ITTC Quality System Manual
Recommended Procedures and Guidelines

Guideline

Wave Energy Converter Model Test Experiments

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Disclaimer

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Wave Energy Converter Model Test Experiments

1. PURPOSE OF GUIDELINE

The purpose of this document is to offer guidance to researchers in performing model tests of wave energy converters (WECs) according to the state of the art.

Model tests of WECs have some differences from tests of other offshore structures. The main challenges of WEC testing and the differences between tests of WECs and offshore structures may include:

- Rapid evolution of design of WECs: great diversity of concepts, some presenting novel challenges for model testing;
- Requirement for simulation and measurement of complex kinematics, material properties and fluid-structure interaction for articulated and/or flexible WECs;
- Requirement to simulate devices with very large dimensions either parallel to or normal to direction of wave propagation;
- Requirement to include a simulated power take-off (PTO) mechanism in WEC tests. One of the important objectives in WEC tests is to evaluate device power capture; Realistic simulation of PTO may require relatively large scale models, leading in turn to a need for large-scale waves;
- Requirement for testing throughout the various experimental stages: the concept validation stage, the design validation stage, the system validation stage, and the prototype and demonstration stage. The model scale depends on the test stage;
- Possible requirement for tests of multiple device models corresponding to an array of WECs, requiring a very large tank for reliable results.

In general, model tests on WECs are employed to validate the device concept, to validate numerical models, to quantify the technical performance variables, to acquire information on the performance of the power take-off (PTO) system, to confirm or optimise performance designs, to confirm survivability characteristics and/or to investigate tow-out and installation methodology.

2. PARAMETERS

2.1 Experimental Stages

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

These stages are commonly described in the renewable energy industry in terms of Technology Readiness Levels (TRLs) (e.g. Mankins (1995)).

OES IA (2010) and later IEC in TS62600-103, grouped different TRLs in five stages:

stage 1) TRL 1-3 correspond to research stages up to and including proof of basic concept by a small scale model,

stage 2) TRL 4 corresponds to component, sub-system and system validation by an intermediate scale (< 1/10) model in operational/survival environments,

stage 3) TRL 5-6 corresponds to prototype demonstration at large scale in operational environment through to system proving via successful deployment.

The main objectives of tests in concept validation stage 1 are to validate the device concept, to validate preliminary numerical “wave to wire” models of the device used to predict energy output, to investigate device variables and physical properties that affect the performance or energy capture, and to optimize the device for power production using small scale models. The scale range in this stage is typically between 1:10 and 1:100.

The main objectives of tests in the design validation stage 2 are to validate the device design, to validate advanced numerical wave to wire models of the device, to develop PTO control strategies for improved power production, and to verify the mooring and anchor system using medium scale models. Installation and tow-out methodologies may also be validated in this stage. If known, the wave spectrum at a specific site should be used. The scale range in this stage is normally between 1:10 and 1:25, however smaller scale models may be used to investigate survivability in extreme waves. Prototype validation stage 3, and the full size and array demonstration stage (TRL 7-9) are typically carried out at large or full scale at sea.

The US Department of Energy (DOE) more recently released the “Technology Readiness Assessment Guide” (U.S. Department of Energy, 2011), a tailored version of the NASA TRL model more relevant to the renewable energy community.

2.2 Type of Wave Energy Converter

2.2.1 Device Types

WECs can be classified in a number of ways. One classification is by the nature of energy absorption: WECs can be categorised as point absorbers, typically small in both horizontal plane dimensions; attenuators, which are typically linear structures designed to be aligned with the principal direction of wave propagation, and terminators, which are typically linear structures designed to be aligned normal to the direction of wave propagation.

Devices may also be categorised by the physical process used to extract the energy. Falcão (2010) classifies devices into the following categories:

- Oscillating Water Columns
- Oscillating bodies
- Overtopping devices

Each of these categories can then be broken down by location (e.g. floating or submerged) and then by mode of operation. The classification is represented diagrammatically in Figure 1. This classification includes many devices currently under development.

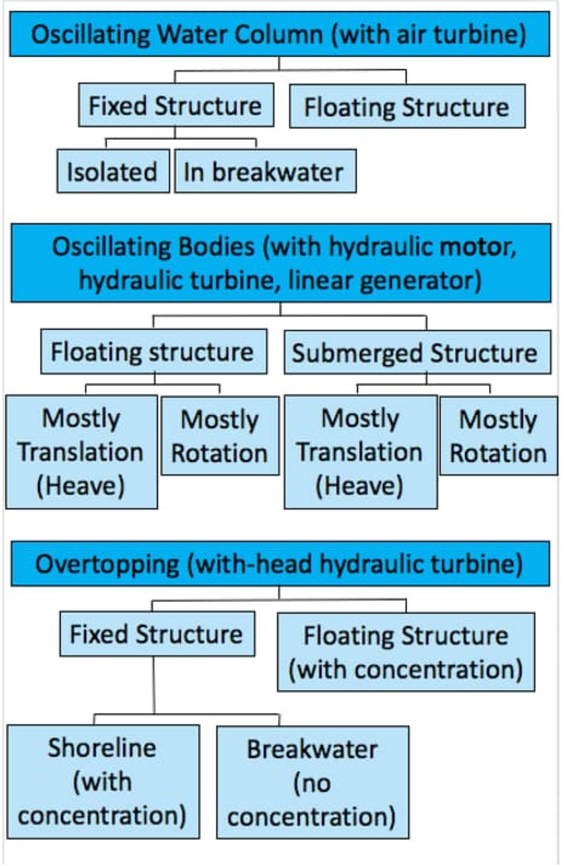

Figure 1: Classification of Wave Energy Devices (after Falcão (2010))

WECs can be installed in the shoreline zone, the near shore to offshore zone, and the offshore zone. In each zone, WECs can be free-floating, fixed on the seabed, or mounted on other structures such as breakwaters, piers or piled structures.

