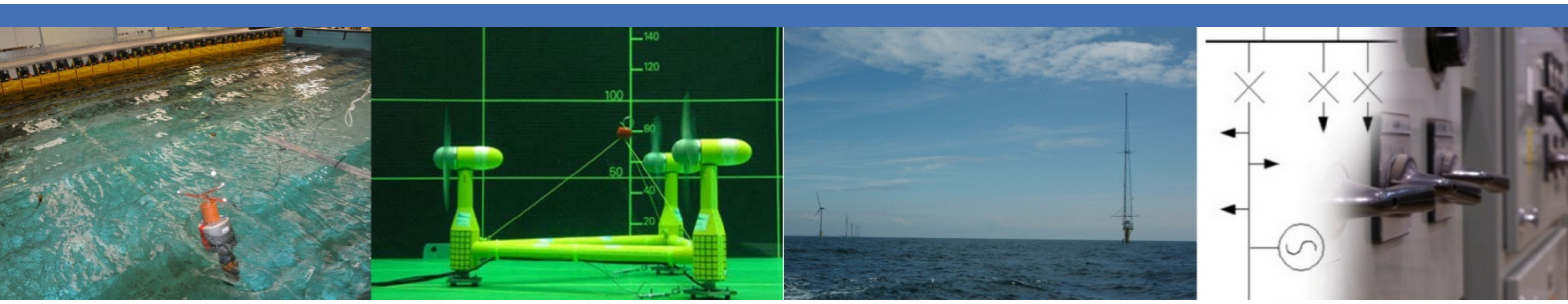
Marine Renewables Infrastructure Network



WP2: Marine Energy System Testing - Standardisation and Best Practice

Deliverable2.28

Model Construction Methods

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ABOUT MARINET

MARINET (Marine Renewables Infrastructure Network for emerging Energy Technologies) is an EC-funded network of research centres and organisations that are working together to accelerate the development of marine renewable energy - wave, tidal & offshore-wind. The initiative is funded through the EC's Seventh Framework Programme (FP7) and runs for four years until 2015. The network of 29 partners with 42 specialist marine research facilities is spread across 11 EU countries and 1 International Cooperation Partner Country (Brazil).

MARINET offers periods of free-of-charge access to test facilities at a range of world-class research centres. Companies and research groups can avail of this Transnational Access (TA) to test devices at any scale in areas such as wave energy, tidal energy, offshore-wind energy and environmental data or to conduct tests on cross-cutting areas such as power take-off systems, grid integration, materials or moorings. In total, over 700 weeks of access is available to an estimated 300 projects and 800 external users, with at least four calls for access applications over the 4-year initiative.

MARINET partners are also working to implement common standards for testing in order to streamline the development process, conducting research to improve testing capabilities across the network, providing training at various facilities in the network in order to enhance personnel expertise and organising industry networking events in order to facilitate partnerships and knowledge exchange.

The initiative consists of five main Work Package focus areas: Management & Administration, Standardisation & Best Practice, Transnational Access & Networking, Research, Training & Dissemination. The aim is to streamline the capabilities of test infrastructures in order to enhance their impact and accelerate the commercialisation of marine renewable energy. See www.fp7-marinet.eu for more details.

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Norway
SintefEnergi AS (SINTEF)
NorgesTeknisk-NaturvitenskapeligeUniversitet (NTNU)

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LEGAL DISCLAIMER

EXECUTIVE SUMMARY

Harnessing wave energy is a new concept that requires the development of new technologies able to extract energy from the waves and transmit it to the shore. A large number of technologies are proposed and given the complexity of the task and the high cost of offshore work, a staged development path is required involving indoor and offshore testing at various scales. This offers a large reduction in the development costs of device testing in hydrodynamic facilities and low energy offshore test sites. This leads to the validation of the operation principle, verification of numerical model result, model optimisation, operation training, etc.

In order to ensure the reduced scale provides an accurate representation of the full scale model, a number of techniques can be applied. Two main scaling methods, called Froude and Reynolds, are commonly used for the scaling of hydrodynamic structures. The full design of a scaled model must follow the chosen scaling method and be chosen taking into account suitable materials which can vary with the scales.

This document aims at reviewing the techniques used for scaling, designing and building models for the best representation of the full scale prototype characteristics in controlled ocean test facilities. It provides a description of the full scale prototype characteristics and the scaling methods available. It then provides useful information on the design techniques and the last section concentrates on the verification methods to assess the quality of the model built. This work is based on experience from MARINET partners and documents such as (Grégory S. Payne 2009), (Luís Mallen, D2.13, Collation of model construction methods 2012) and (ITTC 2014).

The most common scaling method for WEC testing is using the Froude similitude explained in this document and the most appropriate scale depends mainly on the stage of development of the device, the equipment available and related costs. When the approximate scale is chosen, the characteristics of the deployment location and/or the material cost and availability may be used to select the final modelling scale.

For the model design, at the chosen scale, a large number of parameters are presented in this report and must be taken into account. It includes the test objectives (optimisation or validation), characteristics of the materials and instrumentation available. All the design parameters must be accurately set and measured in order to ensure repeatability of the results at all scales of testing. This document also suggests and describes a number of verification methods for the most commonly used parameters, weight and weight distribution, power take off systems, instrumentation and mooring lines.

Although the weight and weight distribution is a critical part in the design and construction of floating or underwater models in motion, this is not relevant for the modelling of fixed devices.

CONTENTS

1 INTRODUCTION

Harnessing wave energy is a new concept that requires the development of new technologies able to extract energy from the waves and transmit it to the shore. A large number of technologies are proposed and given the complexity of the task and the high cost of offshore work, a staged development path is required involving indoor and offshore testing at various scales. This offers a large reduction in the development costs of a device testing in hydrodynamic facilities and low energy offshore test sites. This leads to the validation of the operation principle, verification of numerical model result, model optimisation, operation training, etc.

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2 FULL SCALE MODEL

Model testing at any stage and any scale is performed to represent or predict the characteristics of a full scale device design. The reason for testing at smaller scale is the cost reduction of the overall project leading to the completion of an economically viable full scale prototype. All details of the prototype design cannot be represented at lower scales, it is therefore important to define the full scale model with parameters that will be used in model construction. This section describes the elements commonly present in a Wave Energy Converter (WEC) and characterisation method, which need to be modelled at all scales in order to generate comparable results.

Firstly, whilst there are many different designs proposed for wave energy conversion, the defining factor when designing a model is related to the body being fixed or in motion. Each body, floating or underwater, needs to be accurately modelled with respect to its geometry, weight and weight distribution. However the geometry is the only concern on a fixed body. In this case, the weight characteristics described in this document have no impact on the test results. They may impact the full scale prototype but only on the structural design which is not part of this study.

In this document, the model construction methods described are assuming a device in motion. In the case of a fixed device or body, issues relating to mass are considered to be not relevant.

In general terms, a Wave Energy Converter (WEC) is a structure placed in ocean waves with the objective of harnessing energy in the form of electricity or other types of products (energy in a storage system, desalinated water, etc.). In any situation, the WEC design will include a mechanical structure and a system able to harness energy from the waves. This can be summarised in the following three components:

- one or more mechanical bodies placed in a wave field
- one or more Power Take Off (PTO) system
- A mooring or anchoring system

It is important to note that these three components are interrelated in the full scale device as much as in scaled models. Their behaviour can vary widely when any of these components is altered so they must be modelled as accurately as possible at all scales of testing.

In more detail, the characteristics of a wave energy converter can be fully described with the following parameters:

- General design of the device, including one body or a number of bodies with specific relative movements.
- Geometry of the immersed volumes: this has a direct impact on the hydrodynamic and hydrostatic forces applied by the water to the WEC bodies. The geometry influences the model position in water, stability, forces acting on the structure, etc.
- Surface roughness: the roughness of a material such as metal sheets can be small and neglected in reduced scales. However some devices include structural reinforcements that may introduce greater roughness coefficients.
- Total mass of each moving body.
- Mass distribution: has a significant influence on the device stability and natural periods of oscillation. This can be simplified in two parameters that are considered sufficient to reproduce a similar body motion in the water:
    - Centre of gravity of each moving body. The centre of gravity, or centre of mass, is the average position of the mass of a body. This mainly influences the position of the body in still water and its stability in waves.
    - Radiuses of gyration or moment of inertia of each moving body. This is characterising the body inertia in rotation motions and must be calculated at the centre of gravity for floating bodies and the axis of rotation if connected to another body. This mainly influences the natural periods of oscillation of a body.

- PTO characteristics. This is generally represented by a curve or equation of force versus velocity, pressure versus flow or other parameters. The PTO characteristics may vary in the full scale prototype to adapt to the sea state and improve the power capture.
- Monitoring and control equipment.
- Mooring or anchoring characteristics. For a catenary type mooring system, the linear weight can be easily reproduced at the chosen scale but it may be complex with some mooring systems. For any type of mooring, the relation between force and displacement of the floating body must be known and reproduced at all scales of testing.

Figure 1 shows an example of a wave energy converter, the quarter scale OEbuoy, with one floating body and specific surface beams for structural reinforcements.

Figure 1: Picture of the OEbuoy quarter scale model tested in Galway bay test site.

Depending on the scale and stage in the development path, the full scale characteristics presented above must be modelled in more or less detail with a method to predict the full scale characteristics and test results from the model scale. Scaling methods that can be used for WEC devices are described in the next section.

3 SCALING METHOD

Scaling techniques are required in WEC testing to ensure correct continuity of the results across the range of scales and in turn reliably predict device characteristics and hydrodynamic responses. It is widely accepted that the Froude number “Fr”, described in Equation 1, and the Reynolds number “Re”, described in Equation 2, must remain constant at any scale to ensure hydrodynamic similitude. The Froude number represents the gravitation and inertia forces similitude and Reynold number represents the viscous forces similitude.

In Equation 1 and Equation 2, U is the fluid velocity (relative to the solid), "l" is the solid dimension acting on the fluid, "g" is the gravitational acceleration and "v" is the kinematic viscosity of the fluid.

Equation 1: $$Fr = \frac{U}{\sqrt{gl}}$$

Equation 2: $$Re = \frac{Ul}{v}$$

3.1 Froude similitude

When the Froude number remains constant, the ratio between inertial forces and gravitational forces is also constant. In Equation 1 Fr and g are constant at all scales and therefore velocity and length must be scaled accordingly. This leads to the scaling factors provided in Table 1 with "S" the scaling factor for length.

