through an anonymous email address. Regarding the compilation of data, it is recommended to develop a spreadsheet based analysis tool to draw together all the data for comparative purposes.

4.9 Conclusions

Considerable progress has been made into developing accurate models for WEC PTO systems, devices and arrays, with integrated WEC multi-body models advancing rapidly. Several specific issues continue to present challenges with regard to the accurate prediction of full-scale device performance:

- Modelling of PTO systems both physically and numerically is challenging due to the difficulty in accounting for coupling between PTO systems and loads, the influence of scaling effects, and the generation of realistic and repeatable model conditions.
- Difficulty in numerical modelling due to: the interaction of array devices, possible large motion responses, systems comprising of multi-bodies with complex articulation and components, and prediction challenges in irregular wave spectra.
- Difficult in modelling arrays even at moderate scales in test tanks.
- Experimental uncertainty analysis for single devices and arrays.
- Lack of round robin testing results for facility comparison.
- Need for testing engineering factors such as structural properties, survivability, component testing rather than performance parameters.

5 CURRENT TURBINES (CTS)

5.1 Procedures

The SC-HMMRED reviewed the procedures and guidelines under its responsibility related to current turbines (CTs).

The following procedure was updated:

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

The procedure addresses designing and performing model tests of current turbine devices at small, intermediate, and field-scale in a reproducible environment at a hydrodynamic test facility suitable for testing such devices. Minor revisions were only made to this procedure.

The following new guideline was developed:

- 7.5-02-07-03.15 Uncertainty analysis-Example for horizontal axis turbines

The development of the guideline addressing uncertainty analysis for testing horizontal axis turbines is provided in the following section.

5.2 Uncertainty Analysis for Horizontal Axis Turbines

The committee has completed the generation of the ITTC Recommended Procedure, Uncertainty Analysis-Example for Horizontal Axis Turbine (7.5-02-07-03.15), in completion of our term of reference for current turbines. The final draft of this guideline is in final review by the 28th ITTC. The purpose of this uncertainty guideline is to provide guidance on the application of uncertainty analysis relevant to the small-scale testing of a current turbine following the ITTC Recommended Procedure, Model Tests for Current Turbines (7.5-02-07-03.9).

This guideline covers a summary of error contributions that must be considered relative to marine current turbine testing including but not limited to:

- Model scaling with relevance to the proper use of scaling laws and the impact of improperly applying scaling laws with particular attention to the consequences of improper Reynolds number scaling.
- Errors associated with power take off (PTO) modelling and how to assess levels of uncertainty related to PTO modelling.
- Scale model features that can impact power generation or introduce measurement error related to manufacturing, structural or functional response.

The guideline also summarises relevant ITTC uncertainty guidelines and procedures that should be followed in any test campaign, for example, documents on propulsor, powering, and cavitation testing since a marine current turbine is a marine turbomachinery device. An example of the application of uncertainty analysis applied to a horizontal axis turbine model test is included in the guideline.

5.3 Modelling Arrays of Current Turbines

Numerical Modelling of Turbine Array Interactions. Thiébot et al. (2016) proposed a methodology for representing large arrays of tidal turbines using Shallow Water Equation solvers. This methodology represents individual turbines as small areas where a sink momentum term is applied. The sink momentum term is calculated from the vertical integration of the force exerted on an actuator disk. Thiébot et al. (2016) applied this methodology to simulate the effect of 45 turbines placed in the Alderney Race.

For modelling large scale effects of arrays and associated interactions, shallow water equations have also been used, where the turbines are simulated by applying an equivalent added drag coefficient to the existing parameterisation of bed friction, applied uniformly over the area of the energy extraction zone. This method has been validated experimentally for arrays of porous fences (Coles et al., 2016), where experimental load cell measurements of the total fence drag agreed to within 10% of the numerical formulation of array drag given. Coles et al., (2017) used this drag methodology to assess the resource around the Channel Islands in the English Channel. This work also demonstrated that extracting energy from one site can have a constructive impact on a resource in another site.

Liu et al. (2016) studied the interaction between two turbines by numerically solving Reynolds-averaged Navier-Stokes (RANS) equations with the sliding mesh technique. Two turbines were arranged in tandem with 8 rotor diameters spacing, with full models of the three-bladed turbines simulated to resolve the complete flow field and thus performance behavior of the turbines. The results showed that the downstream turbine produced less than 50% of the power of the upstream turbine at this distance. Importantly, the lateral swaying loads on the downstream turbine were much higher than those on the upstream one due to increased turbulence. In contrast, the performance of the upstream turbine was not affected by the presence of the downstream turbine.

Churchfield et al. (2013) performed the world first Large Eddy Simulations (LES) of tidal turbine array, which can accurately describe the physics of flow (turbulent ocean boundary layer) around the turbine and it later evolved into the popular numerical tool Simulation Offshore Wind Farm Array (SOWFA). The turbines were modelled using rotating actuator lines, and the finite volume method was used to solve the governing equations. They found that staggering consecutive rows of turbines in the simulated configurations allowed the greatest efficiency using the least downstream row spacing. Counter-rotating consecutive downstream turbines in an aligned array also showed a small benefit.

Gebreslassie et al. (2015) investigated the influence of wake interaction and blockage on the performance of individual turbines in a staggered configuration in a tidal stream farm using the CFD-based Immersed Body Force turbine modelling method. The LES modelling technique was implemented, with the impact of the free surface on the turbines taken into account using the Volume of Fluid (VOF) method. Results showed that the performance of the downstream turbines was heavily affected by the wake interaction from the upstream turbines, though there were accelerated regions within the farm which could be potentially used to increase the overall farm power extraction. Closely packed turbines in the lateral direction improved the performance of those turbines due to blockage effects, but could also affect the performance of downstream turbines.

Zanforlin et al. (2016) performed a CFD analysis of the hydrodynamic interactions between three vertical axis tidal turbines set in close proximity for two layouts: side-by-side and triangular. The following key mechanisms were found to increase power with respect to isolated turbines: (1) turbine blockage that entailed flow acceleration outside of the turbines and inside the aisles between adjacent turbines; (2) more favorable direction of the flow as it approached the blade during its upwind travel; and (3) wake contraction, which increased torque generation during downwind blade travel. Blockage was responsible for a moderate performance increase exhibited by the triangular layout. Changes in the direction of the flow approaching the blades and wake contraction only occurred for the side-by-side layout, and lead to significant efficiency increases. The side-by-side layout allowed power gains for a wider range of flow direction, and thus could be adoptable for tidal currents characterised by an incomplete inversion of the current direction.

The simplification of current turbines as actuator disks within 3D incompressible RANS models has been proposed to reduce the simulation scales and time requirements for array models. The accuracy of this methodology in predicting the experimental wakes of a 0.8 m diameter turbine was assessed by Batten et al. (2013). This study compared uniform actuator disks with blade element approximations which also included swirl effects. Hunter et al. (2015) used this methodology to present results for tuning operating conditions across arrays of four and eight turbines, and also the effect of staggering an array of turbines into upstream and downstream sub-arrays. The results showed that the power coefficient of a non-staggered array of turbines is maximised when the turbines are operated with a uniform local resistance coefficient across the entire array. This operating condition results in a non-uniform distribution of thrust and power coefficient across the array. For the staggered array studied it was found that for a given streamwise separation of sub-arrays the power coefficient was maximised by differential tuning of the front and rear rows, however the maximum power coefficient did not exceed that achieved by the equivalent non-staggered array. Additionally, for a given efficiency of extraction, i. e., the power extracted by the turbines relative to the total power removed from the flow, the non-staggered array was shown to have a higher power coefficient than the staggered arrays.

Experimental Measurements of Turbine Interactions for Arrays. Queen’s University Belfast and Wave Barrier Ltd have developed a tidal testing platform to test hydrokinetic turbines at medium scale (Jeffcoate et al, 2016). Multiple turbines can be pushed through still water conditions in steady-state pushing tests. Experiments were conducted to evaluate the interaction between two identical, mono-strut, horizontal axis tidal turbines (HATTs) with 1.5 m Diameter (D) rotors. When placed in-plane, the turbines had no adverse effect on one another, however when spaced in-line with 2D separation between the turbines there was a 63% reduction in the performance of the downstream turbine. At 6D downstream this performance reduction was still 59%, indicating some wake recovery between the 2D and 6D tests, however the influence from the upstream rotor still persisted out to at least 6D lengths downstream. In contrast, the performance of the downstream turbine, when offset 1.5D inline from the upstream device and 6D downstream, approximated the individual turbine performance. There was no negative impact on the downstream turbine when offset by 1.5D or 3D from the inline position at 6D downstream.

Mycek et al. (2014b) conducted experiments to study interaction effects using two three-bladed 1/30th scale prototype horizontal axis turbines in a flume tank, with the two turbines axially aligned with the upstream flow. Both wake and performance analysis were characterised qualitatively and quantitatively, with a large range of inter-device spacing's of up to 12 diameters between the two turbines studied. All configurations were tested with two different ambient turbulence intensities, namely 3% and 15%. This study determined out that, for the considered turbine and blade geometry, higher ambient turbulence intensity rates reduce wake effects, and thus allow a better compromise between inter-device spacing and individual performance.

Stallard et al. (2013) reported on experimental measurements of the velocity field downstream of several line arrays of three-bladed 270 mm diameter horizontal axis rotors. All tests were conducted in the University of Manchester wide flume. The longitudinal, lateral and vertical profiles of both the mean velocity and the turbulence intensity of the wakes of a single turbine, and a single row of two, three and five turbines were presented. These configurations included rotor wakes that were constrained by a lateral boundary on one side only, and wakes that were constrained by adjacent wakes at equal distances on both sides. This data provides improved understanding of the form of tidal turbine wakes owing to different lateral bounding conditions.

Nuernberg et al. (2016) conducted a comprehensive experimental investigation of the flow field characteristics within tidal turbine arrays across a number of array layout configurations and current velocities. Up to four small scale turbines were placed in a circulating water channel to investigate the effects of changing array configuration and wake interaction on the flow velocity and turbulence characteristics in small array layouts. Detailed account of the resulting flow field characteristics was captured by particle image velocimetry measurements at a number of locations within the wake of the array, providing a large set of instantaneous flow recordings for further analysis of flow features and wake characteristics. Results suggest, for a low ambient turbulence environment, that longitudinal spacing in a staggered array configuration has a small effect on the wake recovery in terms of velocity deficit and turbulence intensity. The lateral spacing of the middle row turbines caused more significant variations due to a shift in location where the wakes of the turbines reach the array center-line. Some of the results pointed towards flow acceleration occurring at closer spacing which reduced the initial wake velocity deficit within the staggered set-up.

5.4 Challenges for Physical and Numerical Predictions of Performance of Current Turbines

Recent research has focussed on the influence of shear inflow profiles and turbulence, blockage, and free-surface effects. Early work on understanding the impact of both waves and turbulence on current turbines was performed by McCann (2007), who performed predictions using a blade element approach to model a generic turbine acting with different sea states and levels of turbulence applied as inlet conditions.

