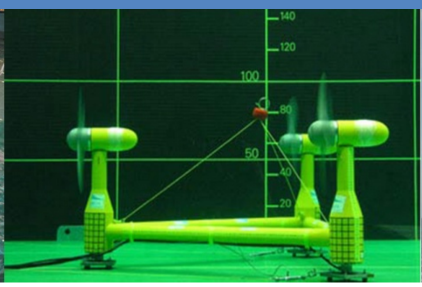
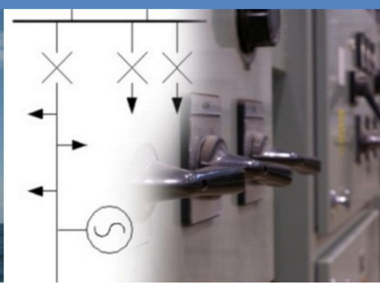
MARINET

Marine Renewables Infrastructure Network



WP2: Marine Energy System Testing - Standardisation and Best Practice

Deliverable 2.13

Collation of 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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Sustainable Energy Authority of Ireland (SEAI_OEDU)

Denmark
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LEGAL DISCLAIMER

EXECUTIVE SUMMARY

Although wave energy has not yet achieved commercial stage, a very large number of Wave Energy Converters have already been tested at several scales, either in wave flumes, tanks or in sheltered ocean areas or lakes. As a consequence, a number of methods have been developed by the institutions responsible for the test facilities and by the technology developers themselves.

Targeting the completion of a MaRINET standard on the laboratory testing of wave energy converters, this intermediate report is a collation of the testing methods being used nowadays in the industry. This compilation of procedures will allow not only the future standard structure to be developed in the right direction, but also to raise a several issues that are not considered yet in current guidelines for the laboratory testing of WEC.

Questionnaires have been filled by WEC developers and Test facilities in order to compose this report that aims to lead future construction and test of WEC devices. An overall six WEC developers (Atgaris, Perpetuwave Power, Resen Waves, Wavedragon, Wello, and Columbia power) and six Test facilities (Aalborg Universitet, WavEC/Instituto Superior Técnico, Strathclyde Univeristy, Tecnalia Research & Innovation Foundation, Queen's University Belfast, and Ecole Central de Nantes) contributed to this task.

Firstly, this report states the main methods and recommendations typically applied when designing and constructing WEC models. For this target a complete analysis of construction, buoyancy, ballasting, and anti corrosion materials is carried out. Also an exhaustive scale study is presented, including construction accuracy, specific tests scaling, forces scaling, and other different scales effects.

Criteria typically applied when designing and constructing large WEC models tested outside tank facilities are also exposed. With this objective different areas as anti fouling and marinisation, hazardous materials, certification and insurance, health and safety, transport, and environmental issues are studied

As a summary of the collation of a WEC device a number of lessons learned and solutions applied when designing and constructing are presented, going throughout the following matters: design and planning, materials, components, instrumentation, and tests.

Finally, the main factors considered when designing and manufacturing a WEC device are exposed. Those factors considered and based on developers and test facilities previous experience, have been classified due to the large amount of random factors provided. This classification evolves different themes as PTO, scale, cost, survivability, tests and instrumentation, numerical modelling, safety and integrity, and general issues.

CONTENTS

1 INTRODUCTION

The construction of physical models to represent wave energy devices needs to have full similarity and scalability between scaled model and prototype. Many of the systems are floating and this brings further requirements in ensuring true dynamic modelling for the testing. As part of the MaRINET project, reviews are being undertaken of the methods of design, construction and measurements of performance of scaled models deployed at each MaRINET laboratory facility and opportunities for harmonisation will be determined. This survey is part of that review. The eventual outcome of the review will be a Handbook on Best Practice for the true scaling of models to reduce uncertainties introduced by scale effects in research and testing.

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2 BACKGROUND TO MODEL CONSTRUCTION EXPERIENCE

2.1 TYPE OF GUIDELINES USED IN CONSTRUCTION PROCESS

The guidelines for the construction of wave energy converters (WEC) are typically founded in best practice approaches. However, much depends on the specific requirements of a particular test, the scale of the model, whether it is a flume test, tank test or sea trial, and the background of the institution performing the test, i.e., whether it is a test facility, a technology developer or a research institute.
Test facilities often resort to established literature in the field, such as [1], [2] and [3]. When applicable, the global recommendations from ITTC [4] procedures are followed when establishing criteria such as dimensions, mass and inertia.

Technology developers, often having to face very specific challenges inherent to the WEC they are developing, tend to base their guiding principles for scale model construction in broader good practices for model design. This includes resorting to the information that is available in textbooks and open literature (e.g. [5]), following standard rules applied in ships, classification society rules (e.g. DNV [6]) and applicable international standards. Typically, main structure and component sizes are maintained at scaled sizing for integrity of results. Froude scaling laws are frequently used in the case of floating models. CAD software tools are commonly employed in the accurate design of the geometry, the mass/displacement, the moments of inertia, the centre(s) of gravity, the mooring tensions and other physical parameters, in order to correctly represent the full scale device equivalents. Minor variations in mass/displacement typically occur as a result of fresh water density difference in tank testing.