Oscillating water columns extract energy from the motion of water in an internal chamber with a free surface, usually driving an air turbine. Oscillating bodies include rigid bodies such as heaving buoys, extracting energy from relative motion between the device and a fixed reference or heave plate, pitching devices reacting against various mechanisms including gyroscopic devices and gravity referenced systems, and articulated devices consisting of a series of floating elements connected by hinges extracting energy from relative motions of the sections. Overtopping devices extract the potential energy of water running up an artificial beach. Cruz (2010) gives details of seven devices which have been tested at full scale.

Device types not covered by this classification include flexible devices (either water or air-filled) constructed entirely or partly from flexible materials typically using pressure variations in waves to pump water or air, generating energy through a variety of mechanisms.

2.2.2 Power Take-Off Systems

Various Power Take-Off (PTO) systems may be installed in different WECs. For example, air turbines are typically used for OWC type devices, linear or rotary generator systems with direct drive conversion or oil-hydraulic systems may be used for heaving, articulated, or flap type devices. Overtopping devices usually use a low-head hydraulic turbine placed at the bottom of the water storage system. These PTO systems must be simulated in the tests.

The PTO system for a moving body type WEC is often modelled by an energy dissipating damper in the concept validation tests. In the design validation tests, a more sophisticated PTO simulator can be considered as a Coulomb damper or linear damper, and an active control system may be utilised. The PTO system for an OWC or other pneumatic device is often simulated using an orifice load in the concept validation stage tests (see section 3.2).

2.3 Test Facilities

Different facilities can be used at different stages of the design process. These may include:

- Wave Flumes / Towing Tanks with wave-makers suitable of generating long-crested waves;
- Ocean basins capable of generating both long- and short-crested waves;
- Ocean basins with Wave and Current Facilities.

It should be noted that the large-scale models required for WEC testing can place substantial demands on wave-making in terms of both wave heights and run durations. Particular care must be taken to minimise build-up of reflected waves and to maintain the quality of the wave field during long duration realisations of large waves.

2.4 Model Parameters and Scale

The choice of scale ratio will be based on the device size, the goal of the tests (e.g. power capture or survivability), the target wave conditions, and the test stage (e.g. concept validation, design validation etc.). It may be necessary to build models at different scales to assess power capture in operational conditions and survivability in extreme seas.

Achievable scale will be limited by the model basin dimensions, and its wave generation capability. Choice of scale should also consider the mooring system to be employed, and the simulation approach for the power take-off (for power capture tests). The impact of channel width on power capture when testing floating devices in a narrow tank is illustrated by Ersdal and Moe (2013).

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

Performance of WECs will normally be scaled using Froude similitude. However, some key parameters will not scale in this manner, leading to scale effects when extrapolating to full-scale. In order to minimize these errors, tests with large scales are recommended. Important factors in energy conversion that are not addressed by standard scaling procedures include, but are not limited to, the effects listed below:

The power output of devices utilising a pneumatic power take off is related to the compressibility of the air, which is dictated by atmospheric pressure and the absolute temperature of the atmosphere. Therefore, the stiffness of the air “spring” including a phase effect (deal with as a complex value or separated into the other terms) will not be scaled correctly using Froude similarity if geometric similarity is maintained. In fixed devices this may be corrected by increasing the volume of air present either by increasing the dimensions of the pneumatic chamber or by adding an external accumulator. This approach may also be adopted in floating devices but may present challenges in achieving appropriate mass properties in smaller models. The issues are discussed in detail by Weber (2007). It is expected that the effect of compressibility is expected to be detrimental on power production. Effects of compressibility are normally stronger at model scale. As the compressibility has the effect of storing tentatively the energy inside of the air column, the wave energy effect appears in the absorbed energy at turbine and may have some time delay. Thus, experimental results for power production may be conservative at model scale.

In small-scale model tests, viscous damping and in particular damping associated with vortex shedding from sharp edges cannot be scaled appropriately with Froude similarity and may be overestimated. Furthermore, surface tension effects might become significant leading to additional uncertainties in scaling up the results.

Mechanical friction, both static and dynamic, should be minimised as far as possible in model construction since it will not be scaled correctly according to Froude similitude.

2.5 Environmental Parameters

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

In testing WECs, particular attention should be paid to impact of wave blockage, since WECs may affect the wave field in a more complex manner than conventional floating structures.

Testing in long-crested waves is commonly adopted at the concept validation stage, for comparative studies, and for component testing where appropriate. This process may include tests with the device oriented at different angles to the direction of wave propagation.

Concept validation testing may involve both regular wave tests to characterise device frequency response as well as testing in irregular sea states appropriate to the intended deployment site in order to estimate mean annualised power capture.