Quantity	Scaling factor	Unit equivalent
Length	S	m
Volume	S^3	m^3
Time	$S^{0.5}$	Sec.
Velocity	$S^{0.5}$	m/Sec.
Acceleration	1	m/Sec.^{2}
Mass	S^3	Kg
Density	1	Kg/m^3
Force	S^3	Kg*m/Sec.^{2}
Pressure	S	Kg/m^2
Torque	S^4	N*m
Power	$S^{3.5}$	N*m/Sec.
Angle	1	
Angular velocity	$S^{-0.5}$	Radian/Sec.
Angular acceleration	S^{-1}	Radian/Sec.^{2}

Table 1: list of scaling factors used for the most commonly scaled WEC parameters.

For the testing of a floating body at different scales, the Froude scaling method is commonly used and widely accepted where the hydrostatic and hydrodynamic forces are the most predominant forces acting on the model. Most forms of wave energy converters can be scaled with this method.

3.2 Reynolds similitude

The Reynolds number, shown in Equation 2, is related to the fluid velocity "U", viscosity "v" and significant length "l" of the solid body. Most of the basins used in the wave energy sector are filled with fresh water, sometimes sea water, and the sea water viscosity does not vary significantly. Therefore the Reynolds number can only be kept constant with the factor U*l constant which does not match with the Froude similitude shown in Table 1.

3.3 Froude and Reynolds scaling limitations

Non-linear behaviours are not scaled properly using the Froude or Reynolds similitudes. Depending on the WEC design the following nonlinear behaviour may be present:

- Air compressibility: the effect of air compressibility on the system is not properly scaled when using the Froude similitude to design the scaled model. As shown in (Weber n.d.), the air chamber volume should be scaled with a factor of S squared instead of S cubed as mentioned in Froude similitude in Table 1. This is particularly relevant when testing Oscillating Water Column (OWC) devices. This behaviour is generally not taken into account in physical testing and can be simulated in numerical modelling.

- Non-linear deformations in materials. The Froude similitude is designed for non-deformable structures but some WECs use deformable materials for stability or power take off. These elements should be scaled with a specific design that simulates their effect on the device at the appropriate scale. For elastic materials, the relation force versus displacement can be scaled using the Froude scaling but the physical dimension may not follow the Froude scaling technique.
- Mechanical friction: friction forces, when applicable, are non-linear and must be designed uniquely at all scales to provide the scaled force to displacement curve.

3.4 MOST RELEVANT METHOD

The choice for the most appropriate scaling method depends on the characteristics of the model and the tests that will be carried out. When water motion is the most significant parameter (ie. Water flow through a tidal turbine) Reynolds similitude is more accurate but in wave energy, with water level and water pressure variations around the model, Froude scaling is generally used.

4 SCALED MODEL DESIGN AND CONSTRUCTION

The scaled model design must be chosen to represent the full scale prototype and the specific requirements at the chosen scale. As shown in the WEC test protocol in (Brian Holmes 2010), five stages are advised to reduce the risk and costs associated with a technology development from idea to full scale commercial design. Within these stages, a number of test locations will be chosen and each scaled model needs to be designed for each specific location, in hydrodynamic facilities or offshore. This section presents the conditions at the test location used for the model scale selection, the test requirements at the chosen scale and the techniques and experience required for the scaled model design and construction.

4.1 SCALE SELECTION

Scale selection is the first step in designing a model. This influences the design requirements, model cost, type of materials used and all the model parameters. Correct choices lead to improved accuracy in test results and significant reductions in the device development costs. It is clear that the larger the scale, the more accurate the results can be but also the higher the costs. It is therefore advised to follow a structured development protocol. The MARINET consortium recommends following the report published by the IEA-OES, (Brian Holmes 2010) which gives the testing programme and model testing requirements depending on the Technology Readiness Level (TRL). The five stages are given below:

- STAGE 1: Concept Validation (TRL 1-3): comprises testing of the idea as an idealised small scale (circa 1:50) model in a set of monochromatic, regular waves followed by panchromatic, irregular sea states. The former tests are to identify and describe the physical processes in relation to the design variables such that the device geometry can be optimised. The latter are to estimate the performance potential in realistic seaways. Hull seaworthiness and mooring suitability can also be established.
- STAGE 2: Design Validation (TRL 4): is a step using a larger, more sophisticated model (circa 1:10) and tests cover a more extensive number of sea states, including realistic survival conditions. During this phase engineering is introduced in the form of a preliminary design and an elementary costing of the system components is established. Based on the measured power absorption in a range of sea states the annual energy production is calculated using a set of generic wave conditions such as shown in Task Report 02-1.1 of this IEA-OES annex.
- STAGE 3: Systems Validation (TRL 5-6): is a schedule including the testing of all sub-systems incorporating a fully operational PTO that enables demonstration of the energy conversion process from wave to wire. If the cost is acceptable, Stage 3 is entered in more detail with the aim to test the complete wave energy converter at a selected sub-prototype size (circa 1:4) that can safely be deployed at sea and produce power. The device is still small enough to facilitate easier handling and operation but large enough to experience deployment, recovery and maintenance techniques at sea. The first involvement with licences, permissions, certification

and environmental requirements will be encountered. Also, design teams will experience Guidelines from regulatory compliance bodies for the Structured Development & Testing Development of Wave Energy Systems Plan 3 manufacturing and production and supply chain issues, though the device may not be grid connected. Productivity remains a key stage gate requirement in these tests.

- STAGE 4: Device Validation (TRL 7-8): is a critical part of the process and covers a solo machine pilot plant validation at sea in a scale approaching the final full size (circa 1:1). This stage is a proving programme of designs already established rather than actually experimenting with new options. Tests can be initially conducted at a moderate sea state site prior to testing at an exposed ocean location. The device as a whole must be proven fit for purpose before this stage is concluded. The device must also be grid connected before the end of the proving trials. Heavy engineering operations at sea are involved so health and safety requirements become important, as do O&M of the plant under realistic conditions. Since only a single unit is involved environmental impact will be expected to be minimal but monitoring of the machines presence in a given location must be undertaken. These trials also need to comply with the marine licencing requirements from the regulatory body which covers the test location. This will incorporate elements such as navigational safety and structural integrity in their review.
- STAGE 5: Economics Validation (TRL 9): the final stage involves multiple device testing, initially in small arrays (circa 3-5 machines) which can be expanded as appropriate. By the conclusion of the previous sea trials, the technology and engineering of a device should be well established and proven. The technical risk of Stage 5 should, therefore, be minimized. However, the consequence of failure would be significant and the financial risks are less certain since it is the economic potential of the devices deployed as a generating wave park that are under investigation. Initially the hydrodynamic interactions of the devices will be investigated, together with the combined electricity supply stability possible via the power electronics. Availability and service scenarios will be important issues as more machines are deployed as will onshore and offshore O&M requirements. Environmental aspects, both physical and biological, can now be studied in detail as well as the socioeconomic effect the wave park will have on the local area. Early stakeholder involvement is recommended.

Additionally, in the MARINET deliverable D2.13, (Luís Mallen, Deliverable D2.13, Collation of Model Construction Methods 2012), scaling ranges for the testing of typical parameters are listed and provided below:

- Operating Conditions tests. These tests are made to estimate the expected power production and are mainly carried out in a scale of around 1:30 (this may vary significantly with the type of WEC and the characteristics of the wave tank).
- Components' tests. Typically a scale of around 1:10 or larger is used.
- Power captures tests. A minimum scale of 1:10---1:20 is typically used, depending on device size, in order to capture correctly some of the wave energy absorption characteristics
- Survivability tests. It is recommended to build the model as large as possible to reduce issues with friction, because extreme waves cause significant viscous forces which are greater at smaller scale. Limiting factor is generally tank blockage, water depth for power capture, and wave height (extreme conditions). Suitable test for design and maximum forces determination. Testing of devices in these extreme conditions is performed at smaller scales due to the limitations, typically: 1/30 to 1/60. (Note: Extreme waves associated with survival testing are inherently non---linear and not well characterized in numerical simulation --- which enhances the importance of lab testing).
- PTO tests. PTOs are inherently inefficient at small scale and should not be used for electrical performance predictions, hence the larger the scale the better. The range of scales goes from 1:4½ to 1:20. The dynamics and control of the scaled PTO model can be tested in---house in test benches developed for this specific purpose. A phased development scheme enables informed design decisions (stage---gate approach), which can help to control risks and reduce costs
- Hull sketching and movements tests. A whole range of scales is used from 1:8 to 1:40.
- Mooring tests. It is a significant challenge to design a scaled mooring to deliver mooring load characteristics consistent in every way with full scale. Mooring component masses, cross sections, added mass, damping, and spring rates do not scale well using Froude similitude. Some developers have built a

programmable mooring controller (PMC) that allows precise definition of the load deflection curve, mooring spring rate, damping, and/or inertia for each mooring leg. Typically scale goes from 1:8 to 1:20.

After considering the stage of development and test objectives presented above, the test location and the precise scaling factor can be chosen according to the following criteria:

- In hydrodynamic facilities (stage 1 and 2)
  - Wave characteristics: each test facility can generate a range of wave conditions within the limits of its wave generation system. Figure 2 shows the typical envelope of wave heights a wave generator with flap paddle can generate. This changes in value depending on the characteristics of the wave generator. Table 2 provides the typical irregular waves used in UCC-HMRC with Bretschneider sea states where the sea states number 1, 2, 5 and 8 are limited in height due to the wave steepness and 10, 14 and 15 are limited in height due to the wave generator limits. In a performance analysis, WEC scale is typically chosen at the largest scale that allows testing of all the commonly occurring sea states and some extremes. Scaling the model for testing the most extreme waves would require a large reduction of the scale factor and reduce the accuracy in the performance results. In survivability testing, the scale is chosen so that most extreme waves at the expected prototype location can be generated in the facility.
  - Water depth: the shape of the waves in shallow water is affected by the water depth and it is better to find a test facility with an appropriate depth and adjust the scale if necessary. This also impacts the mooring or Power Take Off (PTO) tether design if applicable. Some facilities are equipped with a deeper section (pit) or moving floors which provides more flexibility on the water depth and scale selection.
  - Flume or tank width. When the width of the wave facility is limited, large wave reflections from the model and the proximity of the side walls can occur. This has an impact on the test results which would not appear with an offshore prototype. Therefore, the model should be either small compared to the basin/flume width to avoid blockage effect or it is possible to assume the testing represents a model in an array with spacing similar to the width of the facility.
  - Component availability: components that can be directly sourced without modifications can significantly reduce the cost of a model construction. A commonly encountered example are cylindrical sections which can be sourced from standard size pipes, the ready availability of which may influence the scale choice with a view to reducing testing costs.
  - Material and measurement systems to be used. It is sometimes difficult to find light enough materials or measurement equipment to match the lowest scale models, leading to a larger model being adopted for testing.