This work emphasised the importance of fatigue loading on blades, with strong sensitivity to both turbulence intensity and sea-state. The results also highlighted the requirement for detailed tidal measurement studies to validate spectral models of tidal current flow.

The influence of mean flow shear on hydrokinetic turbine performance has gained recent interest as smaller scale devices suitable to river and some tidal installations become more popular. Mean shear and inflow turbulence can impact unsteady energy production, device vibration and radiated noise (Jonson et al., 2012, Lloyd et al., 2014, and Motley and Barber, 2014).

River and tidal installation sites will be characterised by higher mean flow shear and turbulence than in open ocean current applications (Neary et al., 2013). The authors compared measured vertical profiles of mean current velocity and longitudinal Turbulence Intensity (TI) obtained in medium-large rivers and canals. They recommended that a power law mean shear profile and an exponential decay for TI profiles be used to estimate these effects on turbine performance. Since inflow characteristics can impact device performance, device test programs should characterise the inflow structure when possible at the deployment site (Jeffcoate, et al., 2015, and Kilcher et al., 2014).

Forbush et al. (2015) recently conducted tests to assess the performance and control of a cross flow turbine in shear flow, determining that point measurements of inflow velocity cannot provide conclusive turbine power-performance curves in a sheared flow, and they recommended that an array of point measurements should be obtained to spatially resolve the shear flow profile. If the profile is shown to be synoptic over the time-scales of the power output characterisation, temporally and spatially averaged inflow velocities should be used to calculate averaged forms of the non-dimensional performance coefficients to produce consistent performance curves. They also found that velocity shear has implications for turbine control schemes, and that defining a representative reference velocity will be a challenge for any control strategy that depends on knowledge of free-stream velocity.

In addition to inflow characteristics, the deployment area terrain can also impact device performance. Studies are now being undertaken to assess the impact on river depth, proximity to river surface and banks as well as bed terrain on the device. Noruzi et al. (2015) studied installation depth in a tidal application where the device would be susceptible to free surface wave motion, determining that proximity to the free surface can impact device efficiency, cavitation, vibration and fatigue.

The influence of turbulence intensity on model scale current turbines was studied by Mycek et al. (2014a), who conducted experimental trials by applying two turbulence intensity rates of 3% and 15% on a 0.7 m diameter turbine in a circulating water channel at speeds of up to 1 m/s. Results highlighted that while the wake of the turbine is acutely influenced by the ambient turbulence conditions, its mean performance turns out to be slightly modified.

Further studies on the influence of grid generated turbulence on a 0.8 m current turbine was performed by Blackmore et al. (2016) in a circulating water channel at speeds up to 0.8 m/s. The turbine was instrumented to measure overall rotor thrust and torque, and flapwise and edgewise blade root bending moments. The turbine was controlled to maintain constant Revolutions Per Minute (RPM) using a fast response electronic load connected to a permanent magnet DC motor generator. The results showed that increasing turbulence intensity reduces the power and thrust coefficients by over 10% in extreme cases, along with a corresponding increase in flapwise and edgewise blade root bending moments. However, increasing integral length scale increases power and thrust coefficients by over 10% with a larger increase in fluctuations also observed.

Wave motion can also impact device performance in floating barge type device installations. Zhang et al. (2015) investigated the effects of the surge motion of a floating barge on the performance of tidal current turbine suspended below the barge. The authors concluded that surge motion induces an oscillation in the drag and power coefficient, which has a negative impact on the turbine structural integrity and fatigue life. However, average values of the device drag and power are only marginally effected by the surge, implying that annual power output would be minimally impacted. They recommend that surge effects be taken into account in floating turbine designs.

Fluctuating blade loads on a current turbine were studied experimentally using planar oscillatory flow by Milne et al. (2015) using a 0.78 m diameter turbine towed at 1 m/s. In cases where the boundary layer was believed to be attached to the outer sections of the blade, the out-of-plane bending moment amplitude for unsteady flow was up to 15% greater than the corresponding load measured in steady flow, with a phase lead of up to 4.5 degrees exhibited.

Initial studies on a 0.8 m turbine in a towing tank with waves was performed by Galloway et al. (2014), which highlighted significant impacts on unsteady loading with high wave frequencies.

Kolekar and Banersee (2015) evaluated the impact of terrain blockage, proximity to bed floor and free surface, as well as Reynolds number effects on device performance. This type of blockage scenario can occur in shallow river applications. The authors determined that Reynolds number can impact device performance, as has been shown in other studies (Bachant and Wosnik, 2014), and that optimal performance is dependent on the proper vertical placement of the device between the bed floor and the free surface. Device performance was also found to suffer if it was placed too close to either the bed floor or the free surface.

Hill et al. (2016) investigated the impact of bedform topology on turbine performance, determining that certain bedform topologies can result in decreased turbine performance. They also found that turbine-bedform interactions can be expected to be amplified by higher or steeper bedforms, or by a larger rotor positioned closer to the sediment layer. The rotor itself can then impact bedform scour, and effect which should be taken under consideration in array applications.

As a result of the potential scour effect and impact on sediment transport, researchers are now studying the effect of turbine operation on bedform scour and sediment deposition for arrays. Hill et al. (2014) determined the presence of the turbine rotor increases the local shear stress, resulting in accelerated and expanded scour development when compared with typical bridge pier scour mechanisms. The inferred key difference is the alteration of the flow patterns in the rotor wake leading to an accelerated flow region below the bottom tip. The footprint of the rotor is observed in the extension and scaling of the bed surface area, which is impacted by the turbine and consistent with the near-wake region. Temporally-averaged bed topography data from live-bed experiments indicate amplified scour depths in the turbine near-wake region as compared with the clear water results despite spatial patterns remaining qualitatively similar. These scour patterns could influence downstream turbine function.

Neill et al. (2012) looked at the impact of a turbine or array of turbines on sediment deposition and transport. They concluded that the energy extraction of an array of turbines in a tidal bay can impact sediment transport and deposition in the bay. The study demonstrated that an array located in the vicinity of a headland could lead to a considerable change in the maintenance of headland sand banks over a spring-neap cycle. If the scale of this change is demonstrated to be significant compared to the natural range of inter-annual and inter-seasonal sand bank variability, then developers of arrays would be advised to examine ways in which they could reduce the environmental impacts of arrays sited near headlands. The most obvious of these is to limit the scale of the array, but if we assume that developers wish to exploit the tidal energy resource to its maximum, the alternative is to site the array strategically (within the bounds of economic feasibility) such that it will not interfere with the natural morphodynamics of the headland system.

5.5 Testing at Full-Scale and Moderate Scale in-Sea Test Sites

To develop capability and reduce costs a few test sites dedicated for testing tidal current turbines at both moderate and full-scale are set-up or planned around the world. The two well-known established test sites are the European Marine Energy Centre (EMEC) in the Orkney Islands, UK, and the Fundy Ocean Research Centre for Energy (FORCE) in the Bay of Fundy, Nova Scotia, Canada. EMEC offers two tidal test sites, the fall of Warness tidal energy test site which opened in 2006, and a scale tidal test site at Shapinsay Sound which opened in 2011. These dedicated test sites can provide significant cost benefits for the development process as they unitise shared facilities such as grid integration and overarching environmental licences. Both the costs of grid connection and obtaining environmental licences can easily be prohibitive for a single developer. These test facilities also have the potential to provide a shared learning experience.

Several companies have been testing at both moderate and full-scale at these test sites. For a developer producing a turbine of the order 16 m in diameter moderate scale tests are often performed. This can be at anything between tenth and half scale dependent upon the technology readiness level, available funding and resources.

For developers producing devices deliberately targeted at a river or estuary for a full-scale machine, moderate-scale would typically mean the first few devices of an array. This is because these machines are typically around 5 m in diameter and therefore the step up from model scale testing in towing tanks and cavitation tunnels is moderately small.

At moderate scale, tests can be performed using either still water by pulling or pushing a turbine, or in a small-scale site such as a river or tidal estuary. Moderate scale tests are more commonly performed by developers with bespoke installation requirements, or if they require tethered moorings.

Moderate Scale: Towed and Pushed Trials. Moderate scale tests have been performed by a few companies using either pushed tests on the front of a boat, or towed trials across a lake. Pushed trails have highlighted quite a few significant issues, such as the influence of the vessel on the turbine and the accuracy of boat speed (Jeffcoate et al., 2015). These results have produced significant unsteadiness in performance measurements as shown in Figure 10. The Tidal Testing Centre (TTC) in Holland also commercially offer the unique ability to tow or push turbines at large scale through still open water. Turbines with a diameter of up to 4 m can be towed or pushed with a barge with an on board dump load of up to 100 kW (TTC, 2017).

Moderate Scale: Sluice Gate Testing. TTC (2017) also offers tidal developers access to two separate sluice gates. These sluice gates act like a ducted channel with water flows of up to 5 m/s. A feed-in electrical grid-connection with a capacity of 160 kVA for full moderate scale device testing is also available. An example of a device undergoing testing is shown in Figure 10.

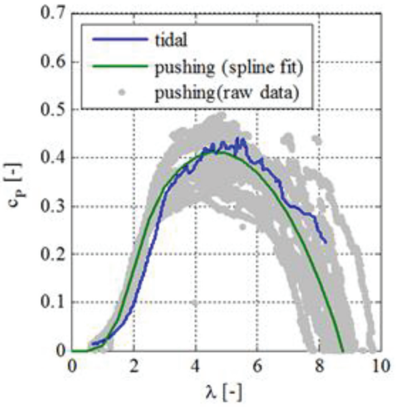


Figure 10 Example of the uncertainty in pushing tests (Jeffcoate et al., 2015) C_p is the power coefficient and λ is the tip speed ratio)

Figure 11 Example of testing in a Sluice gate (TTC, 2017)

Moderate Scale: River Test Site Testing. Several developers have performed tests of various turbine scales in rivers. These tests are normally defined by the developer's requirements and a suitable river is chosen for the required test. Examples include Verdant Power' s New York river site (Verdant, 2017).

Moderate Scale: Seeneoh-Bordeaux Estuarine Test Site. The test site on the Seeneoh in Bordeaux, France is located on the estuary of the Gironde, with the site becoming operational at the end of 2016 (Seeneoh, 2017). The currents at the test site can reach 3.5 m/s, with site depths greater than 8 m. Three berths are available, which are designed to accommodate floating, laying or variable lift technologies, with a total capacity to the electricity network of 250 kW. The test site is being implemented and coordinated by France Energies.

Benign Tidal Current Test Sites. The EMEC test site at Shapinsay Sound offers testing in currents with a peak tide of 1.5 m/s in a full tidal regime in 21 m to 25 m water depths in an area 0.4 km across and approximately 0.9 km in length (EMEC, 2017). This site was developed for not only device performance testing but also for more focused activities such as: installation and decommissioning trials, component testing, new anchor designs, and subsea hub and wet-mate connectors. Figure 11 shows an example of a 1/10th scale device being tested at Shapinsay Sound in 2014.