The power production of some WEC device may depend on incident wave direction; hence, at later stages of the design process, when accurate estimates of power capture are required, tests in short-crested irregular waves considering the azimuth of the principal wave direction may be requested. For these tests, the directional wave spectral density function can be used to describe the short-crested waves. It is defined as the product of the wave frequency spectrum and the directional spreading function. The most popular model for the directional spreading is a cosine squared ($\cos^{2S}(\theta/2)$) function originally proposed by Longuet-Higgins et al. (1963). It is recommended (Goda 1985) to use S as a function of a spreading parameter S_{max} which indicates the degree of the directional concentration of wave energy and $S_{max} = 10$ for wind driven seas, $S_{max} = 25$ for swell with short decay and 75 for swell with long decay distance.

Alternatively, the wave spectrum of an actual site may also be used in the tests. Site data could suggest that sea states composed of multiple wave systems are common at that particular location. Kerbiriou et al. (2007) found out that two-thirds of the time, there are two or more wave systems in the Bay of Biscay, with distinct peak period, significant height and mean direction. When device performance can be compromised by multi-directionality, testing in sea states with multiple wave systems should be carried out.

2.6 Mooring Systems

Floating WEC concepts utilise a range of mooring systems including single point and spread moorings as well as catenary, taut and multi-element systems. Where tests are intended to determine power capture, accurate simulation of catenary moorings is not generally required, as studies have shown that catenary moorings have little impact on device response for oscillating bodies (Muliawan (2012), Vicente (2011)). In contrast, taut moorings can have a significant impact on device motions and thus power capture and should be simulated accurately where detailed design information is available.

Where tests are intended to assess device survivability, accurate simulation of all mooring types is important, as mooring behaviour impacts upon extreme behaviour of the device including motions and loads.

Guidance on mooring installation and calibration can be found in ITTC Recommended Procedures for Floating Offshore Platform Experiments (7.5-02-07-03.1). Where the limitations on the physical size of a testing basin do not allow a full model of a mooring to be accommodated at a reasonable scale within the basin, guidance on the use of a hybrid mooring system may be found in ITTC Recommended Procedure 7.5-02-07-03.4 Stationary Floating Systems Hybrid Mooring Simulation.

At the concept validation stage of testing it is common that detailed information on mooring system properties is not available; in the absence of other information a simple soft elastic mooring can be used for devices which do not utilise moorings as part of PTO systems.

Where taut mooring systems are employed, it is recommended that, where possible, free oscillation tests are carried out with and without mooring systems in order to determine natural frequencies and indicate the likely impact of the mooring systems on the device motions and energy capture performance.

2.7 Test Case Parameters

2.7.1 Experimental Proof of Concept Tests

An experimental proof of concept may be required for an innovative WEC concept whose working principle is new. The main goal of the experiments is to validate the working principle. The scale is typically in the range of 1:50 to 1:100. A PTO simulator is normally not required at this stage.

These tests should be carried out in regular waves using Froude scaling. The response of the WEC device should be investigated in waves corresponding to full scale waves with periods in the range [5-15] seconds and heights in the range [0.5-5] meters. In many cases, visual inspection should be sufficient to validate the working principle. Experiments should be recorded on video for later inspection and other uses such as advertising the WEC concept. Other instrumentation and data acquisition may not be necessary in these tests.

2.7.2 Numerical Model Calibration and Validation Tests

In these tests the aim is to calibrate and validate mathematical and numerical "Wave to Wire" models of the device. "Wave to Wire" models of the WEC device are normally developed in the early TRL stages in order to optimize the WEC design performance. They are normally used to predict a devices' motions, loads and energy generation. Calibration of "Wave to Wire" models is normally obtained by comparing time traces of numerical and experimental results for signals such as motions, pressures, and forces. For validation, it may be obtained by comparing statistical quantities (mean, standard deviations, distributions, etc.)

The scale is typically in the range of 1:10 to 1:50. A PTO simulator may or may not be included in these experiments depending on the scale and the complexity. Indeed, the numerical model may be calibrated without a PTO. If a PTO simulator is included, it shall be carefully characterized so that its effect can be taken into account in the "Wave to Wire" model.

In some cases, it may be difficult or even impossible to build an exact Froude-scaled model of the WEC system because of - for example - air compressibility in an OWC chamber or because of material stiffness for flexible WECs. In this case, an approximate experimental model may still be built in order to calibrate and validate the numerical "Wave to Wire" model. For calibration and validation, the characteristics of the experimental model shall be considered in the "Wave to Wire" model. Once validated, the numerical "Wave to Wire" model may be used to predict the performance of the WEC system at full scale. This is sometimes called the "model of the model" approach.

It is recommended that, firstly, free oscillations and decay tests are carried out in order to calibrate coefficients required in the model, such as viscous damping. Free oscillations and decay tests may also serve for characterization of mooring stiffness.

Table 1: Suggested set of regular waves for numerical model calibration and validation tests. If WEC response is dependent on wave direction, these waves may be run with headings that are appropriate for this device and location.

Period (s)	Height (m)		
	H1	H2	H3
6	0.5	1	2
7	0.5	1	2
8	0.5	1	2
10	0.5	2	4
12	0.5	3	6

Device response should be measured in small regular waves to determine the accuracy of the numerical model in linear conditions.