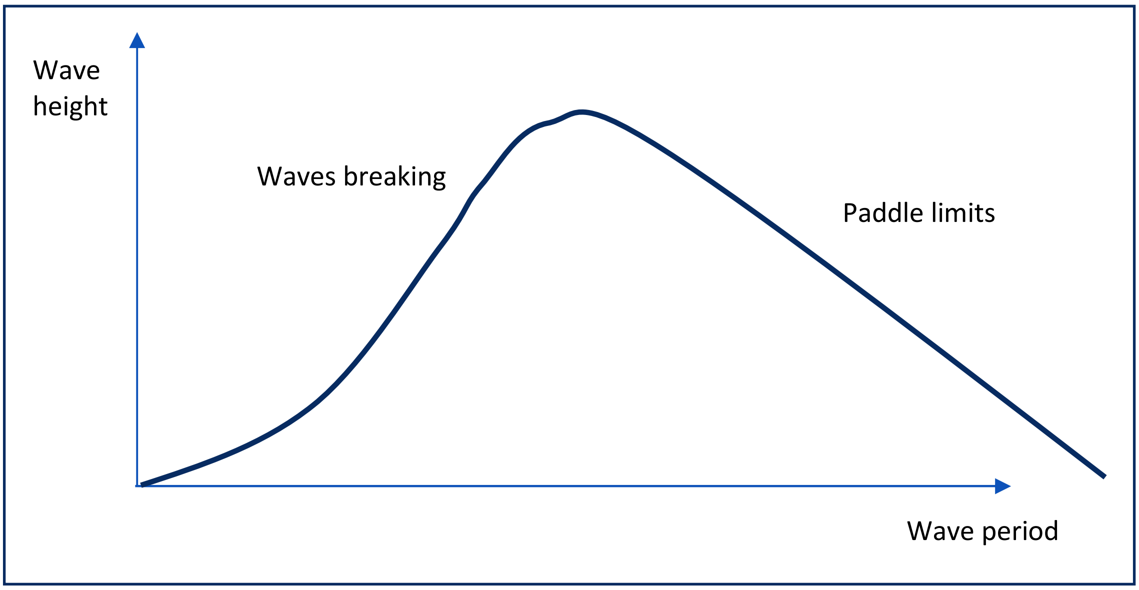

Figure 2: Typical wave generation limits in a wave basin with flap paddles.

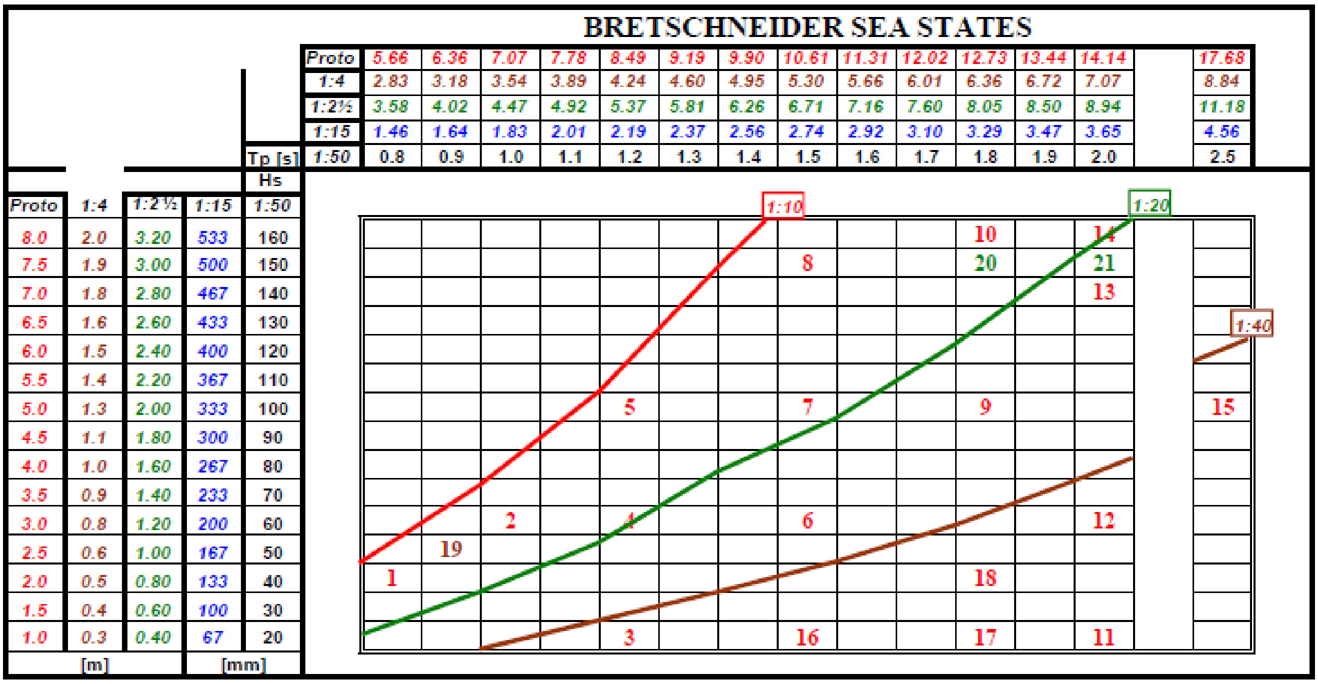

Table 2: Typical Bretschneider sea states generated in UCC-HMRC ocean wave basin (1:50 scale).

- In offshore testing (stage 3 to 5)
  - Wave characteristics: in offshore testing, there is no control on waves present at a given site. Each test site can be characterised by a scatter diagram of previous sea states encountered and must be chosen in relation to this scatter diagram. It is for example possible to choose a fetch limited real sea testing site, such as EMEC's Scapa Flow site; offering a smaller range of sea states, generally at a shorter period due to swell generation being constrained by its position in a natural basin. The sea state characteristics (spectrums, heights and periods) at the chosen site must therefore match the full scale deployment site and the scale must be chosen so that it increases the probability of seeing a good range of representative sea states (some sea states in a test site may not be usable). A full analysis of the occurrence scatter diagram at both locations is therefore required to choose the most appropriate scale. Figure 3 shows the sea states periods and height at the Galway bay test site are representative of typical full scale scatter diagram except for some long periods and small height region. The test site matches sea states scales of typically 1:4 to 1:2.5. For comparison, Figure 4 shows the percentage occurrence of each sea state at the Billia Croo test site in EMEC for more exposed full scale model testing.
  - Water depth: the shape of the waves in shallow water is affected by the water depth and it is better to find a test facility with an appropriate depth and adjust the scale if necessary. This also impacts the mooring or Power Take Off (PTO) tether design if applicable.
  - Production and installation costs: at this stage/scale cost can increase rapidly. The weight and dimensions should be chosen accordingly in order to match the dimensions of local mechanical workshops, materials to be used, locally available installation vessels, dimensions allowed on the roads, etc.

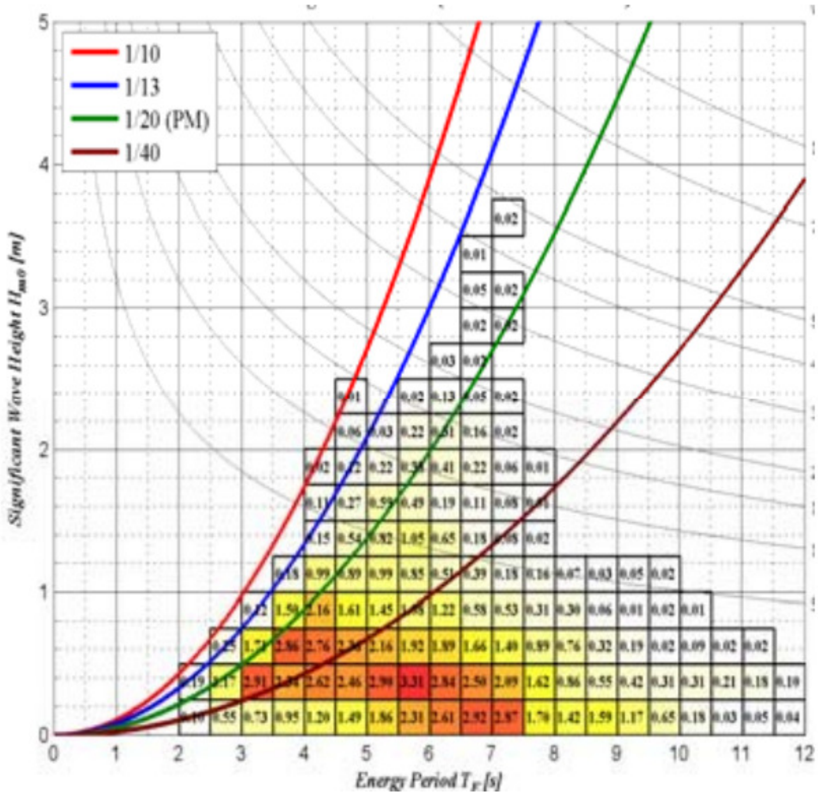

Figure 3: Galway bay test site wave occurrence scatter diagram (year 2010 data)

Significant Wave Height (m)

