WES KNOWLEDGE CAPTURE

REPORT

WP5 – Tank Testing of WECs

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1. PURPOSE

Aquamarine Power has been asked by Wave Energy Scotland (WES) to produce a series of informative knowledge sharing reports. The contract is to facilitate knowledge sharing within the wave energy sector. The aim is to realise cost and time efficiencies by sharing knowledge and lessons learnt from previous experience so that other companies do not have to go through an exercise of learning the same costly lessons all over again.

Aquamarine Power has accumulated a wealth of valuable knowledge and learning through the design, fabrication, installation and operation of the Oyster 1 and Oyster 800 devices. Aquamarine Power recognise that knowledge sharing is a central component for the successful and timely deployment of wave energy projects. As such, Aquamarine Power is keen to share this knowledge for the benefit of the wider wave energy community.

There is a series of 5 reports covering different topics from the experience and knowledge that Aquamarine Power has gained. The topics under contract with WES are:

1. Offshore operational experience;
2. Corrosion & protection in a disturbed water environment;
3. Supply chain (marine components);
4. Tank testing of WECs;
5. Maintainability improvements from Oyster 1 to Oyster 800.

This report covers topic 4 – Tank testing of Wave Energy Converters (WECs).

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2. BACKGROUND INFORMATION

In the current stage of the wave energy industry, experimental wave tank testing forms an integral part of WEC device development. This report documents the experiences and lessons gained from over 10 years of wave tank testing in the development of Oyster. The knowledge and expertise acquired by Aquamarine Power have been developed in partnership with Queen's University Belfast (QUB) with whom the company has a long standing relationship. Aquamarine Power's research office is based within the Marine Research Group (MRG) at QUB and Aquamarine Power have helped to develop the institute's two state-of-the-art wave tank test facilities, one based in the city of Belfast, and the other in Portaferry, Northern Ireland.

Aquamarine Power's experiences in wave tank testing cover a range of activities, as listed below, which have many common themes which will benefit the wider wave energy community:-

- Performance and load testing
- Installation and decommissioning tests
- Operational procedures
- Model-prototype correlation
- New concept development

Where appropriate, explicit examples of each of these themes are referenced in the Knowledge Capture items listed in Section 3.

With the rapid growth of the wave energy industry over the past 10-15 years, several guidelines and standard protocol documents have been published relating to the testing and assessment of WECs. However, as with all emerging industries where knowledge is continuously evolving and developed through a 'learn-by-doing' experience, some recommendations and guidelines can become a little out-dated. Thus a review and assessment of the existing standards documents is a prudent first step to identify what published knowledge is still relevant and applicable to the state-of-the-art of WEC technology.

2.1 Published Standards and Guideline Documents

Six guideline documents (or series of documents) have been identified which address issues concerning tank testing and hydrodynamic assessment of WECs. These are:

1. EquiMar Protocols. (http://www.equimar.org/equimar-project-deliverables.html)
    - In particular the following Deliverable reports are relevant:
    - D3.3 – "*Assessment of Current Practice for Tank Testing of Small Marine Energy Devices*"
    - D3.4 – "*Best Practice for Tank Testing of Small Marine Energy Devices*"
    - D4.2 – "*Data Analysis & Presentation - to Quantify Uncertainty*"
    - D2.2 – "*Wave and Tidal Resource Characterisation*"
    - D2.6 – "*Extremes and Long Term Extrapolation*"
2. HMRC – OES-IA AnnexII, reference (1).
3. HMRC – reference (2)
4. SuperGen – reference (3)
5. EMEC – reference (4)
6. IEC TC114 standards, e.g. reference (5).

The EquiMar protocols are the most comprehensive set of guidelines relevant for small scale wave tank testing activities. However, it should be noted that much of the information contained within the EquiMar standard is actually extracted from some of the other sources, in particular references (1) - (3). Readers may find the presentation style and information contained within some of these other references easier to comprehend and/or of more practical use. For example: the authors of (1) present a generic outline of the possible development phases of a WEC, in terms of Technology Readiness Level (TRLs), from concept inception (TRL 1-3) to design and system validation (TRL 4-6) through to full scale deployment (TRL 7-8) and economic validation of wave farms (TRL 9). This document contains a wealth of information and proposes methodologies and facilities necessary to achieve each development phase. However, the broad and generic scope of this guideline document has restricted the authors somewhat on expanding on the particular details of each testing phase. Nevertheless, it is a very relevant document and is recommended that it is reviewed to put in context the various stages of WEC testing available.

Specific issues associated with experimental wave tank testing techniques are presented in (2) and (3). The former covers a slightly broader scope of topics associated with tank testing whereas the latter arguably elaborates on more specific and practical details of the topics covered. Most of the information contained in both these guideline documents, like the EquiMar protocols, remain relevant to the current state-of-the-art of tank testing.

The most recent series guideline documents relating to the wave energy industry are the IEC TC114 standards, see (5) for example on the performance assessment of WECs. These standards have been developed building on previous iterations and guideline documents such as (4), and those referenced previously. It is thought that in circa 2-3 years these IEC standards will become the leading guidelines for wave energy converter development addressing the broad range of themes associated with the industry needs. However, at the time of writing this report it is thought that the other documents referenced provide just as valid guidance, (arguably of more practical use to researchers) and are freely accessible on the web. In contrast, each IEC TC114 standard document must be purchased for a fee of circa £120 (approximate cost as of June 2015) and so are less likely to be used by the majority of researchers if the relevant information can be found in other sources. Thus for this reason it is likely that the freely available EquiMar protocols will continue to be used as the standards for experimental wave tank testing, at least for the short term future of 3-5 years.

To avoid duplication of work, this document will elaborate more on complimentary and supplementary information than those discussed in the EquiMar protocols and in (2) and (3). Where necessary, explicit reference will be made to information contained within the guideline documents that still holds valid and has been experienced by Aquamarine Power during their tank testing programmes. More importantly however, details and explanations of where experiences and techniques diverge from those published are also documented in this report.

3. KNOWLEDGE AND LESSONS

The original scope of work outlined six principal categories to present the experimental wave tank testing knowledge and lessons experienced by Aquamarine Power. These are:

1. Wave tank geometry – advantages and disadvantages
2. Wave making, calibration techniques and key wave metrics
3. Instrumentation requirements – including calibration procedures
4. Experience from data acquisition & standard processing techniques
5. Considerations for model design and fabrication
6. Health and Safety procedures

The following subsections have a list of knowledge capture / lesson(s) learnt statements associated with each topic. Where necessary these statements are followed up with additional information and detail. Some knowledge capture statements are generic and apply to a broad range of tank facilities and techniques but the focus of this document is on the specific experiences of Aquamarine Power's on the testing of their nearshore, flap-type WEC (or Oscillating Wave Surge Converter (OWSC)), Oyster.

3.1 Wave Tank Geometry

3.1.1 Knowledge Captured / Lesson Learnt:

Over 320 tank facilities exist in Europe alone which could aid in the experimental scale testing of WECs. However, many tank facilities may not be financially accessible to wave energy developers without significant financial support, concessions or grant funding.

Details:

Three primary categories of tank facility can aid in the testing of WECs, Wave Basins (3D testing), Wave Flumes (2D testing) and Towing Tanks (2D testing). The classification of different facilities is discussed in detail in (2) and EquiMar D3.3.

In Europe alone there is over: 70 wave basin facilities, 180 flumes, and 70 towing tanks. A list of many of the tank facilities can be found on the HydraLab web page

(http://www.hydralab.eu/N_facilities_search.asp). Note however, this is not a comprehensive list of all the facilities in Europe, just those that are part of the HydraLab consortium.

A broad range of costs can span from c. £500 - £10,000 per day, where the cost is typically correlated to the size of the tank and testing facility.

3.1.2 Knowledge Captured / Lesson Learnt:

Wave basins are the most appropriate for detailed testing of WECs. Bespoke tests, such as those for installation, decommissioning and possibly extreme loading, may be achieved in both flumes and towing tanks if designed and executed correctly.

Details:

Due to their diffractive and radiative wave properties, the behaviour of all WECs (in terms of power capture and loading characteristics) in three dimensional tests can be significantly different than in a simplified two dimension configuration. In the case of the Oyster WEC, this fact has been definitively proven from mathematical first principles as discussed in (6), and references within.