Next, by increasing the wave amplitude, the limitations on the domain of validity of the model can be investigated. Following Frigaard et al. (2008), sea conditions corresponding to Froude-scaled wave conditions of Table 1 may be used.

If WEC response is dependent on wave direction, device response should be measured for different wave headings. Most relevant sea conditions of Table 1 may be considered for additional wave headings of 10° and 30°.

Eventually, long crested irregular wave cases may be generated to compare numerical and experimental response and power absorption in realistic scenarios. Following Frigaard et al. (2008), sea conditions corresponding to Froude-scaled wave conditions of Table 2 may be used. The Bretschneider spectrum may be used for the wave spectrum. If WEC response is dependent on wave direction, directional spreading should be taken into account. A spreading parameter of $S_{max} = 25$ may be used (see section 2.5).

Table 2: Suggested set of irregular waves for numerical model calibration and validation tests. The Bretschneider spectrum may be used for the wave spectrum. If WEC response is dependent on wave direction, a spreading parameter of s=25 may be used. Spectra parameters should be appropriate for the location of the device.

Peak Period (s)	Significant Height (m)
6	1
7	2
8	3
10	4
12	5

For sake of calibration and validation, knowledge of the incident wave elevation and directional spreading at the location of the model is critical. They should be measured prior to the experiments at the deployment location of the model. Particular attention should be given to the different wave components. Swell components may become significant in some locations and can have different directions than wind generated waves.

2.7.3 Energy Capture Performance Optimization Tests

In these tests, the ability of the device to capture and convert the wave energy is regarded as the most important criterion. The aim is to optimize the energy capture performance in relevant sea conditions. Tests may be carried out only in irregular waves. Sea conditions of Table 2 may be used.

As for the wave spectrum, the JONSWAP spectrum may be used with a frequency spreading factor matching the one of the target deployment location of the technology. If the target deployment location of the technology is not known, the Bretschneider spectrum may be used.

If energy capture performance is dependent on wave direction, directional spreading should be taken into account. The directional spread should match the one of the target deployment locations, if known. Otherwise, a spreading parameter of S_{max}=25 may be used (see section 2.5).

Model tests in irregular waves should normally be carried out for a duration corresponding to at least 30 minutes at full scale in order to gain statistically valid results. Details of procedures for simulation and measurement of irregular short-crested seas can be found in ITTC Recommended Procedures for Laboratory Modelling of Multi-directional Irregular Wave Spectra (7.5-02-07-01.1).

For these tests, the scale range is typically 1:10 and 1:25. It is critical that a high-quality PTO simulator is included. The requirements are that its effect shall be measurable, controllable and repeatable. If it cannot be achieved at the selected scale, the model size shall be increased, or another approach selected (e.g relying on the numerical model for optimization).

2.7.4 Survivability Tests

Survivability tests in an experimental setting are a very important step before undertaking sea trials so as to evaluate the seaworthiness of a WEC, including hull(s), mooring and PTO systems. That said, they are certainly one of the most difficult tests to implement due to: 1) their strong non-linearities; 2) the necessity to include all or most of the different components of the WEC systems and 3) the difficulty in choosing the relevant test conditions.

Non-linearities lead to specific scaling issues. A larger model are preferable to avoid uncertainty in upscaling the results. On the other hand, an experiment using a small model usually allows a larger panel of extreme conditions to be tested. The scale range for these tests varies between 1:10 and 1:100 depending on the TRL. And although Froud scaling is still the norm, viscous damping might become significant in the WEC response in extreme seas and should not be overlooked (Payne (2008), Holmes (2009)).

Dynamic similitude can also be a difficult task where the dynamic response, the mooring response and PTO effects (when relevant) needs to be as accurately included as possible.

Finally, defining the survival conditions is challenging not only because it needs to characterise all the extreme events related to the deployment site, given an appropriate return period (usually 25 or 50yrs depending on the length of the planned deployment, see Webb *et. al.* (2005) and Coe *et. al.* (2018)), but also because it is not always the largest wave that causes the most extreme response and loads (Yu *et. al.* (2015), Rafiee *et. al.* (2016)). Climate change should also be taken into account in defining the average and extreme conditions where the significant wave height has gradually but steadily risen, and the frequency of extreme events are increasing (Young et al. (2011)).

A full design load framework to obtain the load characteristic of the WEC (fatigue and extreme response statistics) should therefore be developed prior to performing the survival tests. This will help in defining the survival and extreme test conditions. A description of the methodology with relevant references and help in defining the survival conditions can be found in Coe *et. al.* (2018). Yu *et. al.* (2015) also offers guidance on determining appropriate conditions for survivability tests. The framework usually includes the use of numerical analysis to ensure more focused experimental tests and therefore cost reduction.

At minimum however, survivability tests must provide distribution of pressure, motions, loads exerted on the hull, mooring line loads, water height on/in the WEC and PTO system survival control strategies (when appropriate) in both in Ultimate Limit States (ULS) and Accidental Limit States (ALS) conditions for the target deployment site. ULS includes testing the intact WEC, whereas ALS requires testing different failure modes such as one or more mooring lines disconnected during experiments to simulate line breaking scenarios. Note that survival/extreme environmental conditions for ALS maybe different to those for ULS.