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
12																										
11.5																0.0014										
11													0.0007	0.0014	0.0014	0.0007										
10.5												0.0007	0.0007	0.0014	0.0014											
10												0.0014	0.0014	0.0028	0.0050	0.0014										
9.5											0.0014	0.0064	0.0014	0.0085	0.0007											
9											0.0021	0.0135	0.0128	0.0099	0.0035											
8.5											0.0085	0.0255	0.0149	0.0071	0.0007											
8										0.0007	0.0276	0.0482	0.0198	0.0028	0.0007											
7.5										0.0057	0.0702	0.0900	0.0248	0.0057												
7										0.0241	0.1446	0.0985	0.0284	0.0071	0.0014											
6.5									0.0028	0.1049	0.2353	0.1559	0.0397	0.0135	0.0043											
6									0.0198	0.2495	0.3069	0.1680	0.0432	0.0191	0.0007	0.0007										
5.5								0.0007	0.0751	0.4983	0.3891	0.1928	0.0553	0.0248	0.0099	0.0007										
5								0.0085	0.2856	0.7889	0.5068	0.2587	0.0843	0.0425	0.0064	0.0028										
4.5								0.0858	0.7251	1.0774	0.6968	0.2722	0.0751	0.0376	0.0213	0.0050										
4							0.0057	0.3778	1.3503	1.2837	0.8584	0.3927	0.1538	0.0673	0.0128	0.0043										
3.5							0.0964	0.9640	1.7586	1.8068	1.0575	0.5181	0.2204	0.0936	0.0305	0.0099	0.0007									
3						0.0085	0.5600	1.9854	2.4064	2.1413	1.2156	0.5713	0.2289	0.1063	0.0475	0.0113	0.0035	0.0028	0.0007							
2.5						0.1396	1.3595	2.7516	3.1471	2.6467	1.4346	0.7343	0.2247	0.0766	0.0319	0.0248	0.0064	0.0028	0.0007							
2					0.0191	0.7159	2.4270	3.3597	3.5370	2.7190	1.5509	0.6911	0.2821	0.1134	0.0546	0.0163	0.0028									
1.5				0.0439	0.3431	2.0045	3.5752	4.6228	4.4038	2.7686	1.3737	0.4933	0.1673	0.0666	0.0220	0.0071	0.0028	0.0007								
1				0.3941	1.0023	3.1648	4.8128	4.7639	3.0032	1.3864	0.5401	0.1680	0.0737	0.0227	0.0113	0.0035										
0.5				0.1446	0.4465	0.9073	1.2305	0.8506	0.3090	0.0787	0.0142	0.0007	0.0007	0.0007	0.0007	0.0028	0.0007	0.0050	0.0035	0.0021	0.0028	0.0007		0.0007	0.0007	

Energy Period Te (s)

Figure 4: Billia Croo percentage occurrence diagram (EMEC)

4.2 NUMERICAL MODELLING

A combination of numerical modelling and physical modelling is widely used when developing a technology. Numerical models can provide performance estimates or other parameters for a large number of model configurations but with a higher degree of uncertainty. Physical models can provide a higher accuracy when sufficient attention is given to the model design and the quality of the waves generated but a limited number of configurations can be tested.

In the first stage, the most common approach is to use a simple and low cost numerical model to validate the design (performance, static and dynamic stability, etc.) and provide an approximation of the optimal model characteristics. The physical tests are then used to validate the numerical model results but need to include large variations on each parameter of the model for optimisation.

In further testing, small variations around the optimal configurations are expected on the physical model based on the previous results and more accurate numerical modelling results can be achieved once the model is calibrated and validated against physical testing results.

4.3 MODEL DESIGN

The model design changes for each test and scale, the test requirements and the materials used may change and a specific design must be produced for each testing run with an accurate scaling of all the full scale model parameters presented in section 2 and appropriate levels of detail. The design for each scale includes the geometry, weight distribution and all the other elements presented in this section such as Power Take Off system, Materials, instrumentation, etc.

The geometry, materials and weight distribution interlink and must be properly documented in order to assist in the physical model construction and provide sufficient details for future projects. SolidWorks or Autodesk (inventor 3D drawing) are commonly used software tools for the representation of a system in three dimensions and the production of two dimension technical drawings for construction. These tools can also calculate the weight distribution (centre of gravity and moments of inertia). The moment of inertia of a body can also be predicted, without the use of advanced software, using Equation 3 (with "m" for mass and "r" the distance of the mass to the centre of rotation). When the shape of the body is too complex, it can be divided into a number of basic shapes, punctual weight, tubes, rods, etc. The total moment of inertial of the floating body is equal to the sum of all the moments of inertias of its subsections.

Equation 3: $$I = \int_m r^2 . dm$$

As an example, a SolidWorks of the model designed for the MARINET Round Robin testing is provided in Figure 5. In this case, the chosen scale at the HMRC-UCC laboratory is 1:50 and includes only basic levels of detail that are represented in Figure 6 and Table 3.

Finally, as the scale of testing increases, some elements will be modelled in increasing detail. For example, the geometry of small or structural items, mainly influencing the surface roughness (metal beams, nuts and bolts, etc.), cannot be accurately represented at small scale. This is acceptable as the viscous forces are smaller than hydrodynamic forces acting on the model. Also, the Power Take Off (PTO) system is a complex element which cannot be directly down-scaled. Therefore, it is generally represented by simplified systems at small scales but with similar damping characteristics.

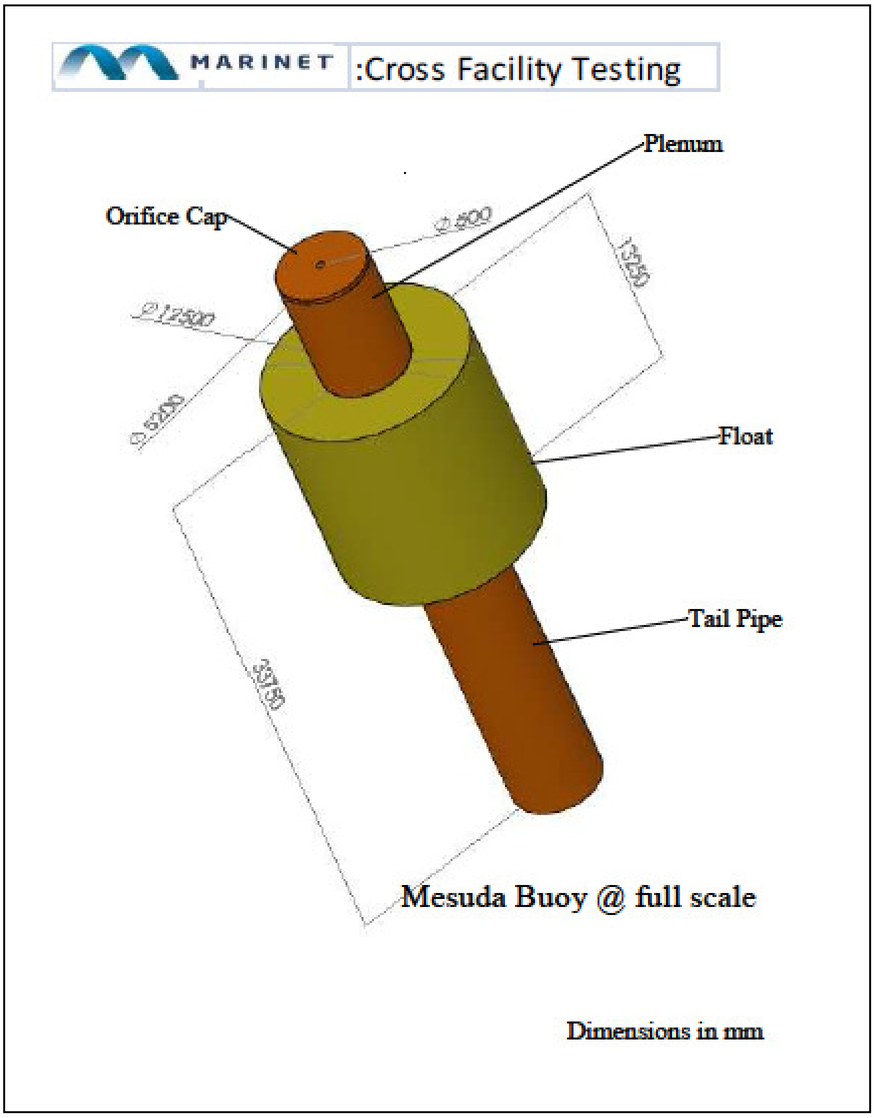

Figure 5: Solidworks, 3 dimension view of the model used for the Round Robin testing in MARINET

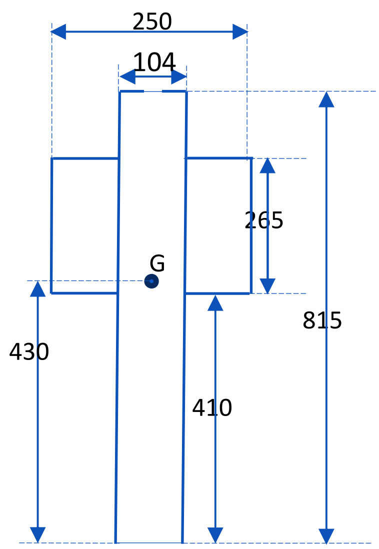

Figure 6: two dimension drawing of the model used for the Round Robin testing in MARINET

	Required		Measured 50th scale	
Parameter	Full scale	50th scale	Full scale	50th scale
Chamber height	40.75 m	815 mm	41.25 m	825 mm
Float height	13.25 m	265 mm	13.25 m	265 mm
Height of the float bottom	20.5 m	410 mm	20.5m	410 mm
Chamber internal diameter	5.2 m	104 mm	5.2m	104 mm
Chamber wall thickness	Not specified		0.15m	3 mm
Float diameter	12.5 m	250 mm	12.5 m	250 mm
Orifice diameter	0.5 m	10 mm	530	10.6 mm
Orifice Coefficient Cd	0.7	0.7	0.74	0.74
Height of the centre of gravity	21.135 m	423 mm	21.5	430 mm
Total mass	$8.1*10^5$ Tonnes	6.48 kg	811.25 Tonnes	6.49 kg
Mass of the OWC chamber	Not specified		180.75 Tonnes	1.44 kg
Mass of the float	Not specified		29.5 Tonnes	0.23 kg
Mass of the added lead weights	Not specified		601 Tonnes	4.80 kg
Moment of inertia, XX and YY	$2*10^5$ Tonnes.m^2	0.64 kg.m^2	$1.98*10^5$ Tonnes.m^2	0.63 kg.m^2
Heave period	7 s	1 s	7	1 s
Pitch period	25 s	3.5 s	23.7	3.35 s

Table 3: summary table showing the characteristics of the model used for the Round Robin testing in MARINET

4.3.1 Optimisation phase:

It is important to differentiate the optimisation phase, (first stage model testing in:(Brian Holmes 2010)), from other testing programmes. Optimisation requires specific model designs to allow large variations of each parameter that may have a significant impact on the model behaviour. At this stage, the full scale characteristics are not set and therefore, the test objective is not to reproduce a design but to build a cheap and simple model, allowing large design variations or easy modifications, which will be used to predict the optimal characteristics and be the reference for further stages of trials at similar or larger scale.
Parameters that require large changes for optimisation differ widely between projects but some examples are given below:

- Weight and weight distribution: it is good practice to build the model with a lower weight than the predicted optimal weight and include optional elements that can precisely control the total weight or be moved on the body to control the weight distribution. These weights should be placed so that they don’t significantly modify the overall geometry of the submerged sections. For example, in Table 3 it can be seen that the total model weight of 6.49 kg includes 4.808kg of lead weights that can be adjusted in location in order to allow large weight and weight distribution modifications.
- Easy change of floats with different geometries: the float materials are often light foams that can be easy and cheap to manufacture.