3.1.3 Knowledge Captured / Lesson Learnt:

A thorough tank mapping process, such as that discussed in (7) and (8), quantifying the stability of the waves propagating in a tank is strongly recommended to identify the inherent characteristics of a tank before any WEC tests are conducted. Such a recommendation is also made in the tank testing guideline document (3).

Details:

It is unavoidable that wave reflections will exist in all wave tank tests. Reflective side walls, different wave tank geometries and bathymetries etc. can set up transverse waves, wave 'hot-spots' and inhomogeneity across the tank. If not addressed the location of a model within a tank can return different results. Quantifying the 'stability' of a wave tank can either inform a suitable location for testing or identify where improvements need to be made to the tank prior to use.

An example of such an experimental mapping process is illustrated in Figure 1 (taken from (8)) which shows the map of the 'empty' (no WEC model installed) Portaferry wave basin facility (owned by Queens University Belfast) before (left) and after (right) optimisation of the absorbing beaches which are on 3 sides of the rectangular tank. The coloured contours show the difference in the surface elevation (in millimetres) from the target long created wave trace. Waves propagate in the positive y-direction and only one half of the tank (symmetric about x = 0) is shown in the figure.

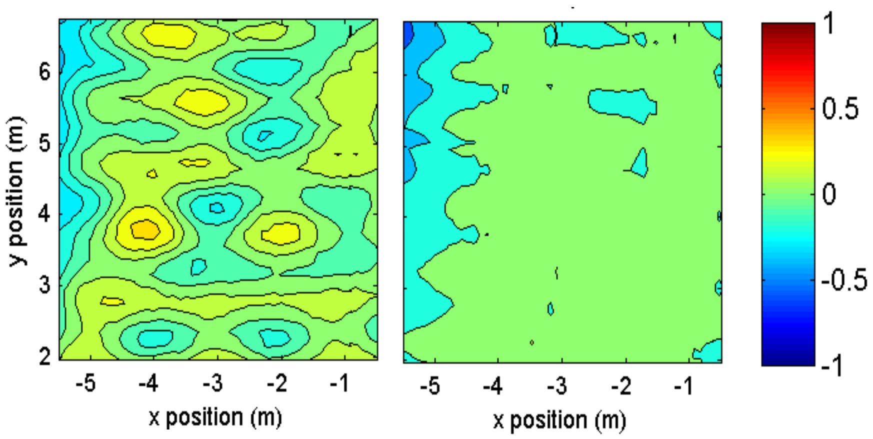

Figure 1 Result of the tank mapping of the Portaferry wave basin facility (owned by Queens University Belfast) before (left) and after (right) optimisation of the absorbing beaches. Figure taken from (8).

3.1.4 Knowledge Captured / Lesson Learnt:

Through full-scale prototype ocean trials, Aquamarine Power have demonstrated that wave tank tests on a 1:40 scale model of Oyster 800 can accurately replicate the dynamic behaviour and power capture characteristics of the full scale device.

Details:

Froude scaling is the law which is almost ubiquitously used in physical WEC wave tank testing. The resulting violation of Reynolds similitude (fluid viscosity effects) is still a widely debated topic, see (2) (3) and EquiMar 3.3 for further discussion. Historically, tank testing at a large-a-scale as practically possible has always been sought in order to minimise the issue of viscous scale violation, without little validated evidence of its perceived influence. However, a seminal piece of research conducted by Aquamarine Power (see (9) for details, with future publications in preparation) has shown that a 1:40 scale model of Oyster 800 can accurately replicate the dynamic behaviour and power capture characteristics of the full scale device, see Figure 2 for an example of how the flap rotation angle compares between the full scale prototype and experimental wave tank tests. The issue of Reynolds similitude violation does not appear to be a dominant influence on the performance and dynamic assessment of the Oyster WEC (at 1:40

scale) following Aquamarine Power's wave tank techniques. This experience also aligns with the EquiMar protocols (D3.3) which advise that 1:40-50 is an appropriate scale (albeit at the small scale limit) to assess the power capture of a WEC.

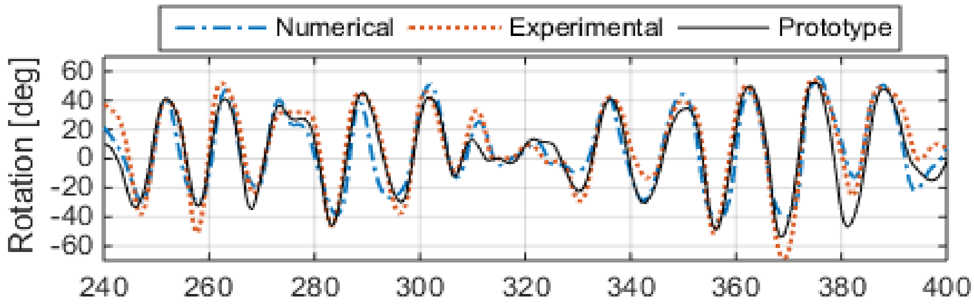

Figure 2 Time trace of an example of the Oyster 800 full scale flap rotation (solid black line), the 1:40 scale wave tank tests (dotted orange) and numerical hydrodynamic model (dashed blue) predictions. Positive rotation angle is flap orientated towards land

This result, of the validity of small scale tank tests, was robustly achieved by being able to perform the experimental tank tests in retrospect to the full scale device operation. The most significant advantage of this procedure is that the exact wave-by-wave conditions experienced by the full scale device can be synthesised in the experiments. Thus enabling the dynamic motion of the device to be correlated to the tank tests on a high temporal resolution time scale. In addition to this, it was found that the as-installed operating condition of the device (e.g. water depth, mass-buoyancy distribution, Power Take-Off setting etc.) must also be replicated precisely in the experimental tests to achieve a fair model-prototype comparison. With a retrospective analysis these conditions can be captured to a high precision and so this work performed by Aquamarine Power proves the validity and value of small scale wave tank tests provided the techniques employed are of high quality and precision.

3.1.5 Knowledge Captured / Lesson Learnt:

Wave tank tests are not only important as a stand-alone research tool for WEC concept development but are often essential to validate the accuracy of a numerical model. Such models can then be used to more efficiently examine a wider design space with more confidence that the results are realistic and not simply an artefact of the numerical technique adopted.

Details:

No further detail

3.1.6 Knowledge Captured / Lesson Learnt:

Potential discrepancies in model behaviour associated with viscous scale has also been shown to be negligible through a robust Computational Fluid Dynamics (CFD) investigation on an OWSC of Oyster 800s size, c.26m wide, see (10) for details.

Details:

The CFD results presented in (10) show negligible (c. 1%) difference in the OWSCs rotational behaviour and power capture characteristics across a range of scales from 1:100 to 1:1. This result also supports the findings of the successful model-prototype correlation study (9) comparing the behaviour of a 1:40 and 1:1 Oyster 800 device (discussed in point 3.1.4 previously). This further supports the results of (6) which indicates that an OWSC of Oyster 800s size is dominated by wave diffraction effects which scale appropriately via Froude scaling laws.

3.1.7 Knowledge Captured / Lesson Learnt:

Due to the significantly different characteristics of deep and shallow water waves, the water depth requirement for the testing of a particular WEC concept is arguably the most dominant constraint when selecting a suitable tank facility to conduct small scale experimental tests.

Details:

From the perspective of a nearshore WEC concept, typically an OWSC such as Oyster, if the wave tank depth is large then the scale of the device must increase. However, if the scale of the model device increases to align with the tank depth then usually the capability of the wave maker then limits the range of tests that can be conducted. Alternatively, a raised platform could be installed in a deep water tank to satisfy the depth condition but in this case the characteristics of the nearshore shoaling waves are not adequately described.

Conversely, if a wave tank facility is too shallow for the WEC (deep water device) the scale of the device usually has to be reduced significantly, to the point that scale effects start to become more of a concern.

Thus selection of a tank facility appropriate for the design and operational philosophy of the WEC is crucial to the success and accuracy of the experimental test programme.

3.1.8 Knowledge Captured / Lesson Learnt:

Nearshore WEC devices are usually sensitive to tidal variations, as such, the water depth in the selected tank facility (often regarded as 'shallow water' wave tanks) must be adjustable to enable the effect of tidal variations to be assessed and quantified.

Details:

Varying the water depth in a tank facility imposes additional requirements on the wave maker which must be capable of functioning correctly at different tank water depths (see Section 3.2 for details on wave making).

In addition to controlling the water depth in the tank, nearshore WEC testing may also require a sloping (often artificial) floor to better capture the shoaling characteristics of the nearshore waves.