Figure 12 1/10th scale Magallanes test turbine installation at EMEC (EMEC, 2017)

Large Scale In-Sea Test Sites. EMEC and FORCE are two dedicated full-scale test sites with overarching permissions to install and test a wide variety of devices for a nominated number of births. Both EMEC and FORCE test centres have setups for continuous monitoring of: wildlife, hydro-acoustics, fisheries, and impacts on the shared coastline. The range of clients at this site is shown in Table 6. Additionally, other test centres in the process of being developed include the Paimpol-Bréhat test site in France (Paimpol Bréhat, 2017), and the

Nagasaki Asia Marine Energy Centre in Japan that aims to go online in 2018 (Tidal Energy Today, 2016).

There are a few other sites currently being considered, including the Morlaris Demonstration zone (Morlaris, 2017) and the Perpetus tidal energy centre (Perpetuus, 2017).

EMEC, Fall of Warness Test Site. The full-scale tidal power test site at the Fall of Warness was chosen for its high velocity marine currents which reach almost 4 m/s at spring tides. The facility offers five test berths at depths ranging from 25 m to 50 m in an area 2 km across and approximately 4 km in length. From each developer berth, the subsea cables follow back along the seabed and then pass under the beach into an external housing next to a substation.

FORCE, Minas Passage Test Site. FORCE's full-scale tidal test site is located in the Minas Passage area of the Bay of Fundy, Nova Scotia, where the world's highest tides area found. The site was chosen for its strong tidal bidirectional currents of up to 5 m/s, with water depths up to 45 metres at low tide, and a sediment-free bedrock sea floor. The facility currently offers four test berths with subseacables that pass to a substation near the observation centre.

Paimpol-Bréhat Test Site. A French test site is currently being developed alongside a EDF tidal pilot project with which it will share part of the infrastructure connecting the offshore area to the electrical grid (Paimpol Bréhat, 2017). A subsea converter will allow for the connection of 2 tidal turbines with a maximum individual capacity of 1 MW. The subsea converter is connected to the onshore substation and the electrical grid through a 10kVDC link.

Developer Case Study: NAUTRICITY. Nautricity's tidal device, the CoRMaT contra-rotating tidal generator, was designed from first principles, and has a single riser mooring as shown in Figure 13.

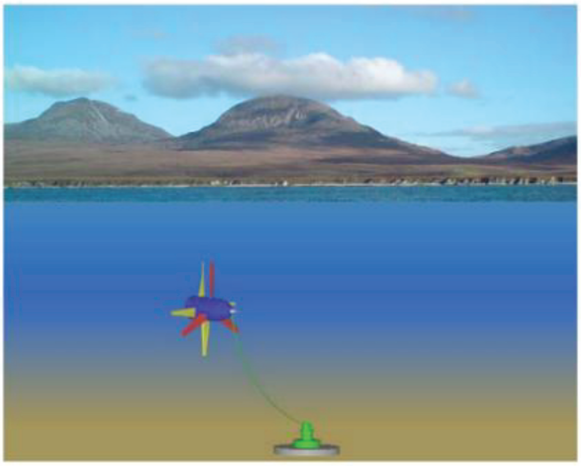


Figure 13 Mock-up of the Nautricity's CorMat device

Nautricity's device has been tested over a range of scale as its Technology Readiness Levels increased. These tests included:

- Initial scale tank tests were conducted at both 1/70th and 1/30th scale. These tests were started in 2000 with a proof of concept grant. The larger scale tests were performed to understand integration with counter rotating generator.
- Moderate scale testing of about 1/7th scale was performed in the Clyde estuary from 2006 and 2007. This was to support investigations of device performance, structural loadings and materials robustness. This confirmed sustained device performance on scaling the device (Clark et al., 2007a). Further moderate scale testing proving the CorMat prototype system were performed in the Sound of Islay (Clark et al., 2007b). These tests demonstrated: the practicality and functionality of a single riser mooring; device stability and continuous alignment within an energetic tidal flow; and the generating ability of a passively cooled flooded permanent magnet contra rotating generator.

Table 6 Current and previous clients of EMEC and FORCE（EMEC，2017 & Force，2017）

Clients	Location	Installation Date	Power
ALSTOM (FORMERLY TGL)	EMEC, Fall of Warness	2013	1MW
ANDRITZ HYDRO HAMMERFEST	EMEC, Fall of Warness	2012	1 MW
Atlantis Resources Corporation	EMEC, Fall of Warness	2011	1 MW
Atlantis Operations Canada Ltd	FORCE, Minas passage	In Review	-
Black Rock Tidal Power & SCHOTTEL	FORCE, Minas passage	In development	40 turbines (total of 2.5 MW)
Blue Water Energy Services	EMEC, Fall of Warness	Cancelled 2016	-
EC-OG	EMEC, Shapinsay Sound	Planned 2017	1/10 scale model
FLUMILL	EMEC, Shapinsay Sound	2011	-
Halagonia Tidal Energy Ltd	FORCE, Minas passage	In development	Three 1.5 MW turbines
Kawasaki Heavy Industries	EMEC, Fall of Warness	In review	-
MAGALLANES	EMEC, Shapinsay Sound	2014	-
Minas Tidal-IME-Tocardo Parnership	FORCE, Minas passage	In development	4 turbines (total of 0.25 MW)
NAUTRICITY	EMEC, Shapinsay Sound	2013	Deployment testing
NAUTRICITY	EMEC, Fall of Warness	Planned 2017	-
Open hydro	EMEC, Fall of Warness	2006, 2014	0.25 MW
OpenHydro & Cape Sharp Tidal	FORCE, Minas passage	Planned 2017	2 MW
Scotrenewables	EMEC, Fall of Warness	2012, 2016	0.25 MW, 2 MW
Sustainable Marine Energy	EMEC, Fall of Warness	Planned 2017	-
TOCARDO	EMEC, Fall of Warness	Planned 2017	-
VOITH HYDRO	EMEC, Fall of Warness	2013	1 MW

Table 7 Leased tidal sites in Scotland from the Crown State（Neilla et al.，2017）

Site Name	Tenant Name	Project Status	Capacity (MW)
Ness of Duncansby	Atlantis Resources Ltd.	In development	100
Westray South	Westray South Tidal Development Ltd.	In development	200
Brough Ness	Sea Generation (Brough Ness) Ltd.	In development	100
Fall of Warness	EMEC Ltd.	Operational	n/a
Sound of Islay	Atlantis Resources Ltd.	Pre-construction	10
Inner Sound	MeyGen Ltd.	Under construction	400
Bluemull Sound	Nova Innovation Ltd.	Under construction	0.5
Shapinsay Sound	EMEC Ltd.	Operational	n/a
Lashy Sound	Scotrenewables Tidal Power Ltd.	In development	30
Sanda Sound	Oceanflow Development Ltd.	Under construction	0.035
Mull of Kintyre	Argyll Tidal Ltd.	In development	3
Brims Tidal Array	Brims Tidal Array Ltd.	In development	200
Stronsay Firth	EMEC Ltd.	In planning	n/a
Islay Demonstration Zone	EMEC Ltd.	In planning	n/a
Mull of Galloway	Marine Current Turbines Ltd.	In development	30
Kyle Rhea	Atlantis Resources Ltd.	In planning	8
Isle of Islay (West Islay)	DP Marine Energy Ltd.	In planning	30

- Testing at the EMEC test site at Shapinsay Sound in 2013 allowed for full-scale mooring assembly tests. In a second phase, this also included the deployment of a full-scale turbine onto the mooring assembly at EMEC, and observation of its performance in wave and tidal environment. Both tests significantly reduced risks before large scale tests started.
- In April 2017, large scale testing was started at EMEC with the installation of a 500kW CoRMaT turbine.

Developments Outside Designated Test Sites. Several companies are developing their devices outside the key test sites several companies due to lack of access or for other commercial reasons. There are currently 17 possible test sites in various stages of development in Scotland, UK as identified in Table 7, of which one is an additional demonstration zone proposed by EMEC in planning.

5.6 Conclusions

Large and full-scale tidal turbines are being deployed throughout the world with mixed success: blade and drive train failures are a common theme, caused in most cases result by an underestimation of unsteady operational forces or the magnitude or frequency content of these unsteady forces. Major challenges still exist, including:

- Physical and numerical performance modelling in unsteady flow phenomena and conditions.
- Tidal turbine conditions at the full-scale environment can be difficult to replicate within a model scale test facility.
- Simulation of realistic turbulence and vibration levels at model scale.
- Interactions between current turbines within small and large scale arrays.

Developments at both moderate and full-scale test sites are helping to mature the industry. The use of designated test sites is also aiding in reducing development costs and provide some shared data.

6 OFFSHOR WIND TURBINES

6.1 Procedures

The SCHMRED reviewed the procedures and guidelines under its responsibility related to OWTs.

The following guideline was updated:

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

The guideline for testing offshore wind turbines was updated to include the recent advances in hybrid testing technology. Hybrid testing technology is applied for hydrodynamic testing of offshore wind turbines where the aerodynamic loads are replaced by numerical simulations and physical actuators enforcing the simulated aerodynamic loads on the structure. The main purpose of using a hybrid method is to overcome the mismatch of full-scale and model scale Reynolds number related to the Froude downscaling of the wind turbine rotor blades-changing the aerodynamic behaviour of the rotor.

6.2 Numerical Simulation Tools

The OC3 and OC4 projects were extremely useful in showing the influence of different modelling approaches on the simulated response of an offshore wind system. Code-to-code comparisons, though, can only identify differences. They do not determine which solution is the most accurate. To address this limitation, IEA Wind approved a new project named the Offshore Code Comparison Collaboration Continuation, with Correlation (OC5). This project will begin the validation of offshore wind modelling tools through the comparison of simulated responses to physical response data from actual measurements. It started in 2014 and will run for 4 years. The project will examine three structures using data from both floating and fixed-bottom systems, and from both scaled tank testing and full-scale, open-ocean testing. Phase I and Phase II considered two cylinders and a semisubmersible, respectively, using data from the scaled tank testing, while Phase 3 in 2017 will consider a jacket structure using data measured from the Alpha Ventus Wind Farm (Robertson and Jonkman, 2014).

In Phase I of the OC5 project, two different datasets were analysed, both focusing on validation of hydrodynamic loads on cylinders, with no wind turbine present. The datasets used came from wave tank experiments, with Phase Ia (Figure 14) examining a suspended, rigid cylinder tested at Marintek, and Phase Ib (Figure 15) a flexible cylinder fixed to a sloped floor, tested by the WaveLoads project. Findings from Phase I included the need for the proper choice of hydrodynamic coefficients, higher-order wave theory, complex seabed models, and nonlinear hydrodynamic theory (such as wave stretching and 2nd+ order models) in order to accurately predict the hydrodynamic loads and response of a structure (Robertson et al., 2015).

Phase II of the project, builds on this work by examining a more complicated floating offshore wind system with a wind turbine (Figure 16). The system is a floating semisubmersible, tested by the DeepCwind consortium in 2013 at the MARIN wave tank under combined wind and wave loading. It is similar to the system analysed within Phase II of OC4, except that the turbine modelled in this project is the one tested in the tank experiment, rather than an idealised model of the NREL 5-MW Reference Wind Turbine. OC4 only compared results between simulations, and did not work with test data. By using a similar system, the work done in OC4 can be used to support and advance our understanding of the system within OC5 (Robertson et al., 2016). Table 8 summarises the codes used in OC5 and the other codes.