- Easy change of an arm length or significant model geometry. When an arm is used, it is generally designed so that its length can be adjusted. Precautions must be taken on the repeatability of the position with accurate markings or predefined holes.
- Easy adjustment of the PTO damping characteristics. A PTO should be designed so that its damping can be modified. Precautions must be taken to ensure the repeatability of damping characteristics.

At this stage, except for fixed structures, any added weight must be taken fully into account (1g at 50^{th} scale represents 125 Kg at full scale). In particular, sensors and connection cables must be of minimum weight and stiffness and included in the model design.

Structural loading on the structure in this phase is generally low and no structural design is required.

4.3.2 Optimised model

Following the optimisation phase, most of the prototype parameters are accurately known and can be used for the model design. The general model construction based on a reference design can therefore be used. This was introduced in section 2 where a number of reference parameters are defined and must be reproduced accurately at any scale using the scaling methods introduced in section 3.

Once the full set of characteristics are chosen based on the previous testing and scaling methods, the design techniques are in this case similar to the construction of any mechanical structure which does not fall into the scope of this document.

4.4 Power take off

The Power Take-Off (PTO) is designed to extract energy from the waves generating pneumatic, hydraulic, electrical or other forms of energy through one or more transformation steps. Many types of PTO systems are utilised at full scale, from direct drive linear electrical generators to multi stage energy systems. Thus the PTO must be modelled for energy dissipation at all scales of testing as it significantly affects the behaviour of the entire system. It is widely recognized that there is a general paucity of literature providing guidance for PTO simulation. ITTC, EMEC and EquiMar guidelines are occasionally used where applicable.

At small scale, stage 1 and 2 of the development protocol, building a PTO that can produce energy (electrical generator, hydraulic circuit or turbine) is generally challenging. It may be more expensive than all other costs involved and its weight or dimensions may not be suitable for the chosen scale. Therefore, it is generally replaced by an energy dissipation mechanism such as pneumatic damper, braking system or pumping system. The performance results are dictated by the accuracy of the modelled PTO. It is therefore important to use a system that is properly calibrated and reliable. In the first stage of testing, an envelope of predicted performance can be sufficient to show when a device is ready for the next stage. The accuracy of the results must however increase with the scale.
Examples of systems commonly used at stage 1 and stage 2 are shown in Figure 7 and described below:

- Pneumatic orifices (1) or porous membranes (2) representing full scale pneumatic turbines.
- Pneumatic piston (3) representing a linear PTO. This must be limited to low pressures in the piston to limit the non-linearity of the PTO. The ideal pneumatic damper has the largest acceptable diameter and low friction.
- Mechanical breaks (4), (passive or actively controlled) representing either a linear or rotational PTO
- Small electrical servomotors (5) representing a rotational PTO.
- Water pumping (6) representing systems that would pump water at pressure that allow the installation of an elevated water container.

Figure 7: PTO system at stage 1-2 from left to right: pneumatic orifices (UCC) porous membrane (UCC), pneumatic piston damper (UCC), electromagnetic break (OGURA website), Elevated tank (UCC, MARINET "Wavepump" trials), servomotors (UCC, MARINET "W2P" trials)

It is important to note that the PTO must dissipate energy, and whilst it may be tempting to consider the use of springs to create the required force on a linear PTO, this approach is not acceptable at any scale. This is because spring materials do not dissipate energy, cannot match with the full scale behaviour and do not allow estimation of energy production. A PTO testing program should also be considered, as shown in Figure 8.

At larger stages (stage 3 and more, in offshore testing) more complex PTO systems, which are similar in design to the full scale system, are commonly used which should have the functional capacity to enable validation of control strategies and power performance. This is recommended before engaging with construction of the full scale model as costs involved are generally much higher at higher TRLs. The design of the PTO either in linear or rotational motion can vary from the full scale design but the control and maximum power capabilities must be similar to the full scale PTO using Froude scaling.

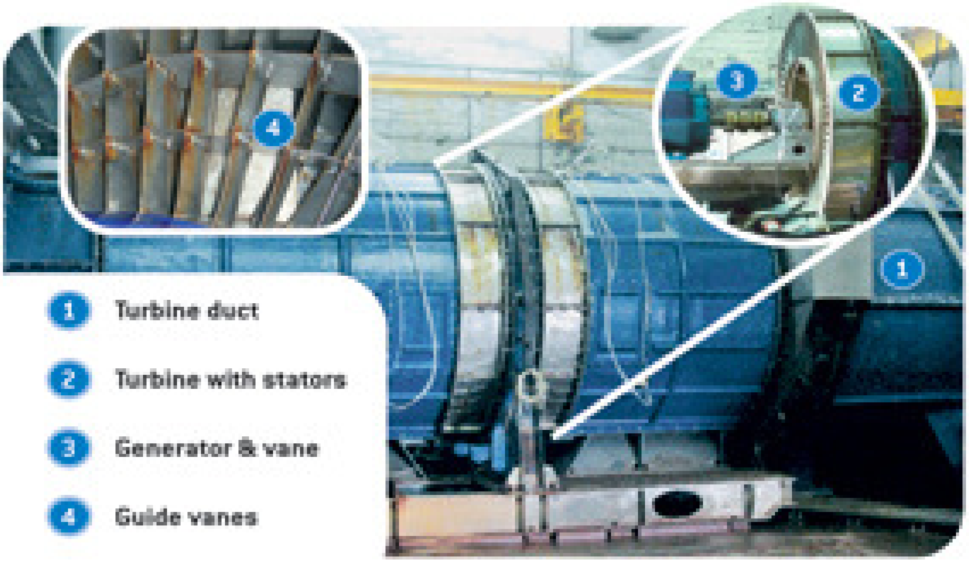

Figure 8: PTO system at Pico OWC power plant including the air turbine and electrical generator (www.pico-owc.net)

More details on PTO systems used in wave energy device testing are provided in the MARINET deliverable *D2.05, Instrumentation Best Practice*.

4.5 MATERIALS

The choice of material is also critical and varies for each testing scale, at large scales cheap and robust materials are preferred and may be built with a high level of detail, whilst for smaller scales, the lightest possible materials are used with correspondingly lower level of detail. A large number of materials are available, especially at smaller scales, and the final choice is generally economical or environmental.

Wave energy models are used in wave basins or offshore and therefore require specific materials suitable for the hydraulic environment and the forces applied to the structure. The main characteristics that are required of the materials used are:

- Waterproof: any material in contact with the water must be fully waterproof and not absorb water into its surface which can affect the weight of the model. This includes not only the surface and body of the material but also any structural connections (glue, seal, welding, etc.). Some plastics can be waterproof but difficult to glue or weld, some foams can be waterproof but absorb water on the surface, etc. The waterproof characteristics of the material need to be guaranteed for the duration of the project. Even in hydrodynamic facilities where models are used for a limited duration (typically 1 to 4 weeks) materials can be significantly affected. Some materials commonly proposed by early stage developers that should be avoided are listed below:
    - Metals: some metals, such as non-protected mild steel, can react with water in less than a week.
    - Plastics: some plastics can react with water by dissolution or water absorption.
    - Wood: various varieties of wood, wood products and timber laminates exist and nearly all require specific water protection to prevent ingress. Some types of wood can change volume and absorb very significant volumes of water in periods of less than one day.
- Strength and stiffness: it is important to ensure the material and chosen geometry will resist the load applied to the model. Unwanted deformation can affect the test results or give rise to cracks which in turn can affect the waterproofness of the model and potentially damage equipment.
- Density: this should allow the model to be constructed with a similar weight to the expected weight, using a suitable scale conversion method. Thicknesses are often not properly scaled at small scales, detailed structures are generally replaced by flat plates, and therefore lower density materials are required.

- Manufacturing process: simple manufacturing processes are preferable, as these can be more easily modified or adjusted on-site, especially for small scale testing programmes.

The choice of the materials also depends on its intended purpose in the structure (i.e., whether it is part of the main structure, a buoyant body or a ballast) and on the scale of the model. Table 4 lists the most common materials used for the key design elements at each stage of development.

Purpose	Stage 1 and 2 (scale 1:100 to 1:10)	Stage 3 and 4 (scale 1:5 to 1:1)
Structure	Stainless steel Aluminium Galvanised steel PVC Timber and ply laminates Composites (carbon or glass fibre) Light closed cell foam High density closed cell foam Concrete	Steel Reinforced concrete Composites
Buoyancy	Light closed cells foam High density closed cells foam Wood Enclosed air volumes	Enclosed air volumes
Ballast	Stainless or galvanised steel Lead Sand water	Concrete Sand Water Steel shot
Mooring lines	Leaded ropes Elastic materials Stainless or galvanised steel chains	Galvanised steel chains Synthetic rope (i.e. Dyneema) Steel wire
Anchor	Lead Bolted on the ground	Concrete Steel chain clumps

Table 4: list of materials used for each wave energy system component and development stage.

The most common materials are described in more detail in the following list:

- **Light or high density closed cells foam**: for example, high density polyurethane foam, Styrofoam sheets, Divinycell, etc. These materials are easy to shape and very light but they may absorb a small amount of water on the surface even in the case of closed cells type. They can also be damaged during handling and testing by relatively small knocks or suffer deformation when coming into contact with hard objects. To minimise these effects and cut down water ingress parts should be covered with compatible paintings or fillings. This class of materials is normally only considered suitable for light models that can be manually handled, and are the most common materials at stage 1. They can also be used in the following stages, enclosed in a protected volume, to ensure for example a minimum floating volume in case of leaks.
- **Stainless steel:** this is an excellent material for the water environment but it can be expensive or too high density for small scale floating applications. This is mainly used for small elements at larger scales or non-floating structures at smaller scales.