3.1.9 Knowledge Captured / Lesson Learnt:

Aquamarine Power has had huge success using wave tank test facilities to design and develop installation and decommissioning strategies for their Oyster technology. This has been demonstrated on both the Oyster 1 and Oyster 800 full scale prototype projects. Thus the value of an experimental wave tank extends well beyond the realm of WEC power, load and survivability assessment.

Details:

Aquamarine Power have successfully and safely installed two full scale Oyster WECs in the nearshore region, namely Oyster 1 (2009) and Oyster 800 (2011). In both cases, experimental wave tank testing was central in the development of the installation approach and in the quantification of the environmental conditions within which the operation could safely be conducted.

1:20 and 1:25 scale installation tests were conducted for the Oyster 1 and Oyster 800 WECs respectively at the wave tank facility in Queens University Belfast. The Oyster 800 WEC also required extensive wet-towing tests which were also conducted at 1:25 scale in Strathclyde University, Glasgow and in Montgomery lake Northern Ireland (QUB) using catamaran towing techniques. The wave tank tests conducted on the more mature and feasible installation strategies were witnessed and supervised by various key stakeholders of the full scale operation such as: independent naval architect(s), vessel master(s), offshore dive representative(s) and responsible design engineers. This approach ensured that key knowledge was fed into the process at an early stage and where necessary improvements made to the strategy. Figure 3 show various pictures of the modelling and offshore operation of the Oyster 1 and Oyster 800 WEC installations.

Experience gained from the full scale offshore installation of both Oyster 1 and 800 showed that: the dynamic behaviour of the WEC and the environmental ocean constraints matched those identified through wave tank testing. Thus verifying the value such small scale wave tank tests can add to this aspect of WEC lifecycle.

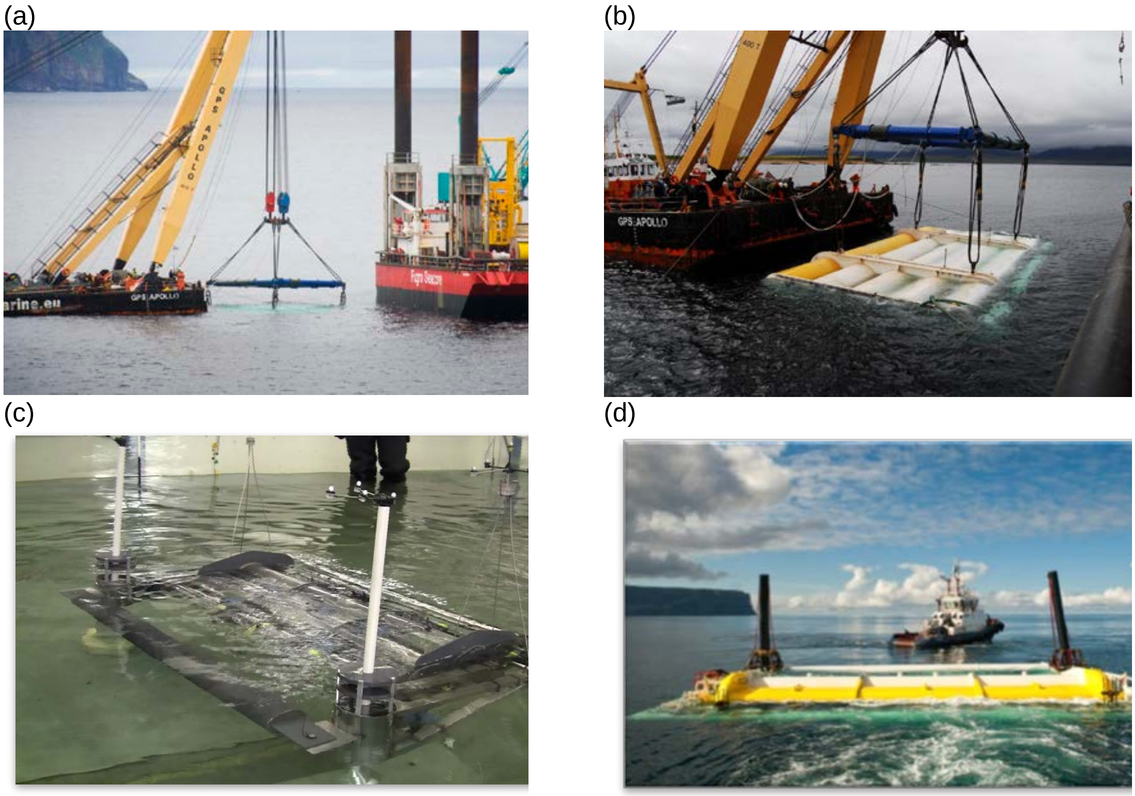

Figure 3 (a), (b) Oyster 1 installation (2009) at EMEC, Orkney, Scotland, (c) 1:25 Oyster 800 wave tank tests at Queens University Belfast, (d) Oyster 800 installation (2011) at EMEC.

3.2 Wave Making, Calibration Techniques and Key Wave Metrics

3.2.1 Knowledge Captured / Lesson Learnt:

Two different types of wave makers/paddles are typically used depending on whether the tank test (and facility) is focused on shallow or deep water tests. A piston wave maker is preferred for shallower water tests where as a flap-type wave maker is preferred for deeper water tests.

Details:

A piston wave maker/paddle covers the tank depth and moves in a purely horizontal motion. As such it is appropriate for shallow water wave tanks as it excites the entire water column. A flap-type wave maker/paddle causes the water particles to develop a more orbital motion more rapidly and so it is favoured for deeper water wave tanks. Further discussion is given in (2) and EquiMar D3.3.

3.2.2 Knowledge Captured / Lesson Learnt:

All contemporary tank facilities deemed suitable to meet the quality needs of the present day wave making requirements should have; an efficient absorbing material (often porous) referred to as the ‘beach’ at the end of the wave propagation path, or an alternative active absorption mechanism; and wave makers which operate with a force feedback control system.

Details:

Long-crested, uni-directional waves are what most tank facilities can generate and dissipate in a controlled manner with efficient beach design and active wave paddle control. If achieved correctly, this functionality facilitates a vast amount of WEC testing requirements and has been employed by almost all wave energy developers to date. More sophisticated and modern wave basin facilities, examples of which are: the Portaferry facility owned by Queens University Belfast and FloWave TT based in Edinburgh University, have beach material, or in the case of FloWave actively controlled wave ‘makers’/absorbers, on the lateral tank walls which dissipate transverse waves. This enables multi-directional and short crested waves to be tested in a controlled manner which is accepted as being more representative of the real ocean environment.

3.2.3 Knowledge Captured / Lesson Learnt:

Establishing a Tank Transfer Function (TTF) enhances the control of the wave maker and enables wave conditions to be generated more accurately. However, a TTF is only valid for a fixed water depth in the tank and also assumes the absorption properties of the beach/tank remain fixed. Thus multiple TTFs are required for tank facilities which vary both these properties, such as shallow water wave tanks used for nearshore WEC tests.

Details:

Prior to (or as part of the initial) wave calibration, a common step in the commission of a wave tank is establishing a TTF(s). This relates the gain signal supplied to control the wave paddles to the height of the wave created within the tank. This relationship is also frequency dependent. Generation of an accurate and high quality TTF can take some time to achieved (circa. 0.5-1 day per TTF) and so should be factored into the testing schedule if the facility does not already have a TTF which is fit-for-purpose.

3.2.4 Knowledge Captured / Lesson Learnt:

In terms of wave measurements, the experience of Aquamarine Power is that a simple and inexpensive conductivity wave gauge/probe is appropriate to record sufficiently accurate surface elevation data.

A static 2-3 point wave probe calibration technique has also been found to be adequate.

Details:

A host of wave measurement techniques exist, a detailed and valid presentation of each is given in (3). It is also relatively easy to adapt the conductivity wave gauge technique so that the sensor is fixed to the WEC model itself, thus resulting in an immersion gauge. This has been successfully achieved and demonstrated by QUB and Aquamarine Power, see the experimental OWSC model design as described in (11).

3.2.5 Knowledge Captured / Lesson Learnt:

Breaking waves cannot be robustly measured with existing experimental wave tank measurement techniques. However, an accurate experimental measurement of the precise 'height' of a breaking/broken wave is often not required from the WEC testing programme and thus is not a significant drawback.