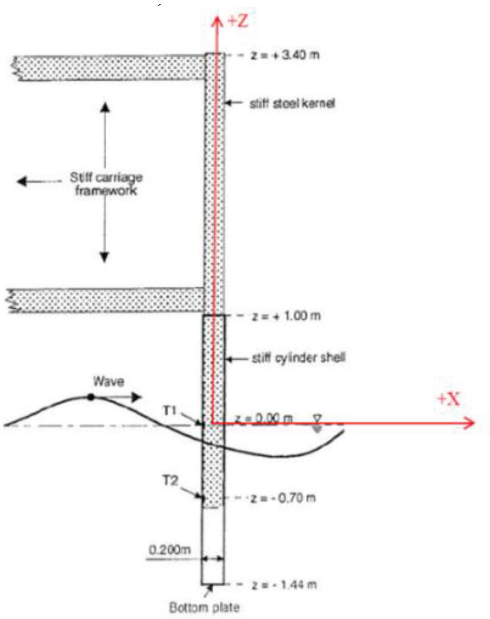


Figure 14 Fixed cylinder test configuration performed at MARINTEK (Phase Ia)

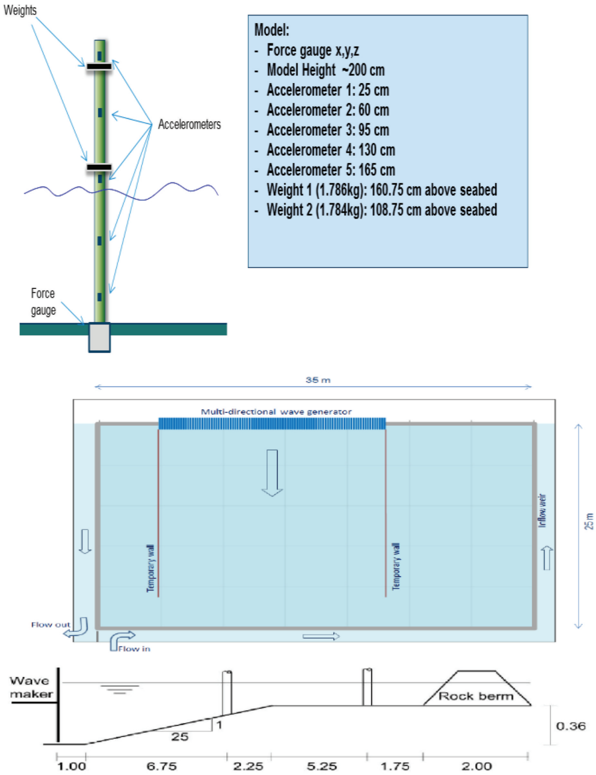


Figure 15 Flexible cylinder test configuration performed at DHI (Phase Ib)

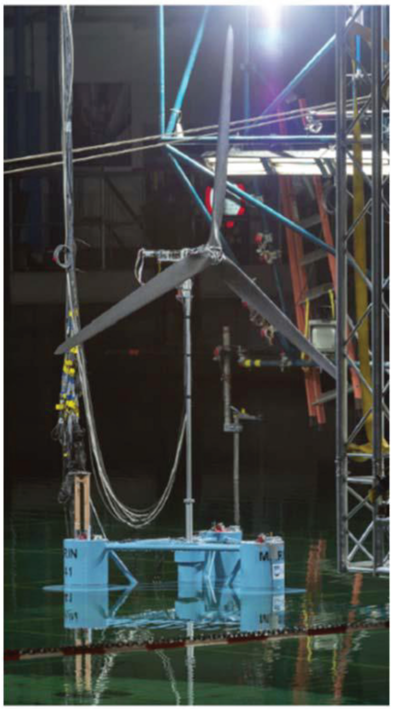


Figure 16 Instrumented OC5-DeepCwind model in MARIN

Phase III is aiming to benchmark and validate simulation tools of a fixed-bottom Jacket structure, open-ocean offshore wind system (Figure 17), not detailed analysis of blade dynamics and loads. Measurements were performed by the research initiative RAVE and the OWT was instrumented with sensors recording strains, deflections, accelerations, etc. (Popko 2017).

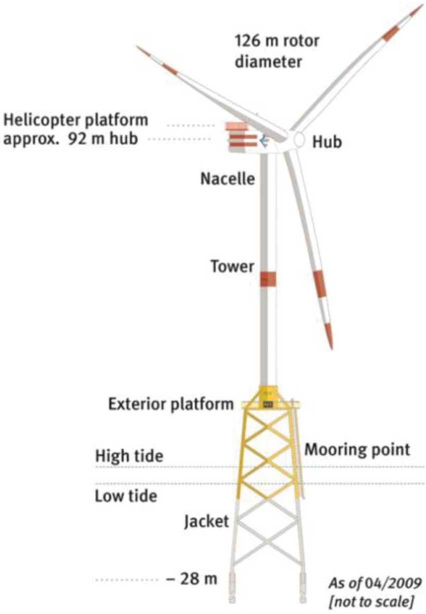


Figure 17 REpower 5M turbine with OWEC quattropod

6.3 Full-Scale Demonstrators of Floating Wind Turbines

Since the first deployment of a full-scale floating wind turbine, Hywind Demo at Karmøy, Norway, in 2009 there has been a handful of other full-scale demonstrators successfully installed around the world. The most recent deployments are Fukushima Shimpuu (2015) and Fukushima Hamakaze (2016), both off the coast of Japan. The turbine sizes are now ranging from 5 to 7 MW on these demonstrators as compared to the 2.3 MW Siemens turbine used on Hywind Demo in 2009. Up till now, the large scale floating demonstrators deployed use either spar type or semi-submersible substructures; however, demonstrators with a barge type (IDEOL) and a TLP (Gicon) substructures are currently under construction. Currently, several demonstration parks for full-scale floating wind turbines are under planning and development. The first floating wind pilot park is currently being prepared for installation off the coast of Scotland. This park consisting of five Hywind spar-type floating wind turbines, each with a 6 MW Siemens turbine. Other pilot parks are currently planned for Japan, China, USA, Portugal and Spain. Table 9 summarises the full-scale floating offshore wind projects installed or under development in Europe, USA and Asia (James & Costa Ros (2015), 4COffshore (2017) and Wikipedia (2017).

Table 8 Codes used in numerical simulations of Wind Turbines

Participant	**Code**	**Aerodynamics**	**Regular Waves**	**Irregular Waves**	**Hydro Model (Reg/Irr)**	**Wave Elevation (Reg/Irr)**	**Wave Surface**	**Mooring**
Codes used in Phase II OC5 Project of IEA Wind Task30 (2015~2016), Robertson, et al., 2017								
4Subsea	OrcaFlex-FAST8	AeroDyn - Beddoes/ Dynamic wake	2nd order stream function	Linear Airy	1st order PF+ME	Computed	IW	Dynamic
CENER	FAST v6 + OPASS	AeroDyn- Beddoes/ Equil. Inflow	Linear Airy	Linear Airy (JONSWAP)	1st order PF + 1st/2nd order damping	Computed	None	Dynamic
CENTEC	FAST8	AeroDyn15 Steady	2nd Order Stokes	Linear Airy (JONSWAP)	2nd Order PF	Computed	None	Dynamic
DNV GL/ DNV GL DM	Bladed 4.7	Glauert momentum/ Beddoes/ Oye Dynamic wake	Linear Airy	Linear Airy	1st order PF + 1st order damping	Computed/ Measured	None	Quasi-static/ Dynamic
DTU	HAWC2	BEM/Beddoes/ Dynamic Wake	Linear Airy	Linear Airy (JONSWAP)	ME	Computed	IWW	
ECN-MARIN	aNySIM-PHATAS v10	BEM + Dynamic stall	Linear Airy	Linear Airy	2nd-Order PF	Computed/ Measured	None	Dynamic
IFP_PRI	Deeplines Wind V5R2	BEM + Dynamic stall	Airy + Wheeler stretching	Airy + Wheeler stretching	1st order PF + ME	Computed	IW	Dynamic
NREL	FAST v8	AeroDyn14 - Beddoes /Dynamic wake	2nd Order Airy/ 1st Order Airy	Linear Airy	2nd Order PF/ 2nd Order PF (diff only)	1st Order Filter/ No Filtering	None	Dynamic
POLIMI	FAST v8.15	DYNIN + BEDDOES	Linear Airy	Linear Airy	2nd Order PF + SS + ME/PF	Computed	None	Dynamic
Siemens PLM	Samcef Wind Turbines	BEM + Dynamic Stall	Linear Airy	Linear Airy (JONSWAP)	ME	Computed	IWW	Dynamic, hydro, SF contact
Tecnalia F7O	FAST7+ OrcaFlex 9.7b	AeroDyn13- Beddoes/ Dynamic wake	Linear Airy	Linear Airy (JONSWAP)	PF + 1st order damping	Computed	IWV	Dynamic
Tecnalia F8	FAST v8.12	Aerodyn14- Beddoes/ Dynamic wake	Linear Airy	Linear Airy (JONSWAP)	PF+ME	Computed	No	Dynamic
UC-IHC	Sesam	BEM + Dynamic Stall	Linear Airy	Linear Airy (JONSWAP)	PF+ME+ MD	Computed/ Measured	IW	Dynamic
UC-IHC	IH-WAVE2 WIRE	BEM + Dynamic Stall	Linear Airy	Linear Airy (JONSWAP)	PF+MD	Computed/ Measured	IW	Dynamic
UOU	UOU + FAST8	AeroDyn14	Linear Airy	Linear Airy (JONSWAP)	PF+ME	Computed	None	Dynamic/Moor Dyn

UTokyo	NK-UTWind (Aero-Dyn)		Linear Airy	Linear Airy	ME	Computed	IWW	
WavEC_ FAST	FAST8	AeroDyn - Beddoes/ Dynamic wake	Linear Airy	Linear Airy	1st Order PF	Measured/ no filtering	None	Quasi-static
WavEC_FF2W	FF2W	Table look-up for thrust and power	Linear Airy	Linear Airy	1st Order PF	Measured/ no filtering	None	Quasi-static
Other codes								
Baayen & Heinz GmbH	Vortexje	Unsteady 3D panel method						No
WMC	FOCUS6	BEM or Vortex wake model						No
Tech. U. of Berlin	Qblade	BEM						No
Chonbuk National U.	UBEM	Unsteady BEM, Skewed yaw model						No
DTU	Flex5	BEM						No
SINTEF Ocean (fmr. MARINTEK)	SIMA	Unsteady BEM + Dynamic stall	Linear Airy 2nd and 5th order Stokes	Linear Airy and 2nd order	1st and 2nd order PF + ME	Computed + measured	IWW / IWV	Quasi Static / Dynamic

* BEM : Blade Element Momentum, DYNIN : Generalised Dynamic Wake, PF : Potential Flow, ME or MD : Morison equation(Damping)