- **Aluminium**: this is suitable for the water environment and lighter than steel but more flexible so care must be taken when high loads are expected. It also requires specific welding equipment which may not necessarily be available at hydrodynamic facilities. Aluminium is generally used in models in stage 1 and 2 only.
- **Mild steel**: this is suitable for the water environment but corrodes quickly and therefore needs to be either galvanised of painted. It is low cost, widely available and easy to cut and weld. Its density is often too high for small scale floating devices.
- **Lead**: this is suitable for the water environment and is commonly used for ballasting on a model or on a basin floor as anchors. It is easy to work and shape but bends easily and cannot be used where loads are applied. It is also considered as a toxic material and should be avoided in offshore projects.
- **Wood**: some woods can be used in the water environment but generally require suitable preparation even for short term immersions. Plywood should generally be avoided as it can absorb large quantities of water and change volume and shape.
- **Plastics:** A large number of plastic types can be used in water (polycarbonates, polyethylene, PVC, delrin acetal, acrylic, etc.). However, all plastics have a water absorption index after 24h immersion and after saturation and some can dissolve in water.
- **Composites**: this includes carbon or glass fibre, fibre glass reinforced plastics (FRP), etc. Composites are generally low cost, have high resistance and stiffness, are light and easy to fix or reinforce. They can however prove expensive especially in the case of one-off models as individual moulds must first be constructed for each item.
- **Concrete**: has the lowest cost to weight ratio and is therefore used in applications where the weight is either needed or not an issue. It can be easily shaped but it is difficult to modify or connect to other parts of the model. It is therefore commonly used offshore for anchors or in large or heavy models.
- **Sand, gravels, and rocks**: can be used as ballast in an enclosed volume. It is however difficult to ensure accurate positioning.
- **Water**: can be used as ballast in an enclosed volume.
- **Enclosed air volumes** for buoyancy are sometimes used. This approach is effective but entails specific risks in the case of leakage or damage during handling or under wave loadings. Even small leaks can have a large impact on the model and may cause a total failure of the project. Some enclosed volumes are filled with closed cell foams, which add security but can lead to entrapped water which can significantly alter the weight of the structure and strongly influence test results.

In addition, galvanic corrosion is an electro-chemical reaction taking place when two metals are in direct contact. Two precautions should be taken to reduce the galvanic corrosion when using metallic materials in long term immersions:

- Avoid contact between two metals with different anodic indexes, the metal with the lowest galvanic index will corrode rapidly.
- Use of a zinc anode to reduce the corrosion. In this case a zinc anode, which has a very low anodic index, is placed in contact with another metallic element (of higher anodic index) and corrodes preferentially. This in turns reduces corrosion on the other component. An example of a corroded zinc anode after 3.5 years immersion on the hull of a ship is shown in Figure 9.

Figure 9: example of a corroded zinc anode on a ship hull (setsail.com)

4.6 FRICTION

Friction is a key issue in model construction because it is hard to predict in the full scale model and hard to characterise in any model. The main guideline for moving part design is to reduce the friction as much as possible with reasonable costs associated. Many smaller scale models have friction forces higher than the full scale prototype and in this case the error caused by friction reduces the expected energy production.
In the case of friction in the Power Take Off system, this friction should be measured with the damping force as it is part of the energy dissipation in the model.

For rotating parts, water resistant bearings are recommended. Past experience shows that a large number of models are built with low friction surfaces instead of bearings, which simplifies the overall design, but this generally leads to higher friction forces. Any friction surface used should be built with non-corrosive and non-absorbent materials, in particular woods and plastics with high absorption coefficients must be avoided.

4.7 INSTRUMENTATION

At all scales, instrumentation including sensors, control and acquisition systems are required on the model. The requirements vary widely with the WEC concept and the scales of testing. The use of such electronic equipment in aqueous environments brings a significant challenge for waterproofing. All equipment and cable connections require sufficient protection as they will be subject to immersion, dripping, condensation and/or high levels of humidity. The following criteria should be considered:

- Industrial equipment designed for wet environments are tested and guaranteed to a given certified protection level, or IP rating which is shown in the summary table in Figure 10. For unhoused sensors used underwater, the maximum level of protection IP 68 is required. Where immersion is occasional or when the equipment is fully sealed inside a waterproof casing, a lower IP rating can be used.
- This IP level should include the sensors and cable connection to the nearest protected area. Most of the water resistant sensors can be ordered with the desirable cable length which should be chosen to reduce unnecessary connections/extensions.
- The operating atmosphere humidity level must be suitable and protection against condensation or dripping water may be required.

- For long term offshore projects, reliable sensors or redundancy is needed as they cannot be regularly checked for calibration.
- Extra levels of waterproofing can be obtained using waterproof enclosures, resin cover, O-ring seals, etc.

A large number of sensors can be used in WEC testing, the list below presents the most commonly used sensors for the corresponding variables measured:

- Wave field: In hydrodynamic facilities, resistive wave probes are the most common. Ultrasonic sensors can also be used. They can be placed at any location in the basin. Offshore, a wave measurement buoy or a linear variable differential transducer (LVDT) is generally used. They are reliable and fully designed for the water environment. They are placed outside the WEC area and therefore have no impact on the test results.
- Model and PTO motions: In hydrodynamic facilities, most of the system motions are measured with stereo-vision systems such as Qualisys. Other equipment such as accelerometers, Inertial Measurement Unit (IMU) LVDT or potentiometers can be used in tests at all scales. The MARINET deliverable 4.09 (S. Bourdier 2015) describes the existing remote underwater motion measurement techniques.
- Pressure: a large choice of pressure sensors with all IP ratings are available and can be used to measure air or water pressures.
- Load: a large choice of load cells or load shackles for mooring lines with all IP ratings are available.
- Structure deformations: strain gauges.
- Torque: torque can be measured with the deformation of a shaft where loading is applied. Torque meters are available for most applications. The torque can also be measured at the electrical generator/motor when applicable.
- Rotational speed: proximity sensors, resolvers or optical encoders.
- Water flow: some flow meters are available in pipes, they must be chosen to avoid water flow disruption and be suitable for rapidly changing flows.
- Temperature: thermocouples
- Electrical sensors: current, voltage, etc.
- Weather station: temperature, wind speed, humidity, etc.
- GPS

First number (Protection against solid objects)	Definition	Second number (Protection against liquids)	Definition
0	No protection	0	No protection
1	Protected against solids objects over 50mm (e.g. accidental touch by hands	1	Protected against vertically falling drops of water
2	Protected against solids objects over 12mm (e.g. fingers)	2	Protected against direct sprays up to 15o from the vertical
3	Protected against solids objects over 2.5mm (e.g. tools and wires)	3	Protected against direct sprays up to 60o from the vertical
4	Protected against solids objects over 1mm (e.g. tools, wires and small wires	4	Protected against sprays from all directions - limited ingress permitted
5	Protected against dust - limited ingress (no harmful deposit)	5	Protected against low pressure jets if water from all directions - limited ingress permitted
6	Totally protected against dust	6	Protected against strong jets of water e.g. for use on shipdecks - limited ingress permitted
		7	Protected against the effects of temporary immersion between 15cm and 1m. Duration of test 30 minutes
am LABELS		8	Protected against long periods of immersion under pressure

Figure 10: Example table providing industrial IP rating descriptions (amlabels.co.uk)

In most projects, this instrumentation is sourced from industrial manufacturers, which does not allow accurate scaling for weight and dimensions. At large scale, impact on model characteristics is usually negligible but for smaller scales, in stage 1 and 2, this can have a significant impact and should be taken into account in the design phase.

Two main parameters can affect the motion of the floating body:

- The weight of the instruments used, which can affect the total weight and the weight distribution.
- The stiffness and weight of the cable connection to external station (signal and power cables). At 1:50th scale, a model can weigh a few kilograms with mooring forces of a few newtons.

In order to limit the instrumentation influence on the test results, their weight must be included in the design of the model. The instrumentation cable used should be as light and flexible as possible and held at the appropriate distance from the associated sensor. See Figure 11 for an example with two black elastic wires supporting the grey cable on the left of the picture.

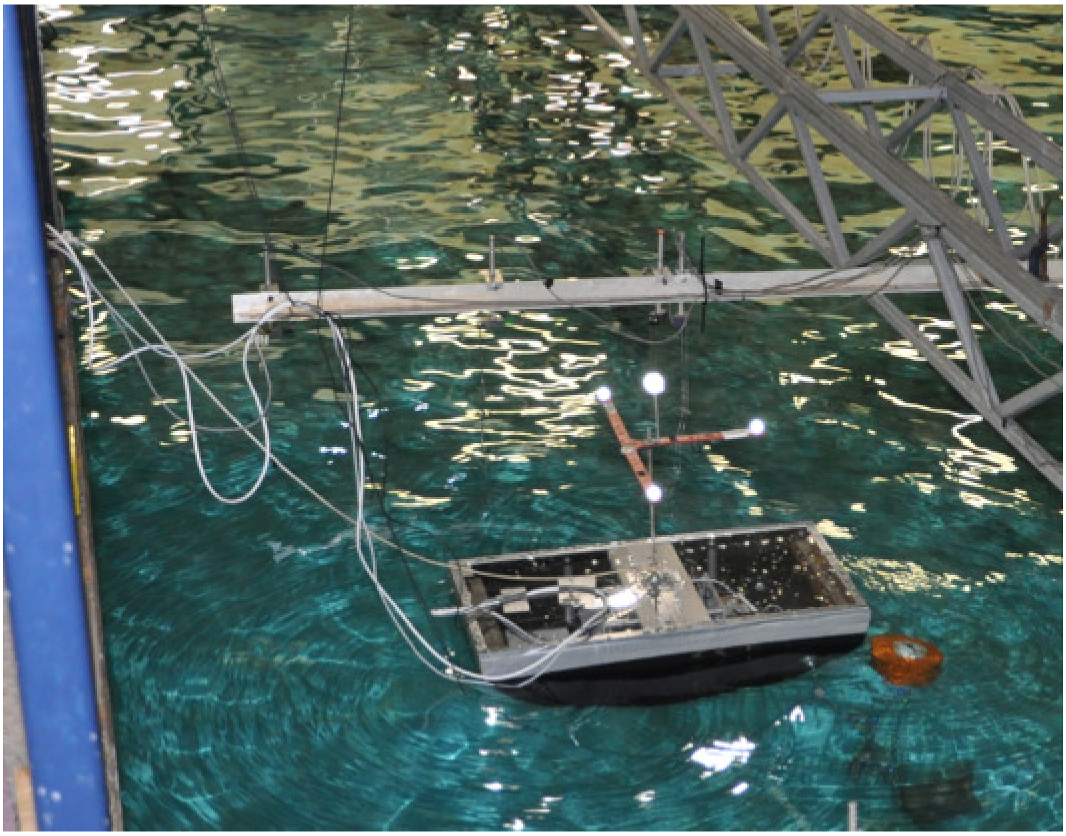

Figure 11: ISWEC MARINET testing, illustration of the sensors cable attachments.