2.2 TYPE OF GUIDELINES USED IN POWER TAKE-OFF SIMULATION

For smaller scale models (typically smaller than 1:15), simplified versions of the power take-off (PTO) system are frequently adopted. Normally, these may consist of damping elements (friction, pressure drop or counterforce) in the case of oscillating and rotating devices, or obstructions to water runoff in the case of overtopping devices. When considering larger scales (typically larger than 1:15), most often scaled real PTO systems similar to the ones of full-scale operating systems are used. This is also the case for small scales when simpler PTO systems are considered, such as a generator converting rotational shaft power to electricity, which scales easily from mW to MW. Moreover, some developers state that the use of scaled real PTO systems considerably improves the credibility and authenticity of the results. These developers defend that, when possible, real PTO’s, drive trains and generators should be used and actual electricity production measured.

It is widely recognized that there is a general lack of written documents that may serve as real guidelines for PTO simulation. ITTC, EMEC and EquiMar guidelines are occasionally used where applicable. The experience gained from industrial developers and past PhD works is significantly valued in this particular field.

The use of software simulation tools for results comparison purposes is of key importance. Focus should be placed on the most important parameters; particularly those associated to the fundamental dynamics, including mass/inertia, force/torque, range of motion, etc. Several real world factors with significant impact on PTO performance typically need to be addressed, in particular when considering small scales. These include static friction from bearings and/or gearing, generator cogging force, dynamic friction and backlash. Solutions to cancel these effects are typically developed on a case-by-case basis.

3 CRITERIA TYPICALLY APPLIED WHEN DESIGNING & CONSTRUCTING WEC MODELS

3.1 MATERIALS USED

3.1.1 Main construction materials

The rationale behind the choice of the main materials used in the construction of WEC scale models essentially focuses on cost and practicability issues. Some of the most commonly used materials include steel, aluminium, PVC, carbon fibre, wood, glass fibre and foam. Other typically used materials are acrylic, resin and concrete. Less common materials also used include FRP (fibreglass reinforced plastic), Divinycell (a specific type of polymer foam), GRB and ultra high molecular weight plastic (UHMW).

In terms of practicability, the choice of the materials depends, to a great extent, on its intended purpose in the structure (i.e., whether it is part of the main structure, a buoyancy material or a ballasting material) and on the scale of the model. Naturally, water resistance is a characteristic transversal to all the materials used.

When considering smaller scales, malleability, ability to be milled and ease of manufacture are important factors. Such materials as wood, PVC, acrylic, foam and resin are commonly applied in this situation.

For intermediate scales (typically inferior to 1:5), such materials as aluminium are typically used. Effectively, aluminium is light, strong, corrosion resistant, easily machined and cost effective for the low volumes needed for scaled prototypes. It may be safely applied in the construction of small-scale models up to 1:5 as the maximum environmental forces for units with this size are considerably lower than in the case of larger units.

For larger scales, there are substantial consistent fatigue loads (every 10s or the wave length) placed on the WEC model. As a consequence, in these circumstances, steel is typically the most commonly used material, since it is much stronger with cyclical fatigue in operation than aluminium. Furthermore, it is a material easy to weld and widely used in naval construction. Reinforced concrete is often used in the construction of full-scale devices, mainly due to its price and durability.

The utilization of other less common materials is justified by similar argumentation. FRP, for instance, is cost effective, representing a flexible means of quick construction, with no corrosion and easily adaptable. UHMW, in turn, has similar density to water, rendering it ideal for design variations. Furthermore, it also is cost effective and easily machined.

3.1.2 Buoyancy materials

Different choices can be done by developers and test facilities when selecting buoyancy materials. The main options recommended for WEC construction buoyancy related are listed below:

- Foam. May be difficult to shape depending on the type of material used.
- Wood. It has a low cost and a high availability.
- Divinycell. There are reports of successful experience using this material.
- Air. It creates a buoyancy chamber. Cavities can be done enclosed by aluminium or PVC.
- Steel. It can be sheeted Styrofoam, sealed as used in industrial freezers, which it has a lightweight and also is quite strong and has positive buoyancy. Other option is make an enclosed steel hull when the device is elongated and floating, combined with 2-6 pounds per square foot closed cell foam, eliminating voids that could inadvertently be filled with water. It adds structural rigidity to WEC structure and does not absorb water.

3.1.3 Ballasting materials

There are different types of ballasting materials used in WEC devices. Both developers and test facilities, agree in the reasons when selecting these ballasts: availability, cost, density and convenience. Below these lines the main Ballasting materials used are listed:

- Metal plates, steel or lead. They are very dense for the cost, and allow precise placement at extreme positions. Readily available and easy to form into desire shape. Good for scale models.
- Sand (difficult to obtain a constant shape)
- Water (difficult to maintain shape)
- Concrete. Can be located at both ends of device´s hull helping to increase inertia at maximum.

3.1.4 Anti-corrosion measures

Anti-corrosion measures are adopted when the device is planned to be in the water for a long term. It is not a significant issue for short term model testing, whether the test is undertook in a tank or in the open sea.

The main practices for anti-corrosion measures are listed below:

- Maintenance of the materials (done after each set of trials).
- Maritime class paint (depending of immersion) and special non-toxic paint for originally for tubes of turbines. It is essential to obtain the best possible surface preparation, quality paint, 3 topcoats, and attention to detail in the painting process.
- Hot dip galvanizing for carbon steel and anodizing for aluminium preserves construction materials from rust.
- Special antifouling coating (epoxy based).
- Proper material selection; coatings, lubricants, and sacrificial anodes. FRP (Fiberglass reinforced plastic) is particularly well suited to avoid corrosion at a low cost.
- Proper material, coatings, or lubricants must be specified. Cathodic protection using sacrificial anodes is a valuable tool in combating corrosion. Avoid placing dissimilar metals in contact with one another in a marine environment; plastic spacers are a good idea.