Details:

WEC survivability tests, especially for nearshore WEC concepts, will involve the generation of extreme sea state conditions which include a significant amount of breaking waves. In the nearshore region this phenomena is predominately induced by the finite water depth, whereas in deeper water it is the wave steepness which triggers wave breaking. In the breaking wave regime the conditions are so highly turbulent and inherently chaotic that recording these conditions in fine resolution (if it were possible) would not effectively inform the process any further.

Wave breaking is a natural limit imposed on ocean waves and in this regime a broken wave contains less energy than the unbroken wave condition which preceded it. Thus it is likely that the measurement of the unbroken condition is of more significance to WEC testing. In these circumstances most of the conventional wave measurement techniques, like those discussed in (3), are still valid.

Typical conductivity wave gauges will underestimate the height of a breaking wave due to the excessive aeration of the water but they will continue to record a reasonable estimate of the wave, albeit with lower accuracy. Other techniques such as optical or laser gauge however will not work at all due to the excessive dispersive scattering of light of the air bubbles.

To supplement the wave surface elevation (and other data) measurements it is advantageous to have a synchronised video of the wave tank tests in these breaking wave conditions. This enables researchers to identify events within the test data post-processing where breaking waves occurred, possibly highlighting regions where the experimental uncertainty is slightly larger than average, if necessary.

3.2.6 Knowledge Captured / Lesson Learnt:

For a wave climate containing tens of kW/m of incident energy, depth induced wave breaking only significantly affects the resource at water depths below circa 10m, see (12) for further details.

Details:

The complex nature of breaking ocean waves means that only limited theories exist to describe their behaviour. Due to the chaotic nature of this wave breaking regime, most WEC developers will design their system to nominally operate outside this environment. The authors of (12) have shown that for wave climates of key interest to WEC developers (typically tens of kW/m incident energy) wave breaking only significantly affects the incident wave resource at depths below 10m. A similar limit is also referenced in (4).Outside of this zone the nominal operating conditions of a WEC (typical power production conditions) can be adequately described using the same techniques as an offshore (deep water) location, such as a standard wave height – wave period occurrence table. State-of-the-art spectral wave models (e.g. SWAN, Mike21 SW, etc.) do account for the energy dissipation effects of wave breaking (typically making use of bore-based model formula) and so they are deemed as valid tools to assess the nearshore energy resource, provided care is taken when implementing the model parameters associated with this energy loss mechanism.

3.2.7 Knowledge Captured / Lesson Learnt:

Survivability wave tank tests of a nearshore OWSC should be conducted at as large-a-scale as practically possible to minimise the effect of the distorted scaling of air bubbles.

This contradicts some of the advice specified in the EquiMar protocols (D3.3) which indicates that WEC survivability tests could be performed at smaller scales of circa 1:80 to 1:100. Although in an independent point the protocols do also suggest that larger scale tests should be employed to mitigate against air bubble scaling issues.

Details:

Survivability tests on an OWSC operating in the nearshore region can initiate a highly complex and nonlinear wave slam phenomenon. This process involves a highly aerated region at the WEC structure free-surface interface, inducing a local high-pressure impact on the structure (http://youtu.be/p3gq7hlNEd4 shows a tank test video posted by Aquamarine Power demonstrating the wave impact phenomenon on an OWSC, which is also illustrated in Figure 4).

The wave impact phenomenon on a nearshore OWSC and its characteristics are discussed in detail in (13), (14) and (11). The EquiMar protocols (D3.3) advise that survivability tank tests of a WEC could be performed at a smaller scale, circa 1:80 to 1:100. At the same time it also suggests that any phenomena which involves air entrapment should be tested at a larger scale (>c. 1:8) to avoid erroneous results due to the distorted scaling of air bubbles.

Due to the complex nature of the wave slam phenomenon on an OWSC (in the nearshore) it is recommended that testing is conducted at as large-a-scale as practically possible to mitigate erroneous results due to the distorted scaling of air bubbles. 1:25 scale tests have already been successfully achieved by Aquamarine Power balancing the wave height, steepness, water depth and instrumentation requirements.

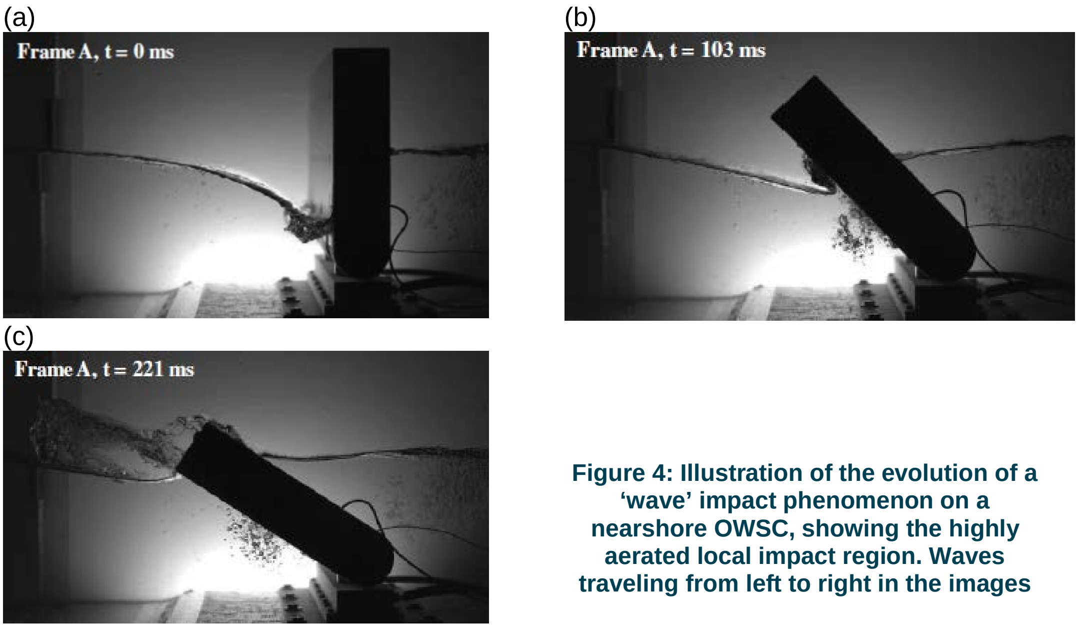

Figure 4: Illustration of the evolution of a 'wave' impact phenomenon on a nearshore OWSC, showing the highly aerated local impact region. Waves traveling from left to right in the images

3.2.8 Knowledge Captured / Lesson Learnt:

Wave calibration should be conducted prior to model testing, at the proposed model location within the tank, without the WEC model present.

Details:

The control of the wave maker should be adjusted until the achieved waves 'on-site' at the proposed model location are deemed sufficiently accurate. This ensures that the influences of wave tank bathymetry and geometry are accounted for in the calibration process. The fact that the wave climate may then be distorted by the presence of the WEC model itself during tests is unavoidable. The tolerance/criteria which declares a calibration accurate enough is entirely at the discretion of the user but accuracy levels well within 5% are easily achieved.

Key metrics which should be used, as a minimum, to assess the calibration are: the significant wave height, mean wave period and the shape of the energy density spectrum demanded, (see Section 5 for further details on wave metrics), although (15) discusses a more extensive list of parameters which should be used to robustly characterise the sea state for the purpose of WEC performance assessment.

3.2.9 Knowledge Captured / Lesson Learnt:

When calibrating long-crested, uni-directional waves, reflection analysis should be employed. The three-probe Mansard and Funke (16) methodology (commonly used in the industry) was found to be adequate and easy to achieve in practice.

Details:

When calibrating waves in the tank (uni-directional waves) it is recommended that a two dimensional reflection analysis is employed as a minimum to decouple the incident and reflected wave components. Calibration diagnosis/refinement is then only applied to the resulting incident wave components until it converges to the demanded waves. (2) and (3) provide a more in-depth and valid discussion on various reflection analysis techniques and expand to calibration techniques applicable to short-crested multi-directional wave conditions.

3.2.10 Knowledge Captured / Lesson Learnt:

The industry-familiar definition of spectral (frequency domain analysis) significant wave height, calculated as $H_{m_0} = 4\sqrt{m_0}$, actually over-estimates the magnitude of real ocean wave conditions of the order of 3%-10%.