Where the device has a survival mode (distinct from the operating mode), tests should be carried out in this condition. In addition, when appropriate, the PTO should be tested both in the fully undamped condition and in the fully locked condition in order to simulate typical failure scenarios which could result in excessive body motions and/or end stop problems.

Finally, the wave conditions should follow the irregular wave extreme sea states selected for a minimum duration corresponding to three hours at full scale. Other conditions should also be considered which includes different wave incident angles, short-crested waves, focused waves as well as specific wave slamming, breaking and overtopping conditions.

2.7.5 Installation and tow-out methodologies' validation tests

These tests aim to validate the installation and tow-out methodology. These tests shall provide distribution of motions and relevant loads (e.g towing lines).

An appropriate test programme shall be defined based upon a description of the installation and tow-out methodology provided by the WEC developer. Tests should be run with irregular waves corresponding to the envelope of the operational conditions. Tests involving failure modes and/or sea conditions greater than operational conditions may be considered.

Installation and tow-out methodologies may also be validated in this stage. If known, the wave spectrum at a specific site should be used. The scale range in this stage is normally between 1:10 and 1:25, however smaller scale models may be used to investigate survivability in extreme waves.

2.7.6 Power production validation tests

These tests aim to validate the power production at the target deployment site. These tests are very similar to the tests of energy capture performance optimization, except that actual sea conditions for the target deployment site shall be used. The developer shall provide the list of sea conditions for the target deployment site. For each sea condition, the directional frequency spectrum shall be provided.

Model tests in irregular waves should normally be carried out for a duration corresponding to at least 30 minutes at full scale in order to gain statistically valid results. Details of procedures for simulation and measurement of irregular short-crested seas can be found in ITTC Recommended Procedures for Laboratory Modelling of Multi-directional Irregular Wave Spectra (7.5-02-07-01.1).

2.7.7 Fatigue Limit State Test

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

2.7.8 Tests for Arrays and Clusters

For an array with many WECs installed, the interaction of WECs may be inferred from tests involving a limited number of devices. Due to the cost and scale constraints, it may not be possible to evaluate experimentally the behaviour of arrays involving a large number of WECs. It may be evaluated by numerical modelling.

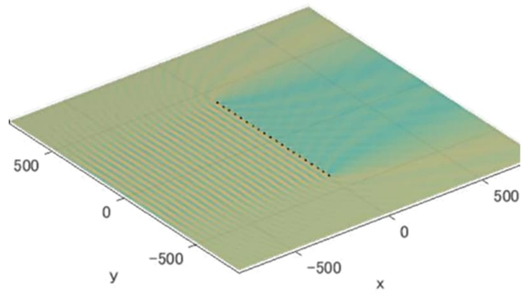

Figure 2; Example of the numerical simulation on arrayed 20 WECs and wave field around the array in regular waves (from Murai *et al,* (2021))

2.8 Energy Capture Performance

The energy capture performance is generally expressed by the concept of a capture width which is the quotient of the absorbed device power and the wave energy flux of the relevant device width (input wave power). For regular incident waves, in linear conditions, the input power P_W transported per unit crest length and unit width is:

$$P_W = \frac{1}{2}\rho g {\zeta_a}^2 c_G \tag{1}$$

where ρ is the density of water, g is the gravitational acceleration, ζ_a is the amplitude of the incident wave, and c_G is the group velocity expressed by:

$$c_G = \frac{1}{2}\frac{\omega}{k}\left(1+\frac{2kh}{sinh\,2kh}\right) \tag{2}$$

where ω, k, h are the angular frequency, the wave number of the incident wave and water depth, respectively (see for example Falnes (2002)). For long-crested irregular incident waves, the power P_W transported per unit crest length is:

$$P_W = \rho g \int_0^\infty c_G(f)\, S_i(f) df \tag{3}$$

where f (Hz) is the wave frequency, $S_i(f)$ is the point spectral density function of incident irregular waves. For deep water, P_W becomes

$$P_W = \frac{1}{64\pi}\rho g^2 H_{W1/3}^2 T_E \tag{4}$$

where the significant wave height $H_{W1/3}$ and energy period T_E are defined by

$$H_{W1/3} = 4\sqrt{m_0}, \quad T_E = m_{-1}/m_0 \tag{5}$$

$$m_n = \int_0^\infty f^n S_i(f) df \tag{6}$$

(see for example Folley *et. al.* (2012)). For short-crested irregular incident waves, the transported power is

$$P_W = \rho g \int_0^\infty \int_{\theta_o-\pi}^{\theta_0+\pi} c_G\,(f) S_i(f,\theta) d\theta df \tag{7}$$

where θ is the direction, θ_0 is the predominant wave direction, $S_i(f,\theta)$ is the directional wave spectral density function. If P_{WEC} is the mean power absorbed by the device, then the capture width C_W is defined by

$$C_W = \frac{P_{WEC}}{P_W} \tag{8}$$

An example of these calculations is given in Park *et al.* (2022) for regular and irregular unidirectional waves. There, the authors test a hybrid wave energy converter for nearshore in a wave tank (1 m wide, 1.5 m of water depth) and evaluate the capture width ratio for several Load Torque of the PTO.