3.2 SCALING CRITERIA

3.2.1 Scale construction accuracy

A common practice when building a model is the use of Froude scaling law, although this has to consider the impact of all the fluid dynamic parameters. Froude scaling law warranties a hydrodynamic behaviour of the model similar to the prototype regarding the most important forces at stake in a WEC: gravity and inertial forces. The use of the Froude scaling law implies an accurate construction of the complete geometry. If a large-scale device is needed the model is constructed to represent that device as accurately as possible with all its details.

On the other hand, basic or generic model designs are used only for research purpose, and not industrial developments. The main purposes for research are production or survivability tests; also generic devices are often tested with the aim of validating numerical models. Simplification of the device therefore enables more efficient numerical modelling, and cost effectiveness in introducing the changes intended to be done in the model.

However models are typically constructed as accurately as possible to scale, a number of changes even at late stage prototypes are often introduced, reducing the accuracy to be closer to the basic idealised construction. (The R& D pathway to commercialisation can be difficult to predict.).

Power take-off has to be part of all scale testing, as its effect cannot be calculated afterwards. The integration of the PTO scaled version or a PTO simulator increases the value of the scale testing and makes it realistic. Providers claim that models built with real power take-off are not realistic.

Therefore, with all the information exposed above, an accurate model can provide the confidence required to take the WEC design to the next stage. Data from scaled testing is used for numerical model validation and engineering design efforts. With an accurately scaled device, this data can then be referred to at any time in the future with a high level of confidence. With the high cost of wave tank test time and engineering it may not make sense to test with a less accurate model.

3.2.2 Scales used in specific tests

A number of specific tests are made in order to test properly the device prior to be fully deployed in the sea. Testing conditions (as well as the scale of the model) are restricted by the laboratory possibilities in terms of size and maximum possible wave height. All the specific tests undertook by developers and test facilities with their scales are listed 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. Small scale PTO’s 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. Phased development facilitated taking design decisions (stage-gate approach), 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 Froude scale well. Some developers have built a programmable mooring controller (PMC) that allows to precisely defining the load deflection curve, mooring spring rate, damping, and/or inertia for each mooring leg. Typically scale goes from 1:8 to 1:20.

3.2.3 Balancing different forces at model scale

The fact that the Froude Scaling is used as the main criteria causes other forces to be misrepresented in the model as compared to the prototype.

It is important to understand the forces that may have a significant role for each model being tested. Some types of devices may imply certain forces to be very significant at in prototype, model scale or in both cases.

Viscous and surface tension:
In the case of devices in which the viscous and surface tension effects are a significant part of the system dynamics (for example in overtopping devices), the effect of these forces is larger at model scale. These effects are difficult to control except by using the larger scale possible

Calibration of viscous effects can be done by comparing the experimental results to hydrodynamic numerical models. This can be done in a number of ways, and even include a representation of the non-linear effects of the model. However, since the Reynolds number is not well represented when the Froude scaling is used, there is always distortion of the viscous effects when testing a scaled model.

Friction

Friction is very relevant in some systems, and in scaled models the friction effect can become very large if it is not dealt with in detail. Calibration of friction sources is essential to have a notion of its magnitude as compared to other forces in the system.

Wave and Impact forces

The wave forces are well represented through Froude scaling a little beyond the linear wave theory.

Impact forces tend to be not well represented - magnitude is larger and duration is shorter - but it can be argued that the representation of the impulse is reasonable in most cases as effects partially cancel.

Pressure and compressibility

The representation of air pressure and compressibility is not well achieved through Froude scaling. This is particularly relevant when testing Oscillating Water Column (OWC) devices. While the misrepresentation can be compensated through increasing the volume of the chamber in fixed OWCs, this is troublesome to apply in practice. In floating OWC devices it becomes almost impossible to compensate for the scaling distortion.

3.3 Handling different effects at model scale

3.3.1 Viscosity, surface tension, friction and compressibility

It is not an easy task to handle the viscous and surface tension effects in model scale, not only because they are difficult to measure but also because viscous numerical modelling of wave-body interactions is still not reliable. Also, in the case of non-standard shapes, it is difficult to understand the effect of the distortion of the Reynolds number.

In some in-depth studies, when the viscous effects on the model are better described, it is also an option to change of some dimensions or roughness of the material to compensate for the distortion of the Reynolds number. Another option is to use CFD models to calculate the effects, but coupled wave-body interaction models are still of very limited use due to its complexity and computational requirements efforts.

Friction:

When possible, friction sources should be calibrated prior to the tank testing for the range of velocities applied in practice. This way the force magnitude can be compared to friction that occurs at prototype scale and to the magnitude of other forces at stake. This is then repeated after testing is complete to verify that the system did not change during testing. If friction must be zeroed in a PTO simulation, in some cases active feedback control can be used to motor the PTO thus cancelling frictional forces.

At larger scales (e.g. 1:4) the friction can normally be handled in the same manner as in the prototypes, as similar parts can be used.

At smaller scales (lower than 1:10) usually both the velocities and forces on moving parts are much different from the full-scale application, and as a consequence specific apparatus have to be designed. Several applications were reported, including grease, Teflon.