* IW : Instantaneous Water level, IWW : Instantaneous Water level(Wheeler), IWV : Instantaneous Water level(Vertical Stretching) SS : State-Space

Table 9 Development of full-scale demonstrators for floating wind turbines and parks

Project	**Capacity (MW)**	**Location**	**Water depth**	**Turbine**	**Substructure**	**Status**
Installed full-scale						
Hywind demo (Statoil)	2.3	Karmøy Norway	120 m	HAWT	Spar buoy	Commissioned 2009
WindFloat (PPI)	2.0	Aguçadoua,Portugal	40-50 m	HAWT	SS	Commissioned 2011 Decommissioned 2016
Goto FOWT (Toda Corp.)	2.0	Goto-nada sea, Japan	96-99 m	HAWT	Spar buoy /Hybrid steel-concrete	Commissioned 2013
Fukushima Mirai	2.0	Fukushima Japan	120 m	HAWT	SS	Commissioned 2013
Fukushima Shimpuu	7.0		100-150 m	HAWT	SS	Commissioned 2015
Fukushima Hamakaze	5.0		100-150 m	HAWT	SPAR	Commissioned 2016
Planned full-scale						
Floatgen (Ideol)	2.0	France	> 35 m	HAWT	Barge	Onshore construction
Gicon SOF (Gicon)	2.3	Germany	17-500 m	HAWT	TLP	Onshore construction
Shingori Pilot	0.75	Ulsan, Korea	50 m	HAWT	SS	Onshore construction
Poseidon P80 (Floating Power Plant)	5.0-8.0	Denmark	45-200 m	HAWT + 4 x WEC	Hybrid wind-wave SS	1:3 scale 30 kW prototype
SeaTwirl (SeaTwirl Engineering)	10.0	Sweden		VAWT	Spar buoy	30 kW prototype

VolturnUS (DeepCWind)	6.0	USA		HAWT	SS	1:8 scale 20 kW prototype
VertiWind (Nenuphar)	2.6	France	50-200	VAWT	SS	Onshore prototype
SEA REED (DCNS)	6.0	France	50-200	HAWT	SS	Commissioning 2017
Dounreay Tri- Hexicon & Atkins	8-12	Scotland	50-500	2 x HAWT	Multi-turbine SS	Commisioning 2018
Planned parks						
Hywind Scotland Pilot Park (Statoil)	30	Scotland	95-120 m	5 x HAWT	Spar buoy	Onshore construction Commissioning 2017
WindFloat Atlantic (PPI)	25	Portugal	85-100 m	3-4 x HAWT	SS	Commissioning 2018
WindFloat Pacific (PPI)	24	USA	300 m	5 x HAWT	SS	Commissioning 2018
WindFloat Japan (PPI)	> 6	Japan	70 m	HAWT	SS	Commissioning 2017
Changing Floating Modular Foundation Demo project	18.0	Bohai Bay, China		9 x HAWT	SS	Onshore construction
Kincardine Offshore Windfarm	49.6	Scotland	45-143 m	8 x HAWT	Semi-spar	Consent authorized
Provence Gran Large (Nenuphar)	26	France	50-200 m	13 x VAWT	SS	Commissioning 2018
Maine Aqua Ventus I (U.of Maine)	12	USA		2 x HAWT	SS	Commissioning 2018
Planned demonstrators						
Nautilus (Nautilus Floating Solutions)	5-10	Spain	50-250 m	HAWT	SS	Concept / early planning
TLPWind (Iberdrola)	5-10	Spain		HAWT	TLP	Concept /Early planning
Tri-Floater (GustoMSC)	5	Netherlands	50-300 m	HAWT	SS	Concept /Early planning
Spinfloat (Eolfi/GustoMSC)	6	France	50-300 m	VAWT	SS	Concept /Early planning
SCD nezzy (Aerodyn Engineering)	8	Germany	35-200 m	Downwind HAWT	SS	Concept /Early planning
TetraFloat (TetraFloat Ltd)		United Kingdom	30-200 m	HAWT	SS	Concept /Early planning
WindCrete (U. Politècnica de Catalunya)		Spain	150-1000 m	HAWT	Spar buoy	Concept /Early planning
W2Power (Pelagic Power)	10	Norway		2 x HAWT + 18 x WEC	Hybrid wind-wave SS	Concept /Early planning
OO Star Wind Floater	5-10	Norway	50-200 m	HAWT	SS	Concept /Early planning
TwinFloat (Nénuphar)	5	France		2 x VAWT	SS	Concept /Early planning
Asymmetric Floating Tower (Nautica)		USA	40-700 m	HAWT	TLP	Concept /Early planning
Pelastar (Glosten Associates)	6	USA	70-200 m	HAWT	TLP	Concept /Early planning
D-Spar (MODEC)				HAWT	Spar buoy	Concept /Early planning

* HAWT = Horizontal axis wind turbine, VAWT = Vertical axis wind turbine, WEC = Wave energy converterer

* SS = Semi-submersible, TLP = Tension Leg Platform

* PPI = Principle Power Inc.

6. 4 Wind Field Modelling Including Froude / Reynolds Scaling Challenges for the Turbine

The demand for scale model tests of offshore wind turbines gives rise to extensive research focused on correct modelling of the response of offshore wind turbines to wind loads. In comparison with scale model tests of other types, the model tests of offshore wind turbines are not only much more demanding in respect of wind field quality, but it is also much more challenging to assure that the response of wind turbine to correctly reproduced wind field corresponds to the response of full-scale device. Thus, this section presents the overview of wind generators used for model tests of offshore wind turbines as well as the results of latest research related to the design of model scale rotors with taking into account the Reynolds number dissimilitude. The requirements for modelling the wind conditions in the model testing facility are: the correct representation of wind profile, minimising the turbulence intensity for steady winds, and the correct representation of turbulence spectra of dynamic winds.

An example of a high-quality wind generator for offshore basin is described by De Ridder et al. (2013). The construction is described as follows: “The developed wind setup consists of a large nozzle of 4×3 m hanging above the free surface level so it is not affecting the waves and current in the Basin. The inlet is rectangular and consists of five horizontal rows of seven fans, which makes 35 fans in total. Clockwise rotating fans are alternated with counter clockwise fans in a checkerboard pattern. The first honeycomb screen is positioned downstream of the fans. The front-view shows the wind outlet. The white screen is a second, more dense, honeycomb structure. Although the screen is rectangular, the wind outlet has an elliptical shape. Inside the nozzle, the rectangular inlet is smoothly faired towards the elliptical outlet. The small contraction rate of the flow results in a homogeneous, low turbulent wind field”.

The wind generator setup is presented in Figure 18, with the wind speed uniformity presented in Figure 19, and Figure 20 comparing the measured and theoretical dynamic wind spectra (Goupee et al., 2012).

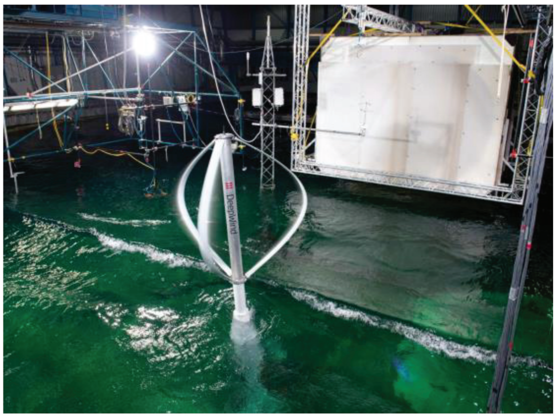


Figure 18 Wind generator in MARIN offshore basin

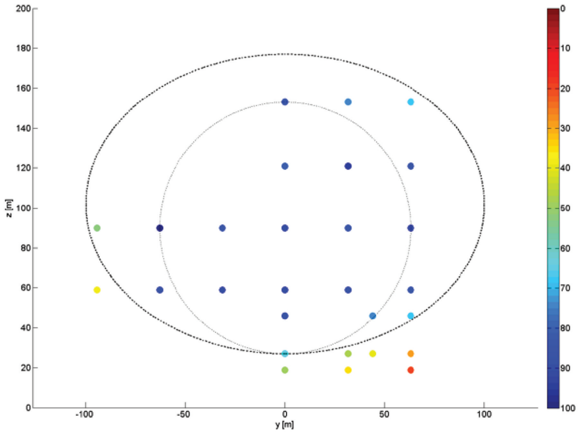


Figure 19 Wind field velocity as percentage of maximum wind velocity in the plane

Thiagarajan et al. (2014) describe the concept of innovative wind generator for University of Maine, presented in Figure 21. It has a recirculating channel, minimising the air motion within the facility and thus improving the wind field quality, as well as a rotatable design, allowing for testing the wind turbines in conditions of non-collinear waves and wind, for full range of misalignment angle.

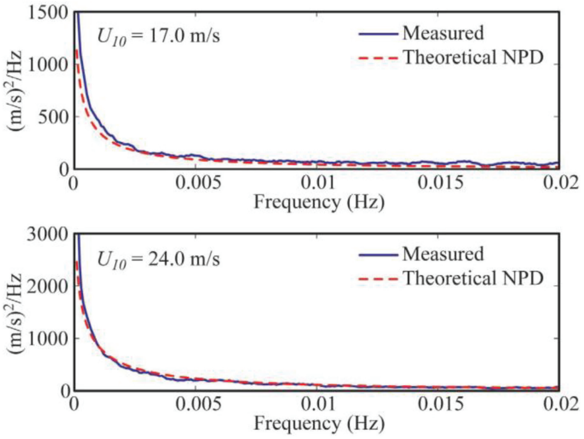


Figure 20 Comparison between measured and theoretical dynamic wind spectra

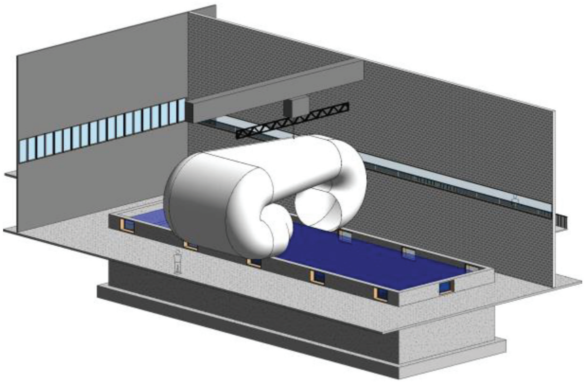


Figure 21 Wind generator designed for University of Maine

Design of Model Scale Rotors for Low Reynolds Number Conditions. Matching the mean thrust of model scale wind turbine in steady wind conditions is relatively simple and possible to achieve in a few ways (e.g. adjusting the wind speed for geometrically scaled rotor, using the drag disc instead of rotor or using the fan instead of rotor). However, correct modelling of the wind turbine response requires matching not only the mean thrust, but also the character of thrust curve (i.e. thrust coefficient vs. tip speed ratio curve). The model scale rotor which is not the geometrically scaled full-scale rotor (geo-sim), but is redesigned so as to match the full-scale thrust curve as close as possible, is referred to as performance-matched model.