Considering the regular wave parameters:
Wave period T = 2.742 [s],
Wave amplitude ζ_a = 0.165 [m],
Group velocity c_g = 2.542 [m/s],
Power per unit length P_W = 338.66 [W],

the measured wave hight along the tank is given in Figure 3 while the extracted power is plotted in Figure 4.

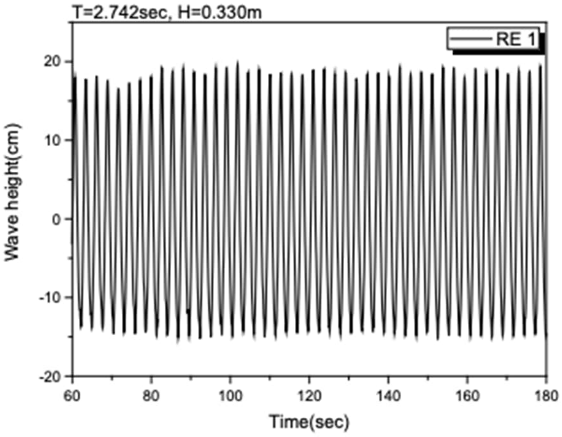

Figure 3: Measured wave height data in the regular waves case (from Park *et al*, (2022))

The calculated average value of P_W is equal to 113.39 [W], with a resulting capture width C_W = 0.3348.

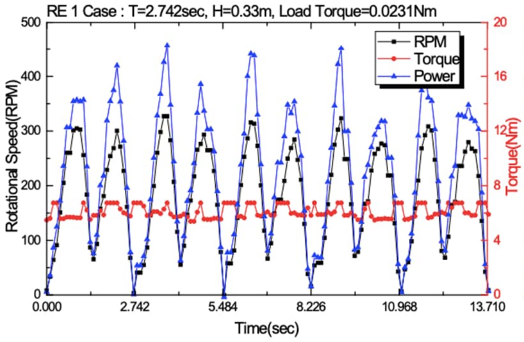

Figure 4: Measured Power, Torque and rotation in the regular waves case (from Park *et al,* (2022))

Similarly, in irregular waves, with parameters:

Energy period T_E = 3.232 [s],
Significant wave height $H_{W1/3}$ = 0.268 [m],
Power per unit length P_W = 79.9 [W],

the measured wave hight along the tank is give in Figure 5 and the extracted power is plotted in blue in Figure 6.

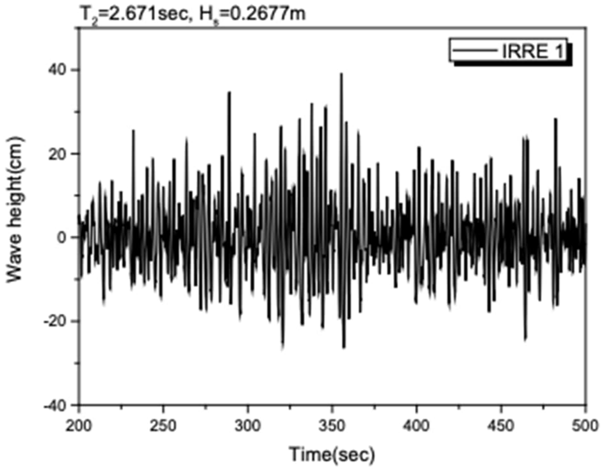

Figure 5: Measured wave height data in the irregular wave case (from Park *et al,* (2022))

In this case, $P_W = 39.05$ [W] and the capture width ratio is C_w = 0.4887.

Note that the expression of incident wave power above is based on linear theory. However, the nonlinear properties of waves increase with the increase of wave steepness, in terms of distortion of wave form and nonlinear interaction among spectral components, etc. For regular waves, nonlinear wave theory such as the second-order Stokes wave theory and the higher–order wave theories may be considered. For irregular waves, the second-order nonlinear random model considering the secondary interaction term of the spectrum may be also considered.

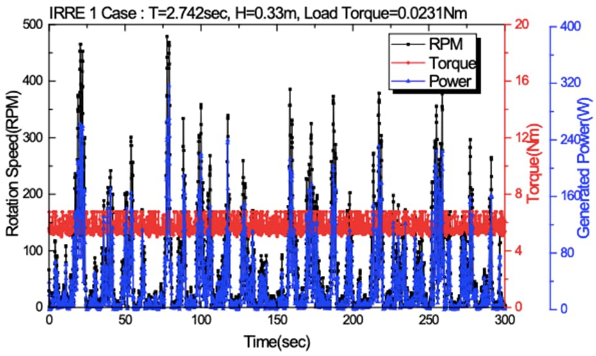

Figure 6: Measured Power, Torque and rotation in the irregular waves case (from Park *et al,* (2022))

3. DESCRIPTION OF TEST PROCEDURE

3.1 Model and Installation

Guidance on preparing the model including model geometry, ballasting and loading can be found in the ITTC Recommended Procedure 7.5-02-07-03.1 *Floating Offshore Platform Experiments.*

Special care should be taken for articulated and flexible models; for articulated models it is important to achieve correct mass properties for each moving segment as well as for the model as a whole; for flexible models it is important to scale the material properties correctly to achieve the correct elastic behaviour at model scale. Particular attention should be paid to the design of moving parts with minimal static and dynamic friction in order to limit uncertainty related to scale effects in extrapolation. This is particularly true for the tests of power production validation, energy capture performance optimization and numerical model calibration and validation (see section 2.7)

The model may be prepared with a PTO simulator. It may be a damping unit or a more sophisticated system depending on the aim of the tests (see section 2.7).