Details:

Despite being ubiquitously used across the industry, its definition, and thus domain of validity, is heavily dependent on idealised assumptions which are not realised in real ocean conditions. An in-depth discussion on this is provided in Appendix A (Section 5.1.1) of this document. In summary however, at present there is still no industry-wide accepted definition of spectral significant wave height which precisely describes real ocean waves and can be adopted to analyse both deep water waves and intermediate/shallow water waves. Thus it is suggested that the analysis and development of a robust wave height metric is a key area of future research in the wave energy industry.

3.2.11 Knowledge Captured / Lesson Learnt:

A time domain calculation of significant wave height $H_{1/3}$ (defined as the average of the highest one-third waves in an irregular sea state) arguably returns a more robust measure of significant wave height. The disadvantage of such a time domain analysis however is that there is no precise link between this significant wave height metric and the incident wave power within that sea state.

Details:

The EquiMar protocols (D2.2) recommend the use of $H_{m_0} = 4\sqrt{m_0}$, as the default wave height metric to use but fail to identify the shortcomings or assumptions behind this definition. These need to be more robustly communicated and it is felt that further research is required to update this definition in terms of realistic sea conditions, especially if it is pitched as a standard pan-industry guideline. An in-depth discussion on this is provided in Appendix A (Section 5.1.2) of this document.

Note: no formal mathematical or robust empirical relationship between H_{m0} and $H_{1/3}$ has yet been established which is universally accepted or used across the wave energy industry.

3.2.12 Knowledge Captured / Lesson Learnt:

The spectral mean wave period, defined as $T_{0,1} = \frac{m_0}{m_1}$, is a robust spectral wave period metric to use for sea state definition. In intermediate water depths it better conserves the incident wave power of a sea irrespective of the spectral shape/frequency bandwidth specified, see (17) for further details.

Details:

Similar to the comment on H_{m0}, the EquiMar protocols (D2.2) recommend that it is energy period, defined as $T_e = T_{-1,0} = \frac{m_{-1}}{m_0}$, which should be used as a default period metric. Although a very stable and useful metric the definition of energy period has its origins more rooted in deep water wave theory. It has been shown (see (17)) not to be as robust a metric when analysing shallow water (non-Gaussian) wave conditions in terms of wave power conservation. Similar to section 3.2.10 it is suggested that further research into more robust wave metrics is a key area of future research for the wave energy industry.

An in-depth discussion and associated wave period equations are provided in Appendix A (Section 5.2.1 and 5.1.2) of this document.

3.2.13 Knowledge Captured / Lesson Learnt:

The robust and correct calculation of incident wave power (P_{inc}) in kW/m, applicable to both deep and intermediate water depths (to an adequate degree of sea severity for performance assessment purposes) is:

$$P_{inc} = \frac{\rho g}{2} \sum_n (A_n)^2 \, C_g(f_n, d)$$

where A_n and C_g are the wave amplitude and group velocity of the f_n frequency component of the sea state in water depth d. ρ and g are the water density and gravitational acceleration respectively.

Details:

In the case of deep water only this equation can be reduced to:

$$P_{inc} = \frac{\rho g^2}{64\pi} (H_{m0})^2 T_e$$

where $T_e = T_{-1,0}$ is the energy period and $H_{m_0} = 4\sqrt{m_0}$. This latter equation however is often used well beyond the domain of validity. The former equation should always be used as standard.

It is interesting to note that the definition of 'energy period' can actually be extracted from the incident power equation under the assumption of deep water group velocity. Thus highlighting that metrics which may be appropriate for deep water wave assessment and testing are not guaranteed to be adequate for intermediate or shallow water.

A more in-depth discussion and associated wave period equations are provided in Appendix A (Section 5.3) of this document.

3.3 Instrumentation requirements

The precise specification of instrumentation required for wave tank modelling is entirely dependent on the type of WEC concept being tested. A useful discussion on typical and appropriate sensors used in wave tank testing is given in (3). Key measurements which are commonly desired from a WEC tank testing programme are:

- WEC motion (position, velocity, acceleration)
- Power Take-Off load (force, torque)
- Structural and foundation/mooring load (force, torque)
- Wave/fluid pressure loads (pressure)
- Wave & WEC immersion (surface elevation probes)
- Visual Observations (video or high speed camera images)

3.3.1 Knowledge Captured / Lesson Learnt:

Instrumentation of larger scale models is generally easier than smaller scales due to geometric constraints. The instrumentation requirement can often dictate the scale at which a test is conducted.

Details:

The scale of the WEC model can significantly influence the type and amount of instrumentation that can be applied to the model, primarily due to physical and geometrical constraints. It is often the case that the available/achievable instrumentation actually influences the scale of the test, within the governing constraints of the wave tank facility.

Measurement of force, torque, dynamics (e.g. position) and wave elevation quantities are readily achievable with relatively simple or established instrumentation techniques (strain gauges, potentiometers, magnetic eddy technology, resistive and conductivity measurements) across a broad range of testing scales from circa 1:80 to 1:20. Outside of this range, geometric constraints (smaller scale) or large loading/stress (larger scale) become increasingly more influential and can limit the applicability and integrity of the instrumentation. In these cases more novel solutions may be required.

The techniques used to measure fluid pressure are arguably a little more dependent on the specific testing conditions. Thus each technique (e.g. piezoelectric, piezoresistive, capacitive, electromagnetic, optical etc.) may have a more limited scale of validity and so one particular technique may not be appropriate across the range of testing scales usually adopted in wave tank tests.

3.3.2 Knowledge Captured / Lesson Learnt:

Bespoke electrical technician support (or in-house expertise) is crucial in maximising the quality and functionality of the instrumentation applied to WEC models during tank test programmes. Investment in the necessary skills and resource to enable in-house development/support is advisable from a cost-benefit perspective.

Details:

Small scale, adequately ranged/rated, cost effective, water-proof sensors are not readily available from suppliers to cover the diversity of variables which need to be recorded to execute a successful tank test programme. The latter requirement of water proofing is often the most limiting factor in the procurement process where an International Protection rating 68 (IP68) is usually required. Thus inevitably bespoke modifications are required before supplier-bought sensors and the necessary cables and connectors are fit-for-purpose for small scale wave tank tests.

In addition to sensor modification works, it was found from experience that in-house fabrication of key sensors can actually turn out to be more cost-effective in terms of both time a money than sourcing from an external supplier. These tailored sensors also improve the quality and accuracy of the results returned from the tests. See Figure 5 for an illustrative example.

(a) (b)

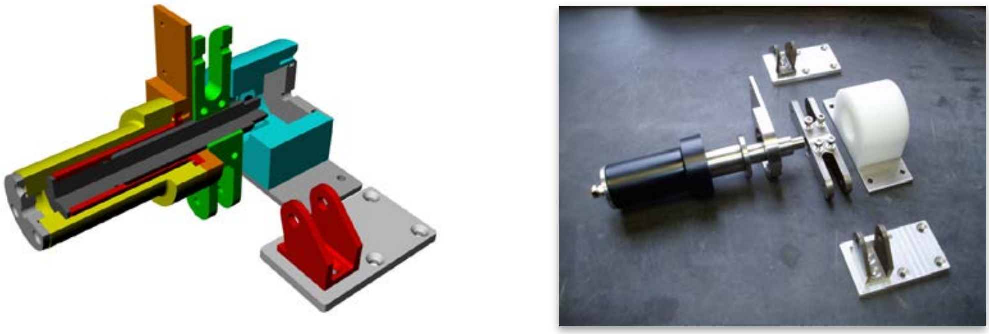

Figure 5 Example of a thin-walled, strain gauged 'torque' tube designed (a) and fabricated (b) in-house for use in 1:20 scale experimental wave tank testing of an OWSC

Measurements of force and torque can be easily achieved (especially in 1 degree of freedom) with simple Wheatstone-bridge strain gauge techniques and so are ideally suited for in-house fabrication. Capacitance and resistive gauges (often used for water elevation measurements) are very simple to construct and custom make. Similarly, position measurements using potentiometers can be achieved relatively easy with a simple mechanical and electrical circuit design. These three categories of techniques can cover a broad range measurements required from small scale wave tank tests. Outside of these measurement principles, the techniques tend to become increasingly more intricate and involved (e.g. piezoelectric, gyroscopic, optical technologies) and so in this case it is often more cost/time-effective to source a suitable supplier rather than custom designing and fabricating the sensors in-house.

3.3.3 Knowledge Captured / Lesson Learnt:

Motion capture and other optical sensing techniques have a significant advantage of being non-intrusive and so will not influence the behaviour of the WEC model during tests. However, they are severely distorted by the influence of the air-water interface and so their applicability are usually limited to bodies operating purely above the surface of the water.