The problem was presented by Kimball et al. (2014); they compared the response of geo-sim and performance-matched offshore wind turbine model in steady and dynamic winds. As shown in Figure 22 while they achieved similar responses in steady winds, qualitative differences were observed in dynamic winds. This results partly from the fact that for geo-sim model the Froude-scaled mean wind velocity was increased to match the mean thrust. The differences in thrust curve in full-scale turbine and geo-sim model scale turbine result mainly from the tendency to premature stall at low Reynolds number, affecting negatively the model scale rotor performance.

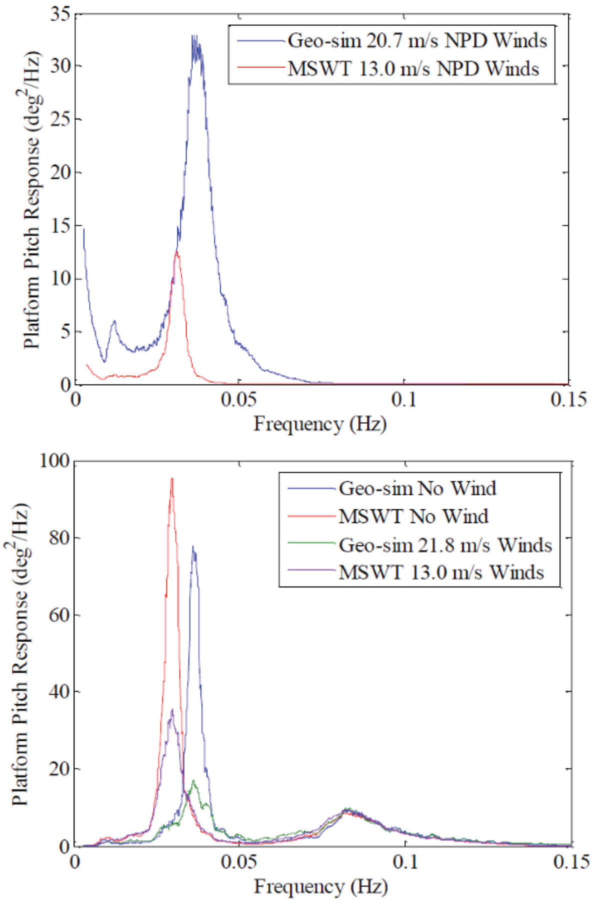


Figure 22 Frequency domain platform pitch response of the DeepCwind semi-submersible in (top) irregular seas and (bottom) calm water with and without wind when using either a geometrically-similar turbine or the performance-matched turbine

Kimball et al. (2014) present the design process of performance-matched turbine model consisting primarily in careful selection of blade sections, optimally suited for operation in low Reynolds number flows. They avoid increasing the chord length, i.e. try to match the geometrically scaled chord as close as possible. They report reasonable matching between thrust coefficient curves and poor matching between power coefficient curves, which are, however, of lower priority (Goupee et al., 2014 -Figure 23, blue and green lines).

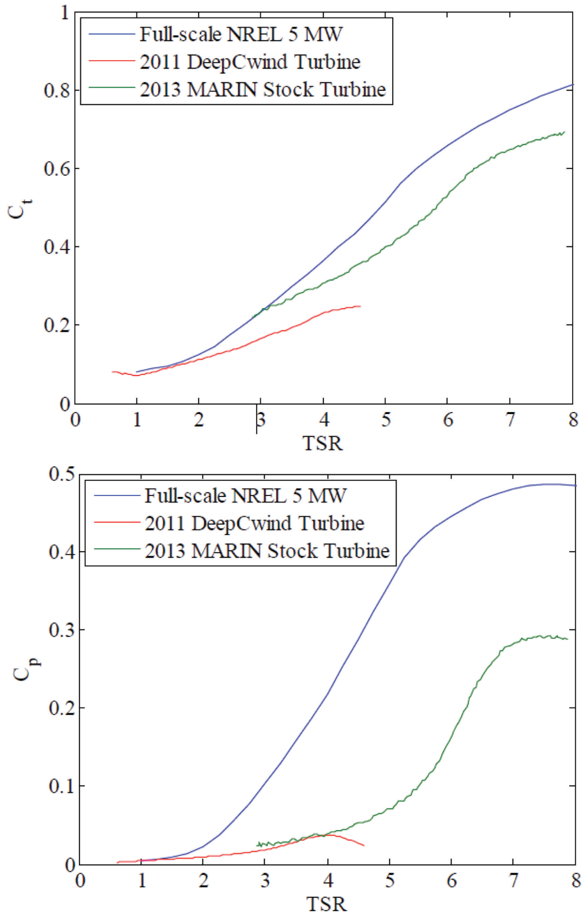


Figure 23 Characteristics of performance-matched model compared with full-scale turbine showing (top) thrust coefficient and (botom) power coefficient

Another example of the design of performance-matched wind turbine model was presented by Martin et al. (2015). Their method is referred to as direct aerofoil replacement (DAR) and it "redesigns the profile of the blade using a multipoint aerofoil optimisation algorithm, which couples a genetic algorithm (GA) and XFOIL, such that the local non-dimensional lift force is similar to the full-scale". The authors emphasise the fact that their method allows for maintaining the non-dimensional chord and twist distributions, which increases the similitude of unsteady response. Comparison between full-scale and model scale thrust and torque coefficients achieved in their design is presented in Figure 24.

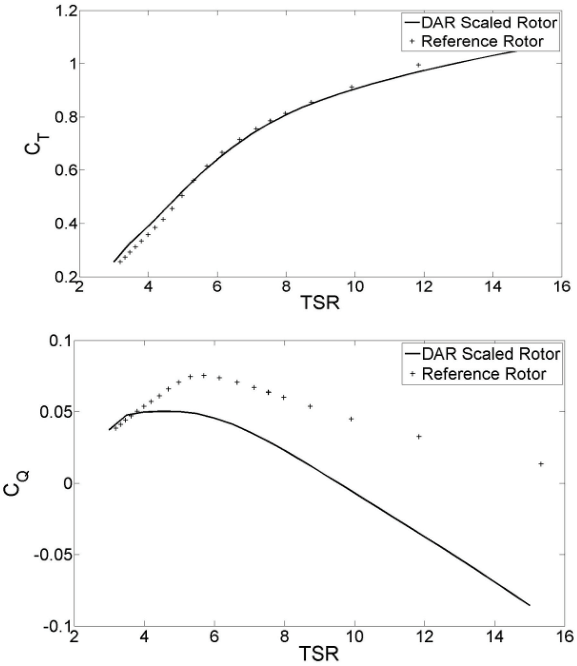


Figure 24 Comparison between (top) thrust and (bottom) torque coefficients for full and model scale

6.5 Impact of Control Strategies and Other Features on Full-Scale Devices on Global Response

The complexity of model tests of offshore wind turbines results not only from Reynolds scaling issues, but also from technical difficulties in modelling the features of full-scale devices, e.g. mass distribution, structural stiffness distribution and, especially, the turbine control system characteristics. In this section, special attention is paid to control systems, which can impose crucial, qualitative influence on the turbine response characteristics.

Introduction-General Idea of Control Systems used in Offshore Wind Turbines. The offshore wind turbines, operating in variable wind conditions, require control systems in order to maximise the power capture in below-rated wind conditions, and keep constant power and prevent the overload in rated and over-rated wind conditions. The existing control strategies are:

- constant rotational speed, stall control (i.e. power reduction at over-rated wind speed due to passive stall);
- constant rotational speed, assisted stall control (i.e. power reduction at over-rated wind speed due to active pitch change in pitch-to-stall direction);
- constant tip speed ratio, active pitch-to-feather control.

Typical power vs. wind speed curve is presented in Figure 25 (Van Kuik and Bierbooms, 2002).

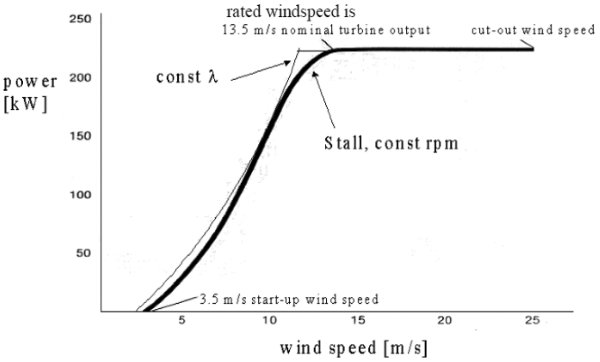


Figure 25 Typical power-wind speed curves for constant rotational speed and constant tip speed ratio turbines

The primary difference between stall control and pitch-to-feather control is that in the former concept the rotor torque is reduced by increase of drag force, while in the latter one, the torque is reduced by reduction of lift force. Although the resulting effect on rotor torque is the same, the pitch-to-feather concept allows for large reduction of bending moment in the blades, at the cost of complicated pitch control mechanism.

In the research related to large floating wind turbine concepts, the constant tip speed ratio with pitch-to-feather control strategy is primarily of interest. Two possible general concepts of pitch control strategy are considered, i. e. collective blade pitch (CBP) control, or individual blade pitch (IBP) control, enabling wider possibilities at the cost of increased complexity of the blade pitch actuators.

Overview of Control Strategies. The actual control strategies and algorithms used in commercial wind turbines are the property of the producers and are obviously not published. However, the principles of wind turbine control system strategy as well the results of extensive research focused on improving the control quality are presented in many publications and conference materials. The descriptions of wind turbine control algorithms use the following terminology related to the wind speed range:

- Region 1: zero to cut-in wind speed (this region is thus not of interest)
- Region 2: cut-in wind speed to rated wind speed
- Region 3: wind speed over rated.
- Region4:above cut-out(extreme conditions)

In Region 2, the blade pitch is kept constant and the generator torque control algorithm controls the speed so as to maintain constant tip speed ratio λ , corresponding to maximum value of power coefficient C_p. In Region 3, the control algorithm controls the blade pitch and generator torque so as to minimise the rotor and generator loads and keep the generator power constant (this can be realised by controlling the power directly, at the cost of additional rotor speed perturbations and loads on the turbine, or by controlling the torque, at the cost of additional power fluctuations).

The basic control system, implemented in National Renewable Energy Laboratory's

(NREL) theoretical 5 MW Reference Wind Turbine (Jonkman et al., 2009), uses the gain scheduled proportional integral controller for blade pitch control. This means that the blade pitch value θ is adjusted on the basis of the error e i.e. the difference between actual and rated rotor speed ω, according to Eqn. (1) (Namik and Stol, 2014a):

$$\theta(\mathrm{t}) = \mathrm{K_P}(\theta)\,\mathrm{e}(\mathrm{t}) + \mathrm{K_I}(\theta)\int_0^{\mathrm{t}} \mathrm{e}(\tau)\,\mathrm{d}\tau \qquad (1)$$

where $e(t) = \omega_{\mathrm{Gen}} - \omega_{\mathrm{Rated}}$.