For a variety of tests (such as: proof of concept tests; numerical model calibration and validation tests; survivability tests; installation and tow-out methodology tests; and for the PTO simulator in the concept validation stage), it should be sufficient for the mechanism to be adjustable at stepped values when applying external damping to the relative motion between the WEC's moving parts. It is typically simulated using a simple passive damper, which should be calibrated to characterise performance. Passive damping systems may involve the use of small-scale hydraulics (oil or water), pneumatic dashpot systems, or callipers. An alternative to dissipating energy through a damper is to store energy through a simple mechanism such as a weight which can be lifted via a ratchet system; however, this may create additional challenges in some cases, such as the impact on stability and moments of inertia on floating devices.

In all cases close attention should be paid to the reduction of unwanted static and dynamic mechanical friction, especially for smaller scale models, from components such as hydraulic seals. Systems based on DC or AC motors may also be used with simple controllers and drives in a manner which simulates the behaviour of passive dampers.

Challenges of simulating PTOs with passive dampers include achieving desired ranges of travel of dampers, especially when using linear dampers on angular systems, and non-linear friction behaviour, especially where coefficients of static and dynamic friction are substantially different. With some simple mechanical damping systems it can prove difficult to set damping in a repeatable fashion, presenting challenges to parametric studies. This can be especially true when temperature and humidity change during testing, and where surfaces may be wet or dry. Mechanisms that are subject to these issues should not be used.

For a PTO simulator in the design validation stage, a more sophisticated PTO is desirable allowing continuous variation of damping. In these stages of testing an actively controlled system may be employed to simulate the behaviour of the full-scale PTO in a realistic fashion, and to investigate the impact of different damping strategies on power capture and extreme loads. This may require the use of a programmable digital controller (e.g. Durand et al. (2007) or Ersdal & Moe (2013)) or a PLC-based system (e.g. Banks *et. al.* (2013)). Such systems may be capable of eliminating friction with an appropriate control strategy. However, care must be taken to ensure that active control strategies do not result in energy input to the system. Other challenges with the use of active systems include weight of system, waterproofing, and impact of cabling on floating models.

Whether passive or active damping systems are used, it is beneficial to carry out appropriate tests of the damping system prior to installation in the model, in order to characterise the linearity of the relationship between damping force and velocity, to provide a quantitative estimate of the magnitude of damping at different settings, and to confirm the repeatability of damping settings.

3.2 Instrumentation and Modelling of PTO Systems

The accuracy, resolution and repeatability of sensors should be examined carefully, especially for the case in which an active control system is used to simulate the PTO.

3.2.1 Direct Drive

For a linear generation system with direct drive in a moving body type WEC, the instantaneous power of the device is obtained from the product of the velocity (dx/dt) of the linear generator and the corresponding force across the PTO simulator. The force can be measured using a load cell whilst the relative displacement of the generator can be measured by using a potentiometer, encoder, LVDT, or can be determined from a video-based motion capture system with markers placed on both ends of the simulated generator. The velocity of the relative motion can be obtained by differentiation of the measured displacement.

A similar approach may be employed in cases where a rotational motion is generated, for example in a flap-type device. If the axis of rotation is submerged, it may be convenient to measure the rotation angle using a video-based motion capture system with markers placed on components either side of the axis of rotation, to reduce the need for submerged instrumentation.

3.2.2 Hydraulic Systems

For hydraulic systems of moving body type WECs, the instantaneous power of the device is obtained from the product of the flow rate and the corresponding pressure of hydraulic fluid.

Since the flow rate and the corresponding hydraulic fluid pressure are calculated from the force acting on the cylinder and the displacement of the piston, a load cell and a potentiometer/LVDT can be used in the tests in a manner similar to that described in 3.2.1.2.1. A similar approach can be employed where the hydraulic system is simulated using another damping such as a pneumatic dashpot. In either case the force may also be obtained from pressure measurements.

3.2.3 Pneumatic Systems

In tests of pneumatic devices, such as OWC type WECs, the air turbine can be simulated using an orifice to restrict the air flow and to increase the pressure in the air chamber. By calibrating the orifice, it is possible to obtain a relation between pressure drop across the orifice and the flow rate. Sheng *et.al.* (2012) suggest that the orifice area for optimal power conversion efficiency is typically 0.5-2.0% of the water column area.

It should be noted that calibration between differential pressure and flow rate may be affected by the frequency in oscillatory flow, and hence calibration in steady flow may induce some error. The pressure drop across the orifice is typically measured by using a differential pressure gauge. In some cases, it is convenient to measure water level using a wave probe inside an OWC device, which can be used to make an independent estimate of flow rate. As discussed in section 2.4, care must be taken to account for scale effects on pneumatic stiffness of the system.

It has been argued that the damping generated by an orifice is less linear than the Wells turbine often intended as the full-scale power take-off for OWC devices, and more similar to the damping from an impulse turbine. One alternative is to use a porous membrane in place of the orifice, which can give more linear behaviour (Lewis *et.al*, 2003). However, Forestier et al. (2007) show that the porous membrane and the orifice PTOs yield very similar power extraction on a 1:15 scale device. Calibration of both types of simulated PTO is discussed in detail by Sheng *et. al*. (2013).