Good description of bearings characteristics is needed, and it should be noted that the contact with water might change these characteristics. It is advised to use of high quality bearings or water lubricated PTFE bushes.

Compressibility:

Distortion of the compressibility of OWC chambers can be tackled using larger air chambers at model scale. However, the distortion is only significant for some OWC systems. If the compressibility effects are small at prototype scale, its distortion will not have a significant impact.

3.3.2 Verification of the hydrodynamic characteristics

A number of tests can be done on the wave energy scaled models in order to evaluate the hydrodynamic characteristics prior the test programme. These tests include free decay tests, forced oscillation and tests with a static model and waves.

Forced oscillation tests can be used to evaluate the forces associated with each oscillation mode. This is especially useful in order to verify the radiation coefficients of the tested model, which are given by the hydrodynamic models, and to evaluate the impact of non-negligible amplitudes of motion in these coefficients. These tests can also include measurements of the mooring forces in order to verify the quasi-static models used to design them.

Tests with a static model can be done to evaluate the excitation force as a function of the incident waves. This is done to verify the excitation force coefficients (amplitude and phase).

Free decay tests can be done in a wave tank to determine virtual mass properties and to characterize model dynamics. Decay tests without mooring can be useful to determine the drag load.

3.3.3 Static and Dynamic behaviour affected by mass distribution

Mass distribution affects the moments of inertia of the bodies. In numerical simulations values can be sweep through moment of inertia to find optimum performance points or areas of greater survivability. Mass distribution is then used to achieve these desired inertial values in test devices, in order to optimize the production in relation to a specific. With scaled models, it is not always possible to achieve the ideal centre of gravity and moment of inertia, but the impact of the distortion should always be well understood.

To identify the typical static and dynamic behaviour affected by mass distribution, different techniques can be used. Find a list below these lines of the main techniques recommended by developers and test facilities:

- Water in a separate drum, and steel weights to simulate mass distribution and to obtain the correct dynamics without much change in volume locations are normally performed previously in SolidWorks so that the adjustment needed in situ is very small.
- Ballast tanks in the hull sections for the platform to sit at the correct operating height, as will be used in the commercial design.
- Working on low weight structures and try to minimize mass and inertia, in order to have a larger margin for adjusting the properties when the model is already more developed.
- Mass distribution built quite exactly as in full scale (effectiveness depends on the mass and inertia introduced by the instrumentation).

3.3.4 Methods to simulate the PTO on the model

The design of the PTO simulator is one of the most important challenges in the design of a WEC small-scale model. These difficulties are aggravated when the specified PTO damping characteristic is non-linear and different characteristic curves are to be tested. For small-scale models, the extracted energy is more conveniently converted to internal energy, as the extracted power scales down with the power 3.5 of the geometric scale.

Several solutions for the simulation of the PTO system have been proposed and tested by different research groups. Methods for simulating the PTO system in a WEC model can be divided in four categories:

- Throttling processes (e.g. porous membrane, orifice plate). In order to simulate PTO systems with simplicity, some developers have recently started to use commercial dampers, which avoid in-house design and calibration of the PTO simulation.
- Eddy current brakes. This method is a well-known application of induced magnetic fields. Electromagnetic methods give the best accuracy and controllability; it also allows making quick changes to the PTO control plan. This method is more expensive and is control/data intensive.
- Pumping water to an upper reservoir.
- Small electrical generators. This solution is not efficient at small scale.

As a final comment note that developers and test facilities do not yet agree whether to test separately the PTO from the device or test the integrated design.

3.3.5 Types of sensors used

Different sensors can be used depending on the application, cost, precision, and the type of measurement. It is highly recommended to instrument and collect as much data as possible to provide a complete historical record for any given test, and then be able to compare and validate the results with the numerical model. The main instruments used by developers and test facilities are listed below:

- Load cells. Ideal to measure forces;
- Strain gauges directly on a structure (submersible when applicable). Can be used to measure loads on the mooring lines;

- Incremental shaft encoders. Also linear, rotary and optical are used;
- Pressure transducers;
- Magnetic displacement sensors;
- Photogrammetric;
- Video;
- Ultrasound;
- Contactless infrared cameras;
- Inertial measurement unit (IMU);
- Flow meters;
- Wave probes. To measure the wave heights different sensors are commonly used: resistance, capacitance, and ultrasonic probes;
- Optical motion capture. Ideal for multi-body displacements, it can be aerial or underwater;
- LVDT;
- Current Transducers;
- Anemometer;
- Thermocouples;
- Potentiometers;
- Laser distance meter;

3.3.6 Position of the sensors

Sensors are typically located where they are needed, which is as close to the point of motion or location of maximum stress and strain as possible in order to minimize the error. The sensors should be integrated in the model design, and depending on the type of model, instruments will be placed under water if necessary and some others sensors above water.

If the model is entirely submerged, all sensors deployed to quantify the movement of the device should be under the water line as well, unless they are not waterproof and then their location in direct contact with the water will be typically avoided and another placement will be identified. When placement is an option is preferred to enclose everything in a watertight enclosure or encased in resin because of friction, risk of flooding and cost.

Wave probes in tank facilities should be positioned a) in the direction of the wave propagation, a few meters before the device, if they are meant to characterize the incident sea state or b) perpendicular to the wave propagation, sufficiently far from the device to avoid the effect of radiated waves, when used to synchronize the incident waves with the measured parameters of the device. Also a three or four probe array configuration is highly recommended in order to allow the analysis of incident and reflected waves of every test.