Scheduling of the gains (i.e. dependence of K_P and K_I coefficients on actual pitch angle θ) is required due to variation in the sensitivity of rotator speed to pitch changes with increasing pitch angle. The generator control system controls the generator torque T_{Gen} according to the following relations:
in Region 2, it maximises the power Eqn. (2)

$$\mathrm{T_{Gen}} = \frac{\pi\rho \mathrm{R_{Rotor}^5} \mathrm{C_{P,max}}}{2\lambda_0^2 \mathrm{N}^3}\omega_{\mathrm{Gen}}^2 = \mathrm{K}\omega_{\mathrm{Gen}}^2 \qquad (2)$$

in Region 3, it keeps the power constant Eqn. (3)

$$\mathrm{T_{Gen}} = \frac{\mathrm{P_{Rated}}}{\eta_{\mathrm{Gen}}\omega_{\mathrm{Gen}}} \qquad (3)$$

In Eqn. (2) and (3), ρ, R_{Rotor}, N, ω_{Gen}, $C_{P,\mathrm{max}}$, λ_0 are air density, rotor radius, gearbox ratio, generator rotational speed, maximum power coefficient and tip speed ratio that yields $C_{P,\mathrm{max}}$, respectively. P_{Rated} is the rated generator power and η_{Gen} is the generator efficiency.

The known drawback of this simple pitch control algorithm is the negative pitch damping effect; its physical mechanism can be explained as follows:

- When the turbine floater is pitching so that the rotor is moving upwind, the rotor speed increases due to increase of relative wind speed. The control system reacts by increasing the blade pitch angle so as to prevent increasing the rotor speed, which causes reduction of the rotor's aerodynamic pitch damping and, in consequence, increased pitch angle.
- When the rotor is moving downwind due to floater pitching, the control system reduces the blade pitch so as to prevent reducing the rotor speed, which causes increased thrust and increased pitch angle.

The investigation of control system algorithms is thus focused on achieving an optimum control of both floater motion and power fluctuation, although these goals are contradictory, as presented above.

The NREL Reference Wind Turbine controller is used as a reference in the research focused on improvement of control quality. Its control system is referred to as NREL baseline controller. The existing literature presents different types of strategies of improving the control quality:

- by optimisation of the control algorithm for collective blade pitch (CBP) control;
- application of individual blade pitch (IBP) control;
- application of other devices supporting the power/motion control.

Within the simplest concept of offshore wind turbine with blade pitch control system, i. e. the one with collective blade pitch control and no additional devices supporting the control, multiple solutions were proposed to improve the control quality; some examples are presented below:

- Tuning the gains to minimise or eliminate negative damping (Karimirad and Moan, 2011).
- Changing the control objective for generator control loop, so that the rated generator speed, which is the set point that the collective pitch control attempts to drive the actual generator speed towards, is no longer a constant value (see Eqn. 3) but instead a variable that depends on the platform pitch velocity (Lackner, 2013). The author declares to achieve considerable reduction of structure loads at the cost of

some increase of power fluctuation. According to the author, this increased power fluctuation is still lower than the variation resulting from operating the wind turbine in large farm.

- Improving the control quality of both power and pitch motion by application of advanced controller types, i.e. linear-quadratic regulator and linear parameter-varying gain-scheduling controllers (Bagherieh and Nagamune, 2015). The authors claim that their approach allowed to reduce both pitch motion and power fluctuation in comparison with the baseline controller.
- Using the controller based on neural network to improve the torque control quality in Region 2, i.e. below rated wind speed (Wang et al., 2014). The simulations revealed better performance in tracking the optimal output power curve in comparison with NREL baseline controller.

An advantage of the individual blade pitch control over collective blade pitch control is that restoring moment, counteracting the floater pitching velocity, can be generated on the rotor. Possible problems resulting from application of individual blade pitch control are:

- Increased blade pitch actuation which may result in blade pitch saturation and/or increased blade loads (depending on the control objectives)
- Increased computational requirements by the control system.The possibility of exciting or destabilising other turbine modes due to coupling with un-modelled and/or unregulated DOFs.

The performance of individual blade pitch control was studied by:

- Namik and Stol (2010, 2011, 2014b); they use state-feedback and disturbance-accommodation control. The authors achieved reduction of damage equivalent load (DEL) in comparison with collective blade pitch control
- Yang et al., 2014; they used the fuzzy logic control strategy to combine disturbance accommodation control model prediction control, and claim to achieve reduction of fatigue loads in comparison with NREL baseline controller.

Examples of additional devices supporting the control systems of power and floater motion, described in the literature, are: feedback of tower-top acceleration, LIDAR-assisted feedforward control, and passive tuned mass damping systems.

The feedback of tower-top acceleration was studied e.g. by Jonkman (2008). In his simulations, using the tower-top acceleration as an additional input to the control algorithm did not improve the power and motion control quality due to contradictory signals from the two applied control loops. The feedforward control using LIDAR (Light Detection and Ranging-a device measuring the wind speed upwind from the rotor) was studied by Dunne et al. (2011) and Kumar et al. (2015). It was proved that the application of LIDAR results in reduced blade pitch actuator activity as well as reduced loads. The passive tuned mass damping systems were studied by Stewart and Lackner (2013). As a result of their simulations, they achieved considerable reduction of loads, especially for monopile and barge structures. Smaller profits were achieved for spar and TLP structures. Ha and Cheong (2016) investigated the effect of application of the multi-layer tuned liquid damper (TLD). They claimed to achieve the pitch motion reduction of a spar by as much as 23%. The idea of the TLD is presented in Figure 26.

Influence of Control Systems on Wind Turbine Motion Characteristics - Literature Review. The details of scale models of offshore wind turbines with working blade pitch control system were presented by:

- De Ridder et al. (2013) the development of MARIN stock wind turbine (MSWT) - Figure 27.

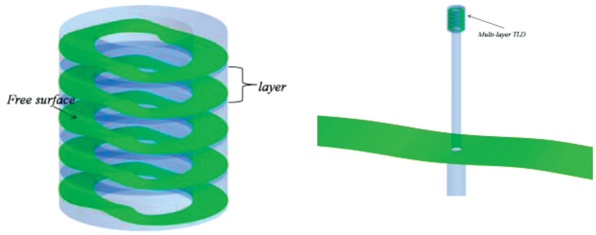


Figure 26 Multi-layer tuned liquid damper

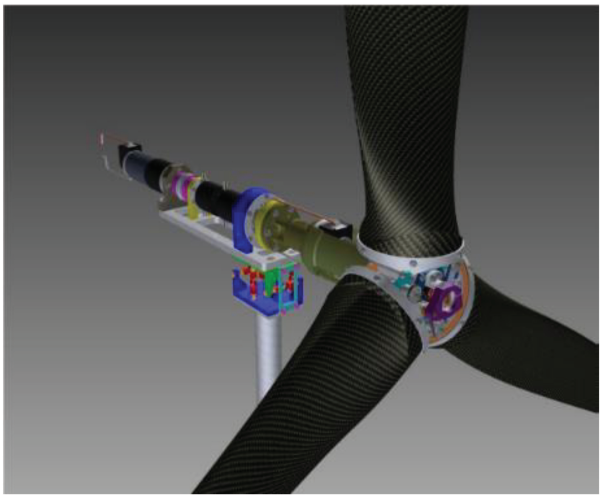


Figure 27 MARIN stock wind turbine (MSWT) CAD model

- Karikomi et al. (2015) development of blade pitch actuator for scale model tests for Mitsubishi Heavy Industries, Ltd - Figure 28.

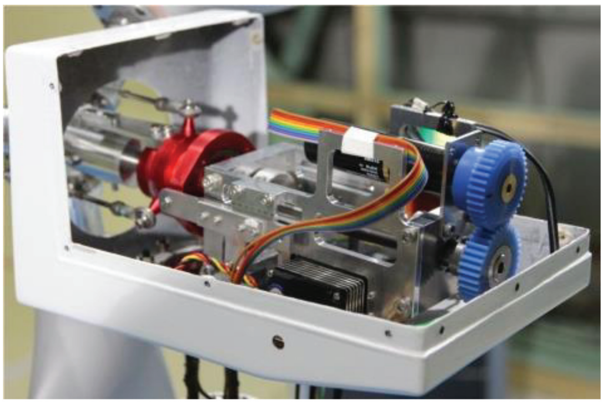


Figure 28 Blade pitch actuator (Karikomi et al., 2015)

- Mizukami et al. (2016) development of improved, lightweight bevel gear blade pitch control system for scale model - Figure 29.

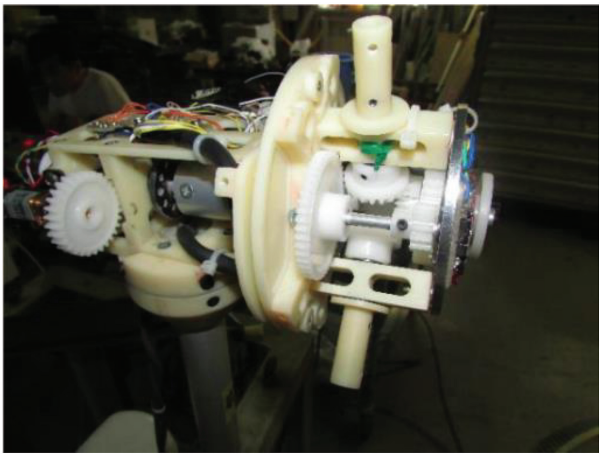


Figure 29 Blade pitch actuator with bevel gear (Mizukami et al., 2016)

Examples of results of model tests with active blade pitch control systems are described below:

- The results of tests with MARIN stock wind turbine were presented by Goupee et al. (2014). They investigated the pitch response of floating wind turbine to irregular waves and steady/dynamic wind, for fixed blade pitch and for active blade pitch control system using different control algorithms. The results are presented in Figure 30. In steady wind conditions, activating the blade pitch control system resulted in considerable increase of pitch response in frequency range close to pitch natural frequency. This effect is similar for both investigated pitch control algorithms. In dynamic wind conditions, it is seen that the MARIN Ci=80 and UMaine controllers significantly reduce the wind-induced low-frequency response occurring below 0.02 Hz that exists in the fixed blade pitch scenario while the MARIN Ci = 20 case does not. The MARIN Ci = 80 controller increases the response at the platform pitch frequency over the fixed pitch configuration while the UMaine and MARIN Ci= 20 controllers yields essentially the same response as the fixed pitch configuration in this frequency location. All four configurations possess essentially the same behaviour in the wave energy frequency range.

- Karikomi et al. (2015) investigated the effect of negative damping introduced by the blade control system for floating wind turbine with the gains tuned for bottom-fixed offshore wind turbine. They were able to capture this effect with scale model (Figure 31) and proposed an enhanced controller including the feedback of floater pitch velocity. With this enhanced control algorithm, they were able to minimise the negative damping effect.