Details:

No further detail.

3.3.4 Knowledge Captured / Lesson Learnt:

Calibration of key sensors should always be done 'in-house' prior to testing regardless if the sensor supplier provides a calibration certificate.

Regular/periodic (circa 1-3 months) re-calibration of all sensors used during tank testing should also be performed.

Details:

As outlined in 'Lesson Learnt 3.3.2' previously, it is extremely likely that some modification to a supplier-bought sensor will be required before it is fit-for-purpose for wave tank tests. Thus a bespoke re-calibration ensures that any distortion due to the modifications are accounted for.

Even if no alterations are required, calibration of the sensor using the same data-acquisition system, electrical cables, connectors, amplifiers etc. which will be employed during the test programme is strongly advised to ensure that all characteristics of this auxiliary infrastructure is accounted for. Thus achieved a more accurate measurement of the physical process experienced during the tests.

Calibration or correction factors can usually be implemented directly within the data acquisition system so that the recorded data has these factors inherently applied. Otherwise, the calibration factors must be applied within the data-post processing analysis routines.

3.3.5 Knowledge Captured / Lesson Learnt:

Amplification of sensor signals (as close to the point of measurement as practically-as-possible), robust electrical shielding of cables and common electrical earthing are vital to the acquisition of quality data.

Details:

Signal-to-noise ratio must be considered early in the sensor design or specification as the magnitude of the signals in scale tests can be very small. In addition, the signal from a scale WEC model often has to travel through tens of metres of cable before entering the data acquisition system, increasing its susceptibility to noise. Thus, early signal amplification and shielding are key to minimise the influence on noise.

There should be a common electrical earth point in the wave tank facility to which all signals are referenced too. Not having a common earth can significantly distort the signals begin returned from different sensors, compromising the integrity of the data recorded.

3.4 Data Acquisition

3.4.1 Knowledge Captured / Lesson Learnt:

To minimise the potential cause for spectral leakage and eliminate the need for windowing and tapering in data post-processing routines it is recommended that the duration of sea state conditions synthesised in a wave tank should always be a multiple of 2^N (e.g. 256s, 512s 1024s etc.) at the wave tank scale for both regular and irregular wave conditions.

All data should be sampled with a frequency resolution which is a multiple of 2^N (e.g. 128Hz, 256Hz, 512Hz, 1024Hz etc.) to facilitate more efficient and accurate spectral analysis post-processing techniques.

Details:

Spectral leakage is an unwanted distortion of the results of spectral analysis techniques which occurs if the data sampled being analysed is not truly periodic. Several mitigating procedures such as data windowing and tapering (as discussed in detailed in EquiMar D3.4) can help reduce this unwanted distortion but often are not implemented correctly and there is no single technique which is universally accepted across the industry. However, in all modern wave tank facilities the wave makers only create waves which have a frequency which are a multiple of a base frequency which is a factor of 2^N, e.g. 32Hz is typical. Thus if a sea state is created and the data acquired for the duration is a multiple of 2^N (e.g. 256s) then the entire duration is precisely one complete period/cycle (i.e. the wave trace will be identically repeated beyond 256s). This allows spectral analysis techniques to be applied directly to the full data set without spectral leakage occurring and without the need to perform additional windowing or tapering processes. Hence, minimising the potential for errors to be introduced during the post processing phase.

In addition to the duration of the sea state, the data should be sampled at a frequency which is also a multiple of 2^N (e.g. 128s). This ensures that there will always be a 2^N number of data points contained within the data set, thus facilitating more accurate and efficient Fast Fourier Transform (FFT) techniques, which is central to spectral analysis.

The criteria presented above to achieve a precise sea state condition assumes that the waves have been fully established and stable within the wave tank. It may take several minutes for this stationary process to be established. However, it should be noted that the behaviour of the WEC system during this wave 'ramp-up' time (from calm water) can also reveal key features of the WEC concept and should not be overlooked as a test scenario. However, the appropriate analysis techniques must also be adopted for this case as the data no longer represents a statistically stationary process.

3.4.2 Knowledge Captured / Lesson Learnt:

Aquamarine Power have had good experience with the data acquisition platforms WaveLab (developed by Aalborg University http://www.hydrosoft.civil.aau.dk/wavelab) and in-house systems developed with LabView (developed by National Instruments http://www.ni.com/labview/)

Details:

WaveLab is a powerful acquisition system which has been developed by Aalborg University specifically for experimental wave tank testing. It is a very user friendly system enabling researchers to record and analyse high quality data, covering almost all possible testing and data acquisition requirements. However, in some unique occasions it does prove difficult to integrate some specialist pieces of equipment, such as a high speed camera or a motion tracking system synchronically into the WaveLab acquisition platform. Such bespoke acquisition requirements effectively require full editorial control for the system and so developing an in-house data acquisition system from first principles using a platform such as LabView is recommended. The initial overhead and investment of time in developing an in-house system can be outweighed by the tailored functionality if more sophisticated wave tank tests are being performed.

3.4.3 Knowledge Captured / Lesson Learnt:

Synchronisation of two independent acquisitions systems can be adequately achieved by triggering both systems to start (and stop) acquiring data with a common input signal (which can incorporate a user specified delay also).

Details:

If using multiple acquisition systems during a wave tank test it is necessary to ensure that they start recording data at the same time. This is best achieved by triggering each system with a signal from the wave maker input to each acquisition system in parallel. Once synchronically triggered, most modern acquisition systems can then reliably sample the data at the user prescribed frequency (within the common sampling frequency commonly required from wave tank tests of 100's of Hertz). If not however, both acquisition systems can be triggered to stop acquiring data at the same time and in this case the time stamp of the more robust system used as the primary signal, and the sampling resolution interpolated on the secondary signal.

3.4.4 Knowledge Captured / Lesson Learnt:

Quantifying the repeatability of wave tank tests, and the associated measurements, is essential to establish confidence in the results output from a testing programme.

Details:

There are multiple sources of error and uncertainty that can occur in small scale wave tank tests. The EquiMar protocols D3.4 and D4.2 give a thorough discussion and classification of the source of uncertainty and present in detail how to assess and quantify each form. Confidence in test results requires a statistically significant set of data which captures multiple incidences of the same physical phenomenon. Thus for more rare events, such as extreme events usually associated with the survivability of a WEC, a greater emphasis must be put on repeating the tests to establish a statistically significant set of data from which a more robust measure of the event can be made.

3.4.5 Knowledge Captured / Lesson Learnt:

Having data post-processing routines developed, quality assured and verified prior to conducting wave tank tests is of paramount importance to a successful test programme.

Details:

Having pre-built analysis code enables immediate data processing (almost real time) of test results enabling early identification of sensor faults, otherwise it is common that several hours of testing can pass without fault detection which can have significant cost and schedule implications.

In addition, developing standardised analysis code, verified by independent staff/assessors, ensure that post-processing routines are correct and minimises the potential for error to be made if multiple users are handling the data. For example, Aquamarine Power have successfully developed a standardised in-house data post-processing analysis suite called CLAMS which filters (if necessary) the experimental data as well as applies all necessary calibration factors and scales the results to full scale units (if desired). CLAMS also allows immediate visualisation of data after acquisition so that inconsistencies and discrepancies can be identified as soon as possible during the test programme. The conditioned and standardised data output from CLAMS can then be used for the more unique analysis associated with the test programme.

3.5 Model Design and Fabrication

3.5.1 Knowledge Captured / Lesson Learnt:

The precision and functionality requirements of the state-of-the-art WEC models and tank testing programmes requires extremely high quality models, parts and subassemblies such as those achieved from a Computer Numerical Control (CNC) machining process.

The material, fabrication and instrumentation costs of a high quality WEC model (of a nominal scale of circa 1:40 – 1:20) is typically of the order of £5,000 - £10,000.

Details:

The possible increased overhead in employing high quality fabrication techniques is by far outweighed by the value and quality of the result achieved from the wave tank test programme.