Instruments for structural measures including hull pressure and slamming effect can be placed below the water and for hull strain tests the instruments can be placed inside.

All PTO related parameters are placed inside the hull since all moving elements are enclosed within.

3.3.7 Waterproofing instruments

Generally the best practice to waterproof instruments is to purchase certified waterproof instrumentation by the construction manufacture wherever possible. Sometimes instruments are waterproofed by technical personnel with resins and silicones over the electric connections but then they are not considered submergible, only slash resistant.

Other options recommended by providers and test facilities to waterproof the instruments are listed below:

- Molded in rubber or 2 component elastomers
- Watertight box with a dry connection to the outside
- Encased devices in resin or potted them. If potting is an option it is preferred, however it makes repairs nearly impossible.
- O-rings
- Magic sealant gel (Raytech)

3.3.8 Data acquisition types for the sensors

Different data acquisition systems are used by developers and test facilities based on acquisition rates, number of channels and functions. As much as possible data collection should strive to be done with a single system. This ensures proper time synchronization of all data channels. This is not practical when several systems are used, in this case it is important to use a common global trigger that all systems recognize and record allowing proper synchronization in post processing.

Following these lines the main data acquisition systems are listed below:

- CANOpen. This based network system can connect sensors throughout, including actuators and wave gauges.
- Microcontroller DSPIC boards from Mickoelectronica. This system can be used for all the acquisition and control tasks. The board can perform data acquisition and control the model at the same time (information is bidirectional); is a standalone board and its functions are programmable case by case, so much more flexibility is obtained.
- Compact Field Point (CFP) from National Instruments. This data logger is used as data acquisition platform. CFP speeds up the development of the data acquisition and control system and it has an affordable cost. This card can be easily connected into either a LabVIEW or WaveLab interface.

3.3.9 Mooring design

Mooring is an essential part of model testing and is recommended to be scaled as close as possible to the prototype. Moorings have been being designed separately from the model, since there the integration in wave to wire models is still limited.

Recommendations and comments made by developers and test facilities regarding mooring design are listed below:

- The mooring design can be done subsequently to the design of the PTO and floating platform design that dictates the mooring design to be used. However, in the case of devices whose displacements are significant, the mooring design should be coupled to the hydrodynamic design. The scaled model tests should measure maximum force on the main forward mooring lines and provide feedback to future designs.
- Moorings can be designed to accurately represent Froude scaled load displacement curves over the region of operation. However it is not straightforward, it is possible to scale the line flexibility and maintaining the Froude similarity. This can be done using materials at the model scale with the appropriate elasticity, adding elastic spring elements to the mooring set-up or introducing feedback motors to simulate the mooring flexibility characteristics. With the development of a programmable mooring controller (PMC), variations could be made in order to vary mooring characteristics and determine their affect on performance. This will allow to optimize some mooring specifications experimentally.

- It takes a lot of effort to test various components and develop and scaled mooring design in hardware. Additionally, elastic spring elements used in model testing have shown degradation and water absorption resulting in inconsistent responses.
- Simplifications are primarily checked by dedicated software (OrcaFlex, DeepLines,...)
- Aerial mooring lines are often used to test basic designs
- Depth scaling can be a problem with respect to a constant water depth in the tank. As a consequence, and following some procedures already used in the offshore Oil and Gas sector, truncating mooring lines is a useful methodology to be developed in the future.

Finally, as a best practice technique some developers recommend the following steps when designing moorings:

1. Initial quasi-static analysis to select mooring configuration.

2. Dynamic analysis to design the best configuration.

3. Wave tank models to test survivability.

4. All data obtained should be compared to numerical models to adjust and optimize designs.

4 CRITERIA TYPICALLY APPLIED WHEN DESIGNING & CONSTRUCTING LARGE WEC MODELS TESTED OUTSIDE OF TANK

4.1 USE OF ANTI-FOULING AND MARINISATION

Based on developers with previous experience in naval construction, the use of special antifouling coatings, as epoxy, is recommended, combined with the use of naval quality steel (Grade A). On the other hand, there are many developers that assure that the use of an antifouling is not necessary, preferring a mechanical remove by pressurized water. This is a problem that has to be addressed at prototype scale, and as a consequence developers should be a concern in large-scale tests.

Another option is to fully marinise the devices when it is based on an Oil and Gas platform design, as a best practice and extensively proven in the offshore marine environment.

Other technique employed is the double enclosure approach. The hull structure of the device is designed to be waterproof and has redundant bilge pumps for dewatering in the event that a leak should occur. Bilge operation notifies personnel. All electrical systems are then contained in an additional watertight enclosure. Desiccant may be used in enclosures to reduce moisture levels.

4.2 HAZARDOUS MATERIALS

As a best practice and in a commercial and environmental reality, toxic materials do not have a place in the ocean. Also there are policies to regulate or forbid the use of hazardous materials. For these reasons no hazardous materials should be used in WECs to be far too risky for the environmental preserve.

Only a minor part of the developers consider this topic non-relevant if the hazardous materials are fully enclosed in the hull to prevent leakages.

4.3 CERTIFICATION AND INSURANCE

As there are no exist any substantial risks in testing on small scale and short-term sea trials (<1 year) if no toxic materials are used, all providers agree that certification and insurance is not required.