4.8 Mooring

Mooring systems are directly connected to the WEC. Each concept is designed with its own specific mooring arrangement, which influences both the WEC and the PTO system. Therefore it is essential to properly scale the mooring system. When the water depth can be modelled in the test location at the appropriate depth, scaling techniques, with Froude or Reynolds similitudes can be used. As an example, catenary mooring lines can be modelled by simply scaling the length of the chain and its linear weight.

However, in many projects, the depth at the test location or in the wave basin is fixed and different to the optimum scaled depth of the prototype device. In this situation, the mooring should be designed so that it provides at both scales considered similar force and displacement characteristics using Froude similitude. Mooring design can be hard to accurately predict but numerical analysis techniques and a number of software solutions can be used effectively (Orcaflex, Deeplines, etc.). Catenary mooring, using heavy chain, is a typical mooring arrangement and formulas exist

to estimate the mooring characteristics in relation to its design. (L. O. Garza-Rios 1999) provides information on catenary mooring calculations.
In the first stage, moorings are sometimes modelled with aerial or underwater lines with flexible and light elements reaching the model close to its centre of gravity and in the horizontal direction so that it has minimal impact on the model behaviour.
Additional information on mooring testing is provided in (Johannig 2013).

4.9 SURVIVABILITY

Survivability is one of the most critical conditions to the success of a WEC design and an essential element of model testing projects offshore. It is however difficult to accurately predict the most extreme wave conditions and to estimate their impact on the WEC. Therefore a number of precautions need to be taken:

- Measurement of wave climate in a location close to the test site for a duration that allows prediction of extreme wave conditions for the duration of the project.
- In earlier stage basin trials, measurement of wave loadings on the mooring and some of the structural components where possible.
- Use safety factors commensurate with the level of uncertainty.
- Avoid any single point failure by ensuring sufficient redundancy of the components that are essential for the security of the WEC. At least two mooring lines should be used with one being sufficient to hold the extreme mooring loads. Double-up any critical control system or sensor when needed.
- Design a model such that it can remain autonomous for long periods, e.g. in excess of a month, without being accessed for maintenance.
- Where water leaks may be an issue, bilge pumps can be used to protect the equipment or voids can be filled with a closed cell foam material to ensure the model remains buoyant in the event of a rupture.

In basin trials, survivability is not as critical as in offshore testing. The most extreme failures can damage the model or some of the instrumentation but the financial impact is not usually a failure for the project. It is however advised, when at risk, to perform extreme condition testing at the end of the tank trials, removing the unnecessary sensors.

4.10 ENVIRONMENTAL ISSUES

Usually an Environmental Impact Assessment is required for offshore applications in order to obtain a temporary permit for sea testing. In most cases no special aspects are found critical for the environment. The main environmental aspects to be considered in the construction of a WEC are listed below:

- No toxic materials to be used
- Simple anchor mooring method ensures minimal impact on the ocean floor
- Avoiding products like oil in hydraulics, use of water as a replacement
- Recyclable materials to be used
- Use of non-polluting coatings, for prevention of leakages and discharges
- During deployment measurements of emissions of acoustic energy, electromagnetic interference (EMI)
- Marine mammals observation

4.11 SAFETY

In typical hydrodynamic testing facilities, personnel safety is the primary safety concern. Models under test must comply with the safety policy of the particular facility in question. These typically deal with:

- Weight and dimensions of the elements to be transported.
- Avoidance of toxic products.
- Procedures for installation and modification of the system in the basin.

Technical failures do not generally cause personal injuries, major costs or impacts on a third party since the trials location is confined in an indoor facility. Therefore, no certifications, insurance or technical design (such as redundancy) is required for the model. A basic mechanical design and extensive model verifications are generally sufficient.

In offshore trials however, failures can cause major impacts on the cost of the project, on the personnel and third parties safety (environmental impact, navigation, etc.). A number of certifications and insurance may therefore be required depending on the country, survivability being a critical design factor in this case.

4.12 MODEL CONSTRUCTION

Model construction methods vary widely, depending on the level of attention given to design and the level of detail provided. When sufficiently detailed drawings and specifications are provided, a model can be sent for fabrication in any suitable mechanical workshop. Difficulties are frequently encountered however due to the level of development of the device and the amount of variations required, especially in the optimisation phase. In the first and sometimes second stage of testing, a large number of modifications can be required due to unexpected results and the optimisation process. It is therefore an advantage to have access to a mechanical workshop in the laboratory where the experiment takes place.

5 SCALED MODEL VERIFICATION

Model verification is important to ensure the integrity of the model built and that its characteristics are a good match with the stated requirements. This is crucial to avoid time loss in the test location when each day of testing may cost a few thousand euros or more. The pre-testing phase is sometimes omitted, or not carried out in sufficient detail in some projects. However this is not advised given the potential to save large amounts of setup time and avoid many of the issues that are frequently encountered in both indoor, and offshore testing. This section describes the most common pre-testing procedures that can be carried out on the model, and when they are applicable.

5.1 LEAKAGE

Leaks are often underestimated, especially in small scale models, but they can significantly affect the test results due to the change of weight and still water level.

In the case of enclosed volumes, two tests are commonly used to unsure the volume is fully sealed:

- Full immersion: when the dimensions are small enough and a wave tank or basin is available. The amount of water ingress can be assessed by measuring the weight before and after immersion.
- Pressurised air: this consists of drilling a small hall in the volume and connecting a pressure tapping to pressurise the volume. Leakage can be quantified by monitoring the pressure over a time representative of the test duration.

5.2 WEIGHT AND STILL WATER LEVEL

The model weight needs to be accurately known at all scales to ensure scalability. If the weight is usually estimated in the model design, it should be measured when the final structure is built as additional weight such as welding, nuts and bolts and sensors can significantly affect the total weight.
At small scale the weight can easily be measured with weighing scales or cranes with weighing capability. At larger scale, an accurate count of each element added on the structure is required. Additionally, the final structure mass can be assessed with its water level in still water.

5.3 Centre Of Gravity (CoG)

The position of the centre of gravity in a floating structure must be measured accurately. It influences the static and dynamic stability of the body.
At small scale, this can be done by either placing the model on a thin frame (angle arm on the ground) or hanging it from a wire. In both cases, the centre of gravity will be on a vertical line from the connection point when no other forces are applied to the model in static stability, see Figure 12.

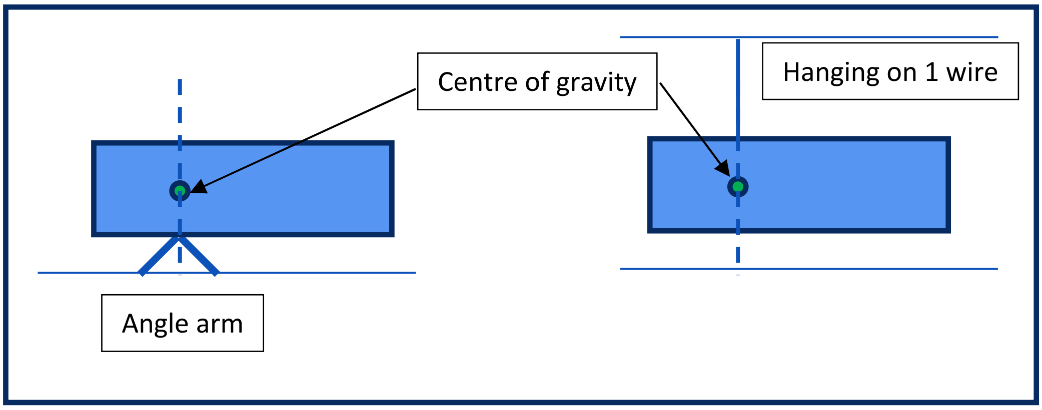

Figure 12: Illustration of the centre of gravity localisation techniques

At larger scale, an accurate count of each element added and their position on the structure is required to control the position of the centre of gravity. Additionally, the final structure can be assessed with its natural position in still water when no external force is applied.

5.4 Radius of gyration or moment of inertia

The radius of gyrations or moments of inertia is another mass characteristic that influences a floating device's dynamic stability. Its value depends on the location in the model where it is calculated and for floating devices they are by convention measured at the centre of gravity of the model. For guided bodies, they may be given at the centre of rotation of the body.

At small scale, the moment of inertia can be measured using the bifilar suspension method described in this section. At larger scale, when the bifilar method cannot be performed, the radius of gyration must be calculated from the detailed design of the structure and an accurate count of each element added and their position on the structure. The moment of inertia calculation can be done using Error! Reference source not found. **where "I" is the moment of inertia around an axis of rotation, "r" is the radius or distance from the axis of rotation and "m" is the mass of each section of the model. The total moment of inertial of the floating body is equal to the sum of the moments of inertias of all its subsections.**

The bifilar suspension method consists of hanging the device with two wires, as shown in Figure 13, and measuring the period of oscillation in its rotational motion around the vertical axis. Both wires must be placed at the same distance "d/2" (in the horizontal plane) from the model centre of gravity, hence "d" is the distance between the two wires. The length "ℓ" of the two wires must be equal and much longer than the body displacement during the tests, in other words, the wires angle to the vertical must remain within a few degrees during the test.

The test consists of creating an initially forced oscillation around the vertical axis passing through the centre of gravity and measuring its natural period of oscillation "T". As a result, the moment of inertia "I" can be calculated with Equation 4 using the mass "M" of the model and Earth's gravitational acceleration "g" = 9.81 m/s^2.