A good example illustrating this is the common issue of backlash which can arise in small scale models, typically between the WEC prime mover and PTO damper system. Backlash can be thought of as a looseness or compliance between the connecting parts of the model. This is usually the result of sub-standard mechanical/fabrication tolerances or poorly specified equipment operating well outside its intended range. Figure 6 shows an example of how backlash manifests in the PTO damping torque characteristics of a poorly designed OWSC model during wave tank testing. On each reversal of the OWSC motion, there are significant periods of time when zero damping torque is applied to the model, despite the fact that the intended damping torque should follow a square wave or Coulomb-type profile. As a result the WEC model is effectively tested with a significantly different PTO damping strategy than intended which can dramatically distort the power capture estimate of the WEC concept. Note, the distortion does not necessarily cause a reduction in performance but the issue is more that the testing is uncontrolled and non-conformant with the original design specification, thus compromising the quality and integrity of the test results.

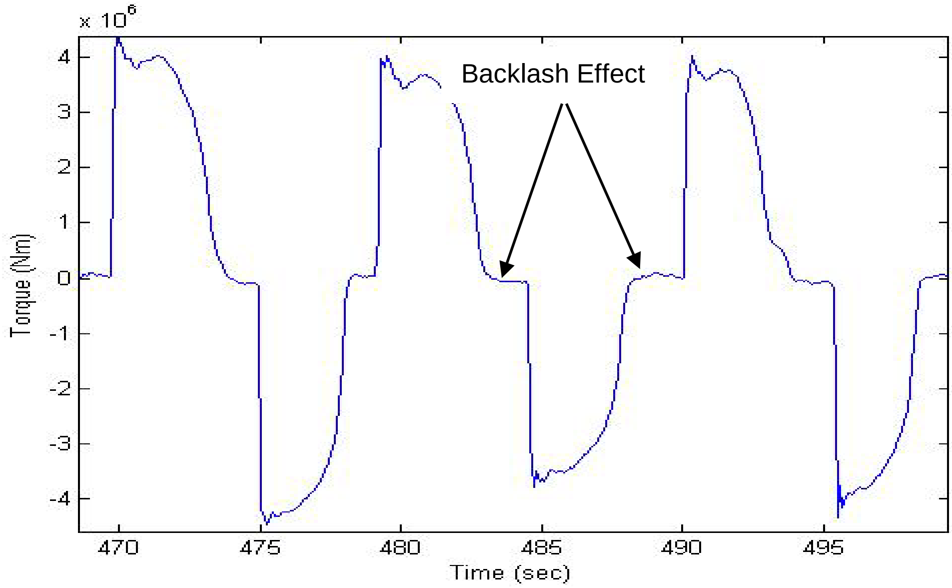

Figure 6 Example of the PTO damping torque from a poorly designed model showing severe backlash. The target damping profile in this case is a square wave or Coulomb-type damping. The effect of backlash manifests as regions where zero PTO damping is applied for a significant period, during which the WEC will continues to move an appreciable distance. Values are all displayed in the equivalent full scale units.

3.5.2 Knowledge Captured / Lesson Learnt:

Irrespective of the scale of the WEC tank tests, a controlled model design process should be followed which includes:

- 3D model design in a Computer Aided Design (CAD) package such as SolidWorks or similar.
- Detailed 2D engineering drawings with necessary tolerance and materials specified on all parts.
- Adequate design review and approval process.
- Robust documentation and revision control process.

Details:

In the interest of accelerating the tank testing process a natural temptation is to assume that because tests are conducted at a smaller scale then the design process does not need to be very thorough or indeed that a formal process is required at all. However, small scale does not necessarily equate to an easier or less complex design and factors such as part tolerances actually become more influential and often need to be specified more precisely. Thus implementing a robust design procedure is of paramount importance and is also more compatible with CNC fabrication processes.

3.5.3 Knowledge Captured / Lesson Learnt:

An important design consideration for WEC models should be on the ease of assembly and disassembly and a 'plug-and-play' philosophy should be adopted where possible. Minimising the time taken to set up, modify and decommission a model from the wave tank can save a noteworthy amount on the overall cost of the test programme.

One key objective which helps this process is to design a model which minimises the variety of tools required to install and decommission it. A good example of this process is the flat-pack furniture from IKEA, which rarely requires more than 1 tool to fully assemble.

Details:

Practical design considerations such as assembly and disassembly are as important to a streamlined and successful test programme as the functional requirements of the WEC model itself. The time overhead in setting up and removing a test from a wave tank facility can add significant cost to the testing programme and can sometimes surpasses the duration of the actual test itself.

If designed according, and the tank facility allows, smaller and more minor adjustments can be made to the model in-situ without removal at all. This can significantly streamline the tank testing programme.

3.5.4 Knowledge Captured / Lesson Learnt:

Building multiple bespoke WEC models each of which focus on acquiring a different category of information (e.g. a performance test model and a survivability test model) will improve the quality of the test results. This can also be more cost effective in the longer term than designing a single model which attempts to facilitate the acquisition of all information required from the different categories, often compromising on the quality of the data.

Details:

The natural desire is to attempt to build a single 'one fits all' model which is capable of recording all the necessary information from a tank test, e.g. power capture properties, extreme wave loads, installation loads and dynamics etc. However, the parts and subsystems necessary for one set of tests can possibly distort and hinder the quality of the result if the model is used for a different classification of tests. For example, recording the power take-off signal of a WEC usually involves some form of force sensor or strain gauged element within the model. However, if this same model is used for extreme wave loading tests (where the power take-off may not be a factor) then this force sensor or gauged element can introduce an unrealistic/unnecessary level of compliance or complexity within the model which can distort the extreme loading results.

Thus tailoring (limiting if necessary) the model design and functionality to the priority objectives of the particular test can improve the quality of the results. This approach may result in multiple models being designed and fabricated but can still be more cost effective in the longer term.

3.5.5 Knowledge Captured / Lesson Learnt:

Friction within the model should be minimised to reduce errors due to scaling.

Details:

Most friction effects do not usually scale correctly according to Froude scaling laws. Thus sources of friction must be minimised in small scale WEC models. Where possible the model design must locate the necessary instrumentation such that all friction effects are actually measured and thus can at least be quantified, irrespective if they were desired or not.

3.5.6 Knowledge Captured / Lesson Learnt:

The choice of material used for model fabrication is essentially open to the user's preference <u>provided</u> the displaced volume, mass and inertial properties of the model are correctly represented.

Details:

If Froude scaling is used to design a small scale wave tank model, it is essential that the exact geometry and inertia characteristics (mass & centre of mass and/or moment of inertia) of the equivalent full scale design are conserved. Provided these two criteria are satisfied the user/designer has some freedom to select the most appropriate material (combination of materials) to fabrication the model from.

3.6 Health and safety procedures

3.6.1 Knowledge Captured / Lesson Learnt:

A “permit to work/test” process is found to be an effective way to manage and coordinate all testing programmes at a tank facility, ensure safety standards are adhered to and risk mitigation measures put in place.

Details:

Prior to conducting a test, the responsible researcher must identify all the risks and mitigation measures required by developing a robust testing Method Statement and Risk assessment. These then are reviewed by the lab manager (or similar responsible supervisor). Only on approval does the researcher receive a ‘permit-to-test’ certificate and the test programme may commence.

In a similar ethos to that outlined in ‘Lesson Learnt 3.5.2” of the “Model Design and Fabrication” section, just because the wave tank testing may be at a small physical scale does not imply that risks are insignificant, hence a thorough and formal procedure should not be neglected.

3.6.2 Knowledge Captured / Lesson Learnt:

All personnel involved in the experimental tank testing programme must receive a formal lab induction and Health and Safety training coordinated by the responsible lab manager.

Details:

Induction and training should be given to all members irrespective of how minor a role it is proposed they play in the testing programme.

Some of the key health and safety issues which should be addressed, and where necessary training provided, which are common to all forms of experimental wave tank testing are:

- Water safety
- Personal Protective Equipment Requirements
- Lifting procedures and manual handling
- Electrical safety and use in proximity to water
- COSHH assessment procedures
- Policy on lone working and supervisory roles
- Emergency response procedure

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5. APPENDIX A – KEY WAVE PARAMETERS

There is a wide variety of different wave metrics which can be employed in the analysis of ocean waves. To date, within the wave energy industry, convergence on a standard and robust set of parameters has not been achieved adequately. Certain ocean parameters can only be applied under particular circumstances and constraint and so some may be more appropriate to describe deep water waves and others intermediate/shallower water waves.

This section discusses some of the most common and influential wave metrics used within the industry and presents the key constraints and assumptions behind their definition, in an attempt to communicate and outline their applicability. It is recommended that this subject of ocean wave analysis (in terms of robust and appropriate metrics) is elevated to a high priority research area for the wave energy industry.