As a good practice, is recommended to insure the device in the design stage when it is tested in full scale to prevent massive recovery costs if a huge wave event where to occur.

4.4 HEALTH AND SAFETY

Safety and Health considerations depend on the shape and the size of the device. As many developers deploy WECs in platforms, they recommend a floating platform design with considerable reserve buoyancy in the legs, and integral buoyancy in the PTO floats. Also, the use of safety railings placed around operating equipment, a firm non-slip deck, and an anti-fire CO2 extinguisher is highly recommended.

Another option recommended is a redundant bilge pumps with status alarms warned of potential hull damage or excess flooding, and a 12 nautical mile navigational beacon and dual radar reflectors to alert boat traffic of the WEC's location.

If health and insurance considerations are included in the basic design of the construction; hence no special precaution is needed.

For those who are testing small devices, consider that health and safety issues will be adopted as the system grow in size.

4.5 TRANSPORT

The scaled units of many developers built to date have not been made wider than permitted on the roads that allow the transport on a truck. Developers occasionally build a purpose trailer to transport scaled units and offloading and loading is done back on at a boat ramp near to the test site.

Due to the size and weight of the WEC devices most of them are transport by truck using a boat trailer and are assembled on the spot, also large 200-300 tones cranes to bring the device into the water after assembly are used. In all cases road transport is made from workshop to the closest port to deployment site. Lifting locations and resulting loads need to be considered during the design process.

4.6 ENVIRONMENTAL ISSUES

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

- No toxic materials used
- Simple anchor mooring method ensures minimal impact on the ocean floor
- Avoiding products like oil in hydraulics water replacement
- Recyclable materials used
- Non-polluting coatings, prevented leakages and discharges
- During deployment measurements of acoustic generation and electromagnetic interference (EMI)
- Marine mammals observation

5 LESSONS LEARNED AND SOLUTIONS APPLIED

All the recommendations presented by developers and test facilities as a result of their own experience can be classified into five main topics; Design and Planning, Materials, Components, Instrumentation, and Tests. In the next sections of the chapter lesson and solutions are described by main topics.

5.1 DESIGN AND PLANNING

Following these lines the main issues regarding Design and Planning are listed below:

- Developments in the ocean environment require considerable forward planning and managing of risks for a successful outcome. A WEC must not have large areas of structure exposed to direct wave impact, as the loading incurred on these designs has resulted in a number of high profile failures that consistently tarnish the industry.
- As survivability is paramount, a good design philosophy is to avoid catastrophic loss from any single point failure.
- Designing systems that provide layers of protection should ensure the system remains survivable even after failures.
- Models have been designed so that they can account for as many different general (yaw angle relative to wave makers, hinge height above tank floor) and PTO (brakes, cylinders) configurations as possible.

5.2 MATERIALS

Different issues are encountered regarding materials that compound the WEC device. Following these lines these main issues are listed below:

- Coatings are still a problem if models are in water for extended periods (e.g. more than 2 weeks).
- Avoid use of wood where possible.
- Waterproofing will be an ever-present threat to WEC systems with risk increasing with age. Use only certified waterproof materials and understand/expect that even they may fail.
- Initially, many models were constructed from welded steel or PVC. Recently models have been constructed using mechanical fasteners (screws) rather than welds so that they may be easily disassembled and re-configured.

5.3 COMPONENTS

Following these lines recommendations regarding device components are listed below:

- Including a complete drive train and generator on a large scaled model incurs little expense but provides highly accurate results that can safely be used for projections without fear they will be over exaggerated as has been the case.
- Connectors are prone to fail in marine environments; if possible, hard-wired connections are more robust.
- Second generation anchors are far superior to the older style designs and should be included as a standard guideline.
- Use of 4-axis CNC machining for complex components geometry is huge benefit.

5.4 INSTRUMENTATION

Different measurements using several methods have been carried out by developers and Test Facilities. The main issues and recommendations are listed below these lines:

- Calibration of all sensors used during tests is critical. The data is only as good and the sensors current calibration.
- Resistance based wave probes can provide a measurement of the model's immersion. In overtopping systems this enables statistical quantification of overtopping over the duration of a particular test as well as a time trace of the immersed volume (which may be used to quantify the instantaneous hydrostatic load).
- Measurements of the torque applied by the PTO is achieved using transducers (built in-house) based on strain gauges measuring the torsional strain on a thin walled steel tube. Minimization of the signal to noise ratio can be achieved by incorporating micro-amplifiers in the transducers. The signal is therefore amplified inside the tank so that contaminants that may be introduced over the cables transmitting the signal to the DAQ are not themselves amplified.
- Rotation tests were initially measured using potentiometers. However difficulty in water proofing these sensors lead to the use of induction based sensors (Gill sensors). Concern regarding the accuracy of their measurements has lead to a recent move towards the use of optical encoders that are extremely accurate and are contained in self-contained units with IP68 protection.

5.5 TESTS

Measurements in the model stage are crucial in order to achieve all the targets desired in the final design of the device. Following these lines the main aspects are listed below:

- It is beneficial to thoroughly test as much of the hardware as possible prior to final installation. This includes: data collection, control systems, waterproofing, PTO, bilge pumps, sensors, energy storage, power electronics and communications.
- Ensure developers know requirements for data on mass properties during tests (and can provide realistic values)
- As testing durations lengthen systems invariably reveal weaknesses.
- If a system is critical for operation redundancy should be considered.