Equation 4: $$I = \frac{M*g*T^2*d^2}{16*\pi^2*l}$$

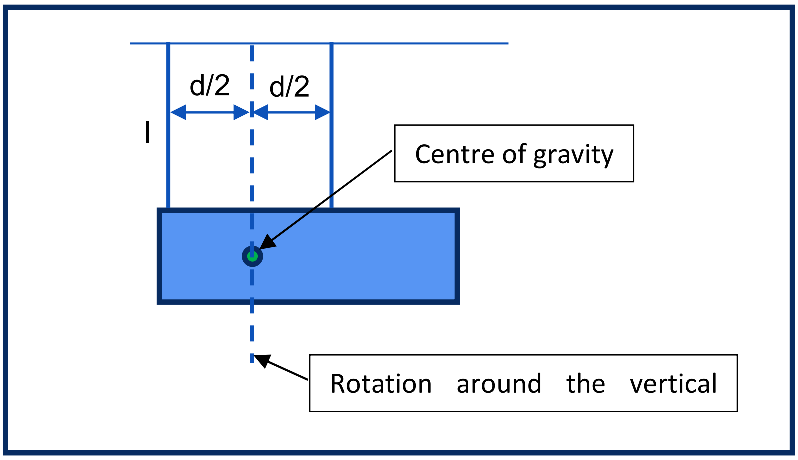

Figure 13: Illustration of the moment of inertia measurement technique

The radius of gyration "Rg" is by definition related to the moment of inertia "I" for a body of total mass "M". This relation is given in Equation 5.

Equation 5: $$I = Rg^2 * M$$

5.5 Natural periods of oscillation

The natural periods of oscillation in all the degrees of freedom when applicable are influenced by the body weight, centre of gravity, moments of inertia, model geometry and mooring line characteristics. Its measurement is therefore important prior to testing. It validates the model construction accuracy and will be used in further analysis and comparison with other physical testing or numerical modelling. When necessary, small weights may be added to correct small errors but all the parameters linked with weight and presented above in this section must be rechecked.

In small scale testing, natural periods can be measured easily and quickly with a manual excitation when the model is placed in the basin or any water volume of sufficient dimensions with still water. The periods can be measured manually using a stopwatch or using a motion capture system, which is available in most hydrodynamic facilities.
Natural periods may vary depending on the PTO and mooring lines and it is advised to measure them in all possible configurations, with and without mooring lines or with highest and lowest PTO damping achievable.

5.6 INSTRUMENTATION AND CONTROL SYSTEM

All the instrumentation for measurement and control of the WEC must be tested prior to installation at all scales. Every model (and sensors) is different so this section will not provide information on calibration and verification techniques but only general recommendations. These include:

- Sensor calibration: calibration may be done by the manufacturer but a verification of the sensor on its final location with final wiring is recommended. In hydrodynamic facilities, sensors may be used for many years and regular verification is necessary.
- Sensors test in a configuration and environment similar to the application. Some sensitive equipment may be influenced by the grid quality, electrical noise or interference on the neutral wire or earth point. It is mainly recommended for offshore applications where modifications are difficult and expensive.
- Control system integration: it is highly advisable to pre-test, especially in offshore applications, the overall system before the testing period, allowing sufficient time for modifications when required. This should be done onshore on the model, prior to deployment. It is also recommended to pre-test the equipment at an earlier stage in an indoor facility, on the model or only with the overall electrical equipment used.
- Control system algorithm: this should be fully integrated and tested before model deployment at the test location. The control algorithm should be remotely accessible and adjustable after installation.

In the CORES FP7 project for example, a quarter scale model of the OE buoy was tested. All the electrical equipment was fully integrated and tested in the UCC facilities with an electrical motor and generator simulating the mechanical power (at designed operational speeds and torques) generated by the OWC turbine and the generator that would be used on the model. It was then dismantled and integrated into the OEbuoy model, including the final version of the electrical generator and an electrical motor to re-test the system on Galway bay docks. It should be noted that for each of these two steps many issues with hardware and software programs were found and corrected, which resulted in significant cost savings relative to having to perform these modifications offshore.

5.7 PTO CHARACTERISTICS

The PTO characteristics must be accurately known as it is critical for the device power production estimation. In small scale testing in hydrodynamic facilities, most of the PTO systems used are either built in-house or supplied commercially for non-research applications and hence, information on exact characteristics is generally limited. In this case, some of the calibration techniques presented here may be recommended:

- For linear PTO or rotating PTO with a lever arm, linear motion and force can be measured during a series of tests for each damping level prior to installation. The motion can be manually actuated in the representative range of speeds and positions or, when available, using an electrically actuated linear motion test rig as shown in Figure 14. Each PTO calibrated needs to include a damping regulation system that is clearly scaled and repeatable to ensure the same conditions are applied during calibration and tank testing.
- The same techniques apply for purely rotating PTO where a torque sensor and position/speed measurement system can be used instead of the load cell and motion sensor.
- Pneumatic orifices are commonly used in OWC or other pneumatic systems to simulate a turbine at full scale. General standards exist for orifice calibration giving the relation between air flow and pressure but the orifice must be accurately built to the specifications and some differences may remain due to the pressure sensor position and shape of the OWC in comparison with the pipes used for the standards. It is therefore recommended to calibrate each orifice tested either in a purpose built pneumatic test rig such as the one shown in Figure 14 where a piston motion is accurately generated inside the enclosed cylinder. The calibration can also be achieved with other techniques, for example, placing the model in still water with manually forced oscillations and measuring both pressure and water surface elevation inside the chamber (for calibration and possibly for the entire testing period).
- Water pumping systems: several systems are designed to pump water to an elevated location. When simulated with an elevated water container, calibration is not necessary. However, an estimation of the

pressure loss inside the water circuits is necessary as it may not represent the scaled pressure loss from the full scale system.

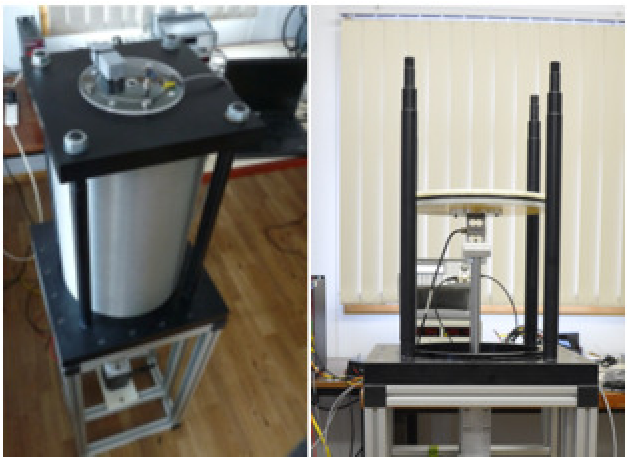

Figure 14: picture of the pneumatic orifice calibration test rig in UCC-HMRC (closed on the left and open on the right)

In offshore trials, the PTO system is typically more advanced and similar to the full scale prototype PTO, such as electrical generator, hydraulic circuit, etc. As discussed in section 5.6, ideally, the PTO system is tested in a suitable test rig (such as an electrical motor for rotating PTO) that reproduces the mechanical power generated by the waves in offshore testing.

5.8 Mooring characteristics

The most relevant mooring characteristic is the mooring force versus displacement of the WEC. For some mooring types, these can be calculated with the design characteristics but in small scale testing these characteristics can also be tested with a simple pull test. This test consist of placing the mooring lines and model in still water and pulling the model slowly in the required direction (in surge or in-line with the mooring line), whilst measuring the mooring force and displacement of the mooring point. A graphical illustration is provided in Figure 15 for an S shape mooring type. This technique does not allow the measurement of dynamic mooring forces due to water friction and mooring line inertia but this can be estimated or properly scaled in each testing campaign when of significant influence.

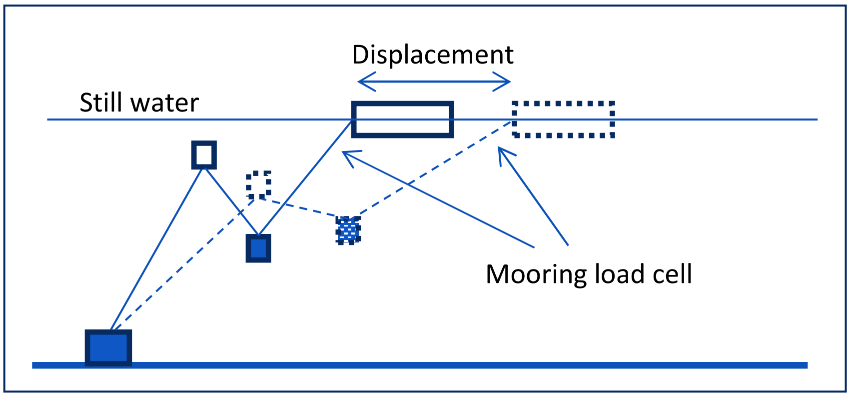

Figure 15: illustration of the mooring characteristics measurement method

6 CONCLUSIONS

This report provides a number of recommendations on the construction methods for a Wave Energy Converter (WEC) model at various stages of its development. This is intended for all developers to understand the challenges in testing WEC models and benefit from the experience of past projects.

The most common scaling method for WEC testing is using the Froude similitude explained in this document and the most appropriate scale depends mainly on the stage of development of the device, the equipment available and associated costs. When the approximate scale is chosen, the characteristics of the deployment location and/or the material cost and availability may be used to select the final modelling scale.

For the model design, at the chosen scale, a large number of parameters are presented in this report and must be taken into account. This includes the test objectives (optimisation or validation), characteristics of the materials and instrumentation available. All the design parameters must be accurately set and measured in order to ensure repeatability of the results at all scales of testing. This document also suggested a number of verification methods for the most commonly used parameters, weight and weight distribution, power take off systems, instrumentation and mooring lines.

Although the weight and weight distribution is a critical part in the design and construction of floating or underwater model in motion, this is not relevant for the modelling of fixed devices.

7 REFERENCES

Brian Holmes, Kim Nielsen. 2010. *Annexe 2, task 2.1, Guidelines for the Development & Testing of Wave Energy Systems.* International Energy Agency - Ocean Energy Systems.

Grégory S. Payne, Jamie M.S. Taylor, David Ingram. 2009. “Best practice guidelines for tank testing of wave energy.” *The journal of ocean technology.*

Johannig, L. 2013. *D2.21, Technical note: mooring testing.* Marinet.

L. O. Garza-Rios, M. M. Bernitsas, K. Nishimoto. 1999. *Catenary mooring line with non lineardrag and touchdown.* University Of Michigan.

Luís Mallen, José Cândido, Miguel Lopes. 2012. *D2.13, Collation of model construction methods.* Marinet.

Luís Mallen, José Cândido, Miguel Lopes. 2012. *Deliverable D2.13, Collation of Model Construction Methods.* Marinet.

Weber, J. n.d. “Representation of non-linear aero-thermodynamics effects during small scale physical modelling of OWC.” *seventh European Wave and Tidal Energy Conference.* Porto.