3.2.4 Overtopping Systems

The power absorbed from overtopping systems can usually be estimated by measuring the change in the reservoir level, which is an indication of both the inlet and outlet volumes.

3.3 Calibration of Environment

Details of the calibration of environment parameters can be found in the ITTC Recommended Procedure 7.5-02-07-03.1 *Floating Offshore Platform Experiments*. Particular attention must be paid to the reflected waves by the beach and the wavemaker in the model test basin. It is possible to evaluate the effect of the reflected waves by using standard techniques of resolving incident and reflected waves.

3.4 Collection of Data

The main measured quantities are typically:

- All degrees of freedom (DOF) of motions of the model; note that 6-DOF is adequate for rigid bodies, but more degrees of freedom will be required to be measured for articulated or flexible devices;
- Wave elevations local to the model to determine phase of response as well as far up-wave and down-wave as appropriate;
- wind and current velocities (where appropriate);
- PTO forces & displacements / velocities (linear or rotational generator type);
- Pressure drops and flow rates across the PTO energy dissipating simulator (Pneumatic type);
- Overtopping rates (Overtopping type);
- Mooring forces where appropriate;
- Video recordings.

Studies may also investigate the detailed flow field around or inside devices, using techniques such as Particle Imaging Velocimetry (PIV), in order to assess how device performance may be improved; however, this may require techniques of phase-averaging to be applied to correct for small variations in response phase during tests (see for example Fleming *et. al.* (2012)).

3.5 Data Analysis

Both time-domain and frequency-domain analysis are applied to analyse the raw data obtained in regular and irregular wave tests. If the WEC is a resonant type device, harmonic analysis can be used to obtain the characteristic of the device effectively. Details of the harmonic analysis of regular wave tests can be found in the ITTC recommended Procedures 7.5-02-07-03.2 *Analysis Procedure for Model Tests in Regular Wave*.

Test data in irregular waves should be subjected to spectral and statistical analysis, as described in the ITTC recommended Procedures 7.5-02-07-02.1 *Seakeeping Experiments.*

3.6 Extrapolation to Full Scale

All test results of the model tests are presented as prototype values. Considering that waves are the driving mechanism for WECs, model values are scaled to full scale by applying Froude's similitude law.

However, as discussed in Section 2.4, there are many important factors in energy conversion tests that are not addressed by standard scaling procedures such as the energy dispersion in the electrical circuit in the PTO system. Special considerations are needed to address their effects.

Moreover, the scale of the experiments should always be explicitly mentioned so that the model scale values can be used for the validation of numerical models.

3.6.1 Presentation of Results

A report on tests of a wave energy device should contain at least the following information:

- List of test objectives;
- Summary of tests;
- Description of test facilities and instruments;
- Basic assumptions, coordinate systems and sign conventions;
- Model description, including principal dimensions, detailed lines if appropriate, mass and centre of mass on individual moving components, moments of inertia about the centre of gravity of individual moving components.;
- Description of experimental set-up;
- Target and actual environmental conditions;
- calibration procedures and results;
- instrumentation calibration procedures, results, and statement sheets;
- Description of test programs, procedures and parameters;
- Description of data acquisition and data analysis procedures;
- Accuracy and uncertainty analysis;
- Tabulated and graphical results for energy capture capability; and
- Conclusions on model behaviour.

The test report should normally also include photographs and video films.

3.7 Uncertainty Analysis

Uncertainty analysis should be performed following the approach presented in ITTC guidelines 7.5-02-01-01 “Guide to the Expression of Uncertainty in Experimental Hydrodynamics”, 7.5-02-01-07 “Guideline to Practical Implementation of Uncertainty Analysis”, and 7.5-02-02-02.1 “Example of Uncertainty Analysis of Resistance Tests in Towing Tanks”.

In general, particular attention should be paid to uncertainties associated with the reciprocating nature of many wave energy devices/PTOs which can result in behaviour which is not directly comparable to steady state motion of similar components.

The ITTC guideline 7.5-02-07-03.12 “Uncertainty Analysis for a Wave Energy Converter” provides a recommended guideline for the application of an uncertainty analysis for a wave energy converter and provides an example of an oscillating water column wave energy converter test uncertainty analysis. Another comprehensive example for deriving the uncertainties in a WEC experiment using the Monte Carlo method can be found in Orphin et al. (2021).

4. LIST OF SYMBOLS

P_W	input power	W
ρ	density of water	kg/m3
g	gravitational acceleration	m/s2
ζ_a	amplitude of the incident wave	m
c_G	group velocity	m/s
ω	angular frequency	rad/sec
k	wave number of the incident wave	1/m
h	water depth	m
f	wave frequency	Hz
$S_i(f)$	point spectral density function of incident irregular waves	
$H_{W1/3}$	significant wave height	m
T_E	energy period	s
P_{WEC}	mean power absorbed by the device	W
θ_0	predominant wave direction	deg
$S_i(f, \theta)$	directional wave spectral density function	
C_W	capture width	
PTO	Power Take Off	
OWC	Oscillated Water Column	
ULS	Ultimate Limit States	
ALS	Accidental Limit States	
LVDT	Linear Variable Differential Transformer	

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