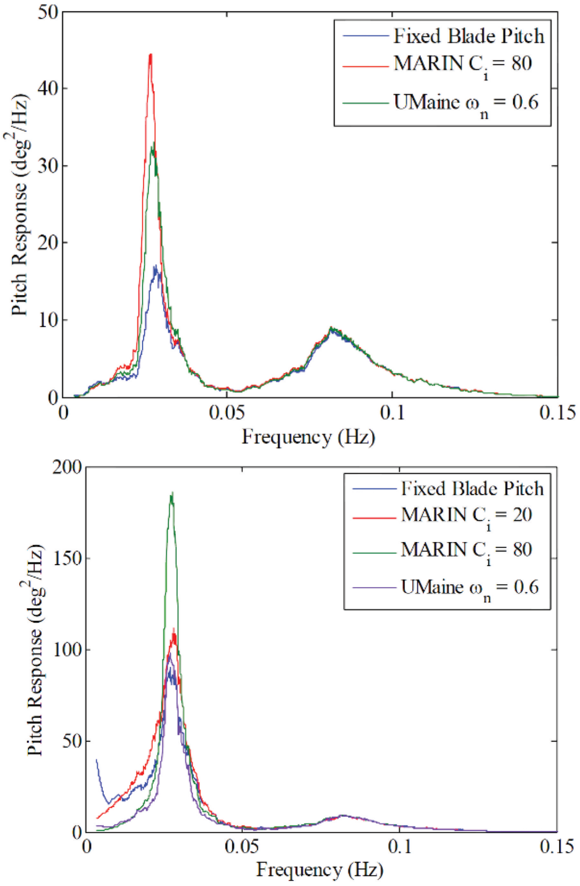


Figure 30 DeepCwind semi-submersible platform pitch response for (top) three different control strategies when subjected to steady 21.0 m/s winds and (bottom) four different control strategies when subjected to NPD dynamic 21.0 m/s winds

- Mizukami et al. (2016) investigated the extreme motions and mooring loads occurring as an effect of blade pitch controller malfunction. The floater pitch motion history in case of sudden blade pitch change is presented in Figure 32. However, similarly as in previous discussed paper, the performance of model scale blade pitch control system is not compared with the actual characteristics of full-scale device.

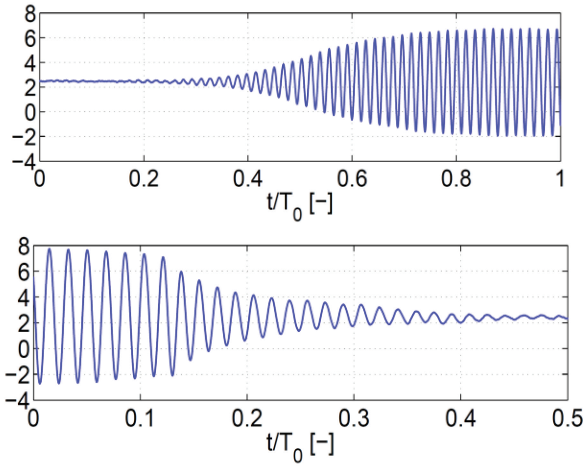


Figure 31 Karikomi et al. (2015) Blade pitch investigation of damping effect for (left) negative damping and (right) enhanced controller

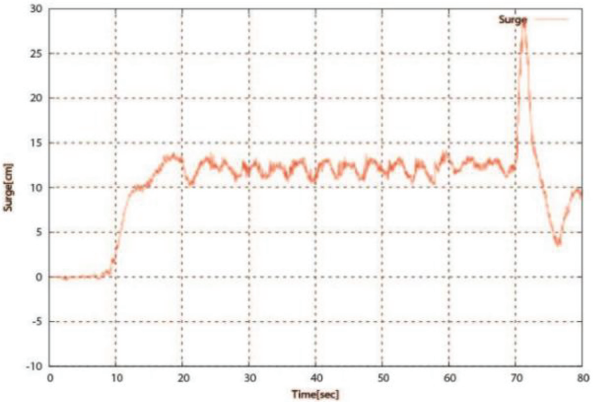


Figure 32 Time series of the pitch motion in only wind

Numerical Analysis of the Influence of Neglecting the Control Systems and Adopting other Simplifications on the Results of Scale Model Tests. The numerical analysis, carried out with the use of FAST software, was undertaken to evaluate qualitatively the effects of different simplifications in modelling the features of spar type offshore wind turbine, including:

deactivating the blade pitch control system, using simplified wind profiles, the incorrect modelling of rotor mass distribution, and the incorrect modelling of rotor blade stiffness and tower stiffness. The analysis was carried out for one of the examples distributed with FAST, i.e. OC3 Hywind spar-type floating wind turbine.

The results show that only deactivation of the blade pitch control system imposes qualitative influence on the wind turbine response. The negative damping effect is clearly visible in Figure 33: the pitch motion series for active blade pitch control system (black line) is characterised by large variations of relatively long period. When the blade pitch control is not active, the platform pitch angle variation is much lower, at the cost of unstable rotor speed and much higher rotor thrust (Figure 33).

6.6 Conclusions

The state-of-the art practice in fully coupled model testing consists in “performance-matched” scaling of the wind turbine rotor, i.e. blade redesign focused on reproducing the thrust coefficient curve at low Reynolds number instead of geometrical scaling. Recent advances in hybrid testing technology have demonstrated the possibility to combine real time numerical simulation with physical experiments. Significant challenges remain in terms of aero-hydrodynamic testing of floating wind turbines due to the scaling challenges as well as coupling between the complex system of steady and unsteady aerodynamic forces and moments with the hydrodynamic response of the platform. These challenges include:

- Defining the most suitable methodology for generation of mean aerodynamic thrust and torque with Froude-scaled rotation speed, as well as unsteady aerodynamic effects.
- The construction of large and extremely lightweight models.
- Generating high quality wind fields over a substantial volume of a wave tank.

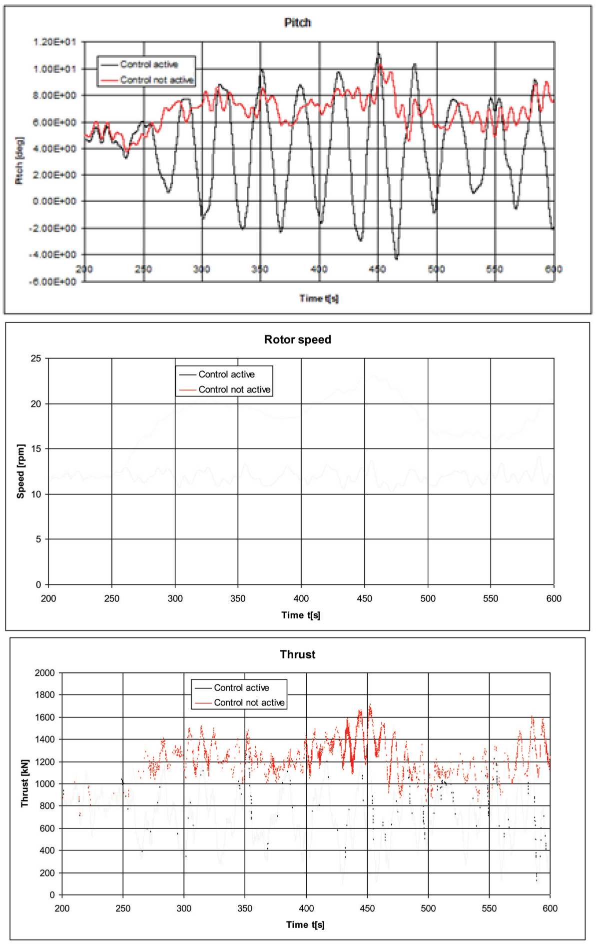


Figure 33 Influence of blade pitch control system on (top) pitch motion and (middle) rotor speed, and (bottom) rotor thrust (black-active, red-not active)

A further challenge in coupled aero-hydrodynamic testing is due to the fact that the blade pitch control strategy is of primary significance for the motion response of full-scale devices in over-rated wind conditions

7 CLOSING SUMMARY

Large and full-scale marine renewable energy devices (WEC, CT and FOWT) are now being deployed around the world in both commercial and development applications. The CT and WEC concepts have seen more deployments then FOWT over the past three plus years with mixed results relative to function, performance and survivability. As these full-scale deployment experiences grow and evolve in all areas, the model testing community needs to exploit these results to improve model scale testing to better address full-scale needs. Hence, the following would provide valuable knowledge to the ITTC:

- Establishing a specialist committee to review and report on medium-scale and large-scale in-sea test site deployment issues.
- Reviewing and reporting on physical modelling focusing on engineering factors such as structural properties, survivability, components testing, etc. (other than power performance), and whether oil and gas deployment procedures are suitable for investigating these factors.

8 RECOMMENDATIONS

The 28th Specialist Committee on Hydrodynamic Modelling of Marine Renewable Energy Devices recommends adopting the following revised and new procedures:

- 7.5-02-07-03.7 Wave Energy Converter Model Test Experiments
- 7.5-02-07-03.8 Model Tests for Offshore Wind Turbines
- 7.5-02-07-03.9 Model Tests for Current Turbines
- 7.5-02-07-03.12 Uncertainty Analysis for a Wave Energy Converter
- 7.5-02-07-03.15 Uncertainty Analysis-Example for Horizontal Axis Turbines

The recommendations for future work relating to wave energy converters (WECs):

(1) Continue to monitor developments in PTO modelling both for physical and numerical prediction of power capture.

(2) Review challenges associated with numerical prediction of performance of WECs in irregular wave spectra.

(3) Review and report on integrated WEC simulation tools based on multi-body solvers which are in development, such as WaveDyn (GL-GH), WEC-sim (NREL), InWave (Innosea).

(4) Review and report on the progress made on the modelling of arrays.

(5) Consider developing a "round-robin" test campaign for a simple WEC device (e.g. oscillating water column) in order to explore facility bias issues (or identify and build on an existing programme).

(6) Develop guidelines for physical modelling of WEC arrays elaborating on uncertainty analysis required for WEC arrays.

(7) Develop guidelines for numerical modelling of WECs.

(8) Review and report on limitations in replicating environmental conditions in test facilities.

(9) Monitor developments on investigations into scale effects from tank tests to prototype.

The recommendations for future work relating to current turbines (CTs):

(1) Continue to monitor development in physical and numerical techniques for prediction of performance of current turbines, with particular emphasis on unsteady flows, off-axis conditions, and other phenomena which offer particular challenges to current devices.

(2) Review and report on progress in testing at full-scale and moderate scale in-sea test sites. Develop cooperation with medium/large test centres.

(3) Review and report on the progress made on the modelling of arrays elaborating on uncertainty analysis specific for device arrays.

(4) Review and report on limitations in replicating environmental conditions in test facilities.

The recommendations for future work relating to offshore wind turbines (OWTs):

(1) Monitor and report on recent research

related to model tests of bottom-fixed offshore wind turbines including modelling the influence of structure stiffness and soil stiffness.

(2) Report on other existing regulations related to model tests of FOWT (e.g. IEC, classification societies, DoE). Interact with these bodies to get the guidelines aligned with each other.

(3) Collect the feedback from full/moderate scale tests and check how these can be used for validating model scale tests.

(4) Continue monitoring the development in model testing methodology with respect to Froude/Reynolds scaling issues and incorporating the control system strategies.

(5) Consider the possibility of elaborating a separate guideline for uncertainty analysis for model testing of offshore wind turbines.

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