6 MAIN FACTORS CONSIDERED WHEN DESIGNING AND MANUFACTURING A SCALED WEC.

Developers and test facilities based on their experience and expertise provided the key factors to take an account when designing and manufacturing scaled WEC's. Below these lines all these factors are presented divided by main topics as: PTO, Scale, Cost, Survivability, Tests and Instrumentation, Numerical Modelling, Safety and Integrity, and General Issues.

6.1 PTO

All the comments provided related to PTO main factors are listed below these lines:

- **Performance & Design of the PTO**. Performance is a critical first step to identifying a WEC design that can potentially be a game changer for the industry. A history of exaggerated results of previous WEC appears to have done nothing to inform the markets and has not resulted in succession of development or learning for most WEC developers. The key traits of abstract designs, with minimal "marinisation" still appear to hold favour. Simplicity is also a key value, but not to the detriment of performance as without significant electricity production there will not be a positive commercial outcome.

  There is also the history of failed or poor performing air turbine projects that include the Mighty Whale and the Limpet project to name a few of the earlier ones where there is some transparency on the electricity performance results of these units, which indicate that they have at the very least, missed the performance expectation by a considerable margin. It can also be considered that wave energy is a complex low level energy source and it will only be commercially viable via a high-density energy extraction system.

  It is interesting to note New Generation technologies including a rubber-based design in a recent report. The rational that rubber is a material that is more suited to the ocean environment is correct but this not consider that as far as any production is concerned that rubber surely will not be commercially viable due to the physical expanding properties of it and how these are different to the requirements of an efficient drive train system.

- **Make small scale testing with real PTO from day one.**

- **PTO simulator.** Design of the PTO simulation is the biggest challenge for obtaining satisfactory results.

- **Check repeatability carefully in setting parameters (e.g. PTO damping).**

- **Dry tests of PTO in workshop prior to assembly into prototype**. PTO malfunction or failure could severely delay sea trials' program since maintenance at sea was limited.

- **Simulation of PTO**. Accommodation of multiple PTO mechanisms and configurations if necessary.

- **Scaling or not of the PTO**. Complexity of the scaled PTO, needs of specific developments for control (dynamic accuracy of the scaled PTO) constraints about powering, leaks, weight and inertia of the system.

6.2 SCALE

Scale influences directly the whole test program, materials to be used, facilities etc., and it has a big effect in costs. Below these lines are presented the main issues regarding the Scale topic:

- **Choose scale most appropriate for test goal and facilities**. Development may require several models at different scales.

- **Device similarity**. The purpose of a scaled WEC is to understand the full-scale system in operation. Therefore, every effort should be made to create an accurate scaled device.

- **Influence of scale effects**. Ensure model is large enough that scale effects (e.g. surface tension effects) are negligible – influences lower bound of model's size.

- **Replication of device geometry**. Ensure model is large enough that all significant geometric effects (which may be identified by numerical analysis) may be replicated without significant difficulty.

6.3 COST

In many cases it is assumed that the cost comes in near last place, as if the other key determinates are all accomplished, then the cost of electricity will be lower than any other design. Following these lines are listed the main cost issues:

- **Funding.** Available conditions in the model design;

- **Avoid cheap components, small extra cost get a much more reliable**. Replacement in open sea is expensive and complicated.

- **Reducing cost as much as possible**. Off-the-shelf components & design simplification of scaled device.

- **Cost effective**. Materials, components, test facilities, and operation often have to fit within tight budgets. Cost overruns are common with one-off prototypes.

- **Final Cost**. Possibility re-use of the model in future (improvement).

6.4 SURVIVABILITY

The main issues reported regarding survivability are listed below:

- **Extreme seas**. If possible any scaled WEC should be subjected to appropriate extreme (i.e. 100 year) sea conditions to develop and understanding of how the WEC and mooring react in these conditions.

- **Marinisation**. Survivability is paramount to the future of a WEC technology. Having a technology "marinised" is significant in the conceptual development path and abstract designs that are not marinised might be expected to suffer survivability issues, and there is considerable evidence of failures of previous abstract devices that have had little marinisation.

- **Contingency planning**. Consider all contingencies and design a system that can avoid catastrophe from single point failure. Having plans to deal with unexpected operation, performance, or failure. This may include design alternatives, redundancy, spare parts, etc.

- **Avoid all complex procedures in open sea**. Replacement in open sea is expensive and complicated.

- **Mooring**. Mooring is a significant component of a scaled WEC. Mooring design may be integral to WEC performance and survivability. Scaled mooring components may be relatively inexpensive but their implications towards full scale can have a significant cost. Having real world expectations for scaled mooring systems and understanding possible influences with full-scale constraints is necessary.

6.5 Tests and Instrumentation

All the main factors recommended about Tests and Instrumentation are listed below:

- **Testing location**. Understanding the capabilities and limitations of the given test location will help prepare for testing. Having a well-prepared test plan in advance will ensure that the hardware is fully capable.

- **Type of tests to be carried out**. Simulation and measurement of PTO load is of primary importance in performance tests while in extreme sea tests the device's kinematic response and foundation/mooring loads are most significant.

- **Knowledge of the wave tanks characteristics.** Most wave tanks have their own specificities that should be understood in order to obtain waves with satisfactory quality.

- **Capability of facility**. Size of waves (wavelength and wave height) that may be generated influences scale at which model is built (influences upper bound of model's size).

- **Dimensions of prototype**. Radiation – diffraction effects in the width of the tank, Cost of the model, Structural stiffness / Ability to handle it safely (for the model).

- **Data acquisition and electronics.** Systems for data acquisition and their electronics have to be adequately prepared in advance in order to obtain good results.

- **Equipment.** Do not use unnecessary equipment to keep things simple and costs down.

- **Calibration**. Data is only as good as calibration. Sensors should be calibrated with the same data capture hardware used in deployment before and after any testing.

- **Measurement of model's response**. Ensure dynamic and kinematic response of device provides signals large enough to be measured by available sensors. Incorporate micro-amplifiers if necessary.

6.6 Numerical Modelling

Following these lines all the numerical modelling main factors are listed below:

- **Start simple and improve the mathematical model as the experience is built up**. Constant interaction between modelling and real well instrumented sea trial.

- **Accurate numerical models**. Those are essential to understand the results obtained and make good use of them.

- **Obtaining valuable information to validate numerical models**. Use of many sensors and bespoke data acquisition platform.

6.7 SAFETY AND INTEGRITY

All the Safety and Integrity main factors are listed below:

- **Remember water (and particularly salt water) gets in everywhere**. Try to make sealing following a two-layer approach. Instruments and tools that have been in contact with salt water can be looked at as "contaminated"
- **Marine growth can be expected everywhere**. Can be a problem if not foreseen like in small ducts
- **Fatigue; or repeated vibration everywhere**. Extra safety precaution with bolts; pins; shekels.
- **Reduce friction in moving parts.**
- **Ensure watertight integrity of device and instruments.**
- **Safety at sea.** Marked area & real-time communication
- **Marinisation**. Component selection, material selection, coatings, lubrication, waterproofing, and cathodic protection are all employed to create a sea worthy device with a high level of integrity.

6.8 GENERAL ISSUES

Finally after these lines, several general issues are listed below:

- **Drive Train Design**. The design of the drive train is a sub critical consideration of a WEC as the PTO's are typically spaced over a distance that then dictates that the efficiency of the complete system must be high. The long distance of energy transfer typically results in significant energy being lost through twisting of shafts or through the major losses of hydraulics systems that are often conveniently used to ill avail.
- **Operational availability**. The ability of a WEC to efficiently operate over a wide range of wave height conditions is significant for a design to provide the availability and electricity production that is required to be commercially viable.
- **Use 20/80 rule**. With 20% of the effort you get 80% of the way and then make sea trials before going back to the drawing board make some improvements and then make new sea trials even with small units.
- **Over load the scaled units in the open sea.** Gives feedback of real problem areas that are difficult to imagine. If a small system surviving in big waves can be made, it will provide a huge advantage before more money is invested.
- **Work with grid connection from 3 kW as you scale.** Gives a very good indication of how a big scale system will perform.
- **Redundancy.** Make sure that as many important systems have a redundancy option.
- **Material**. Ease of manufacturing, inertia.
- **Manufacturer**. Subcontractor or own manufacturing. Certain details are more economical and faster to manufacture in-house.

- **Careful design and implementation of ballast to achieve mass properties**

- **Trying novel solutions in non-critical components**. Gather experience for design decisions in next full-scale device.

- **Selection of component & system suppliers**. Aim of establishing a long term collaboration Building the future supply chain.

- **Extensive use of naval construction & verification methods**. Ensure adequate prototype quality.

- **Near zero maintenance**. Over-designed components.

- **Deployment logistics**. Understanding ground transportation, lifting, service vessels, response times, towing, and getting the WEC into and out of the water are all important items to understand early as they will influence the design.

- **Team**. Having access to experts who have knowledge and experience in related subject can prepare you well for successful testing. These people can also provide insight and solutions when things do not go as planned. Properly executed Testing is demanding work where only hard work and dedication will result in success.

- **Range of device configurations required**. Angle relative to incident waves, attachment to floor/mooring configuration, etc.

- **Water depth of the project**. Needs or not to correct the depth of mooring points, accuracy of the kinematics of the waves.

7 CONCLUSIONS AND RECOMMENDATIONS

Questionnaires have been filled by WEC developers and Test facilities in order to compose this report that aims to lead future construction and test of WEC devices. An overall of six WEC developers (Atgaris, Perpetuwave Power, Resen Waves, Wavedragon, Wello, and Columbia power) and six Test facilities (Aalborg Universitet, Wavec/Instituto Superior Técnico, Strath Univeristy, Tecnalia Research & Innovation Foundation, Queen’s University Belfast, and Ecole Central de Nantes) contributed to this task.

This collation shows that there is large number of different concerns in multiple areas of the WEC laboratory testing. Some of these are related to the more scientific aspects of the similitude laws and force representations, while many others are part of the model construction process itself.

As a general note, it should be mentioned that the more the scaled models address and try to capture the real problems of a certain WEC, the most useful becomes the output of a certain set of tests.

From the reading of the answers obtained in the questionnaire, the future MaRINET standard should be based on existing sources, such as the EquiMar guideline and the book by Hughes, and include some focus on the following items: recommendations on the methods for PTO modelling or simulation at smaller scales; a description on how to handle in practice the scaling problems (with examples); suggestions on materials and sealing that can be useful in these tests; indication of suggested sensors to be used and how to deal with the contact with water; suggestions on how to perform the mooring modelling (probably adapted from the offshore industry); a check list to be used by developers when preparing the tests.

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