5.1 Significant Wave Height

Significant wave height is arguably the most common wave parameter employed in the industry. It can be defined and calculated in two independent ways.

- Spectral Domain (H_{m0}):
  Proportional to the square root of the zeroth spectral moment (m_0) of the non-directional energy density spectrum S(f) of a sea state.

- Temporal Domain ($H_{1/3}$):
  The average of the highest one-third wave heights in a given sea state.

Each of these are discussed in detail in the corresponding sections below with the underlining strengths, weaknesses and constraints listed.

5.1.1 Spectral Domain (H_{m0})

The spectral significant wave height is calculated as

$$H_{m_0} = a\sqrt{m_0} \qquad [1]$$

where ***a*** is a proportionality 'constant' and *m_0* is the zeroth spectral moment of the energy density spectrum (*S(f)*) which can be found from the formula:

$$m_n = \int_0^\infty f^n S(f)df \qquad [2]$$

The commonly accepted (albeit incorrect for real ocean conditions) value for the proportionality constant in equation [1] is ***a***=4.01 given the familiar formula for significant wave height as:

$$H_{m_0} \cong 4\sqrt{m_0} \qquad [3]$$

An attractive feature (for the wave energy industry) of calculation the significant wave height in this way is that there is a direct relationship between the wave height and wave energy/power in the sea state, see Section 5.3 for details. However, equation [3] is only correct under some strict mathematical assumptions, which in fact are violated when analysing any real ocean wave conditions. The critical assumptions are:

The water surface elevation, from the mean level, follows a normal or Gaussian distribution.

The energy content of the sea state has a narrow-banded energy spectrum.

The first assumption, (which can be interpreted that on average the wave crests and wave troughs in the sea state are of the same magnitude) holds valid for the majority of wave conditions in deep water, but is violated in intermediate/shallow water. The use of the standard spectral analysis techniques also start to break down due to the introduction of artificial high frequency harmonics in the signal which attempt to describe the nonlinear characteristics of the shoaling nearshore waves.

The assumption of narrow-bandedness indicates that all energy in the sea state is sharply concentrated about a single wave frequency. This assumption is violated by all real ocean wave conditions, irrespective of the water depth. Thus under no practical/real scenario does equation [3] accurately estimate the true magnitude of the significant wave height, yet it is generally accepted and ubiquitously used by the wave energy industry.

Violating the narrow-banded assumption, upon which equation [3] is fundamentally based, can result in an over-estimate the significant wave height of the order of 3%-10%. The degree of over-estimation will depend on the actual spectral bandwidth of the sea state under investigation and several authors have suggested alternative derivations of H_{m0} (see (18) and (19) and references within for example). These propose that the proportionality constant, ***a***, is a function of the spectral bandwidth. However, the precise dependence has not yet been fully validated with real ocean data or accepted by the industry.

A preliminary attempt could/should at least be made to account for the over-estimation by a simple scaling of the proportionality constant. A reasonable estimation (see (20)) based on some analysis of typical real ocean wave conditions would be a 5% reduction giving

$$H_{m_0} = 3.8\sqrt{m_0} \qquad [4]$$

Further research is required across the industry to enhance and better understand this metric so that it more accurately reflects the characteristics of real ocean wave conditions in both deep and intermediate/shallow water regions.

5.1.2 Temporal Domain ($H_{1/3}$)

A time domain analysis is an alternative approach to define and assess the significant wave height. In this case it is defined as the average of the highest one-third of the wave heights within a given sea state sample. Each individual wave height can be calculated based on a zero-up crossing or zero-down crossing technique, as illustrated in Figure 7. The title of each technique reflects the slope of the surface elevation as it crosses the still water line and defines one complete wave cycle in an irregular sea state. Further detailed discussion on zero-crossing analysis is given in EquiMar D2.2.

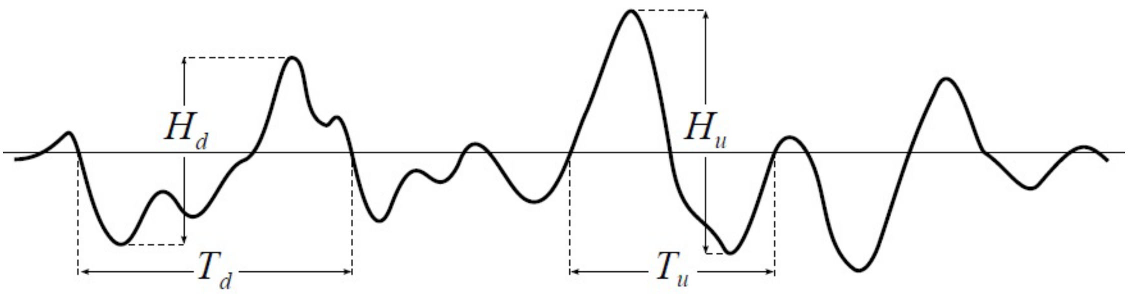

Figure 7 Surface elevation time traces showing the measurement of the zero-up crossing wave period Tu and height Hu, zero-down crossing wave period Td and height Hd. (image taken from (3))

An advantage of this approach is the simplicity of the calculation, minimising the potential to violate any inherent mathematical assumptions or introduce noteworthy analysis errors. A disadvantage however is that there is now no direct relationship to the associated wave energy/power contained within the irregular sea state. Thus, assumptions and approximations must be introduced to establish this connection.

The two approaches discussed above are independent of each other and thus there is no formal relationship between H_{m0} and $H_{1/3}$. Unfortunately an assumption sometimes made within the industry is that both these metrics are the same (due to the common label 'significant wave height') and are completely interchangeable. Differences between these two however could be expected to be as large as circa 10%. Thus depending on the objective of the analysis one metric may be more suitable to employ than the other, but the underlying assumptions and constraints must be well understood.

As the wave industry progress and more and more real wave data samples are recorded, research efforts could focus on establishing a more robust empirical relationship between these metrics and a better quantification of the interdependencies on various other ocean wave conditions.

5.2 Wave Period

Wave period is another very important parameter which has multiple definitions, applications and domains of validity. One key source of confusion can stem from the descriptive titles/labels that have been given to each wave period metric. As a result, knowledge transfer and dissemination of result between two /institutes can be more susceptible to misinterpretation/miscommunication. Similar to the significant wave height, wave period can be calculated using either spectral or time domain analysis techniques, both of which are discussed here.

5.2.1 Spectral Domain

Employing spectral analysis techniques undoubtedly provides a richer variety of options for the definition of the wave period of an irregular sea state. This choice however inherently carries with it more opportunity for misunderstanding and inconsistent usage. The definition of the most commonly used spectral wave period parameters are listed below followed by an explanation of each of their strength and weakness as a practical metric.

i. Energy period: $T_{-1,0} = \frac{m_{-1}}{m_0}$

ii. Mean period: $T_{0,1} = \frac{m_0}{m_1}$

iii. Zero-crossing period (spectral): $T_{0,2} = \sqrt{\frac{m_0}{m_2}}$

iv. Peak period $T_p = \frac{1}{f_p} \quad \text{where} \quad \left.\frac{d\,S(f)}{df}\right|_{f=f_p} = 0$

where again each m_n variable is the n^{th} moment of the non-directional energy density spectrum *S(f)* calculated from equation [2].

Energy Period – has its origin as a wave period metric from a calculation of wave power (see Section 5.3) in deep water. It describes the period of the equivalent monochromatic wave which transmits the same amount of energy as the irregular sea under investigation. Usually a preferred metric across the industry due to its link with wave power calculations, however, its origin in deep water wave analysis means that's its usage for nearshore waves may not be as robust.

Mean Period – truly an average metric as it is based on the mean of a continuous distribution function using standard mathematical moment calculations. Similar to the energy period, this is also a stable metric due to the use of the lower order spectral moments. The authors of (17) show in the intermediate water depth region (typically 10m-20m), if a sea state is defined in terms of T_{01} and H_{m0} then the incident wave power is better conserved across a broad range of energy density spectra/frequency bandwidths. Conversely, if a sea state is defined according to the energy period, then the incident wave power of intermediate water depth waves was found to vary more significantly depending on the bandwidth of the energy spectra assumed. For example, the incident power of waves in intermediate water depths with a Bretschneider energy spectra is similar to the power in a JONSWAP spectra (with a more peaked distribution) if the mean period T_{01} is used to define the spectra instead of the energy period T_{-10}.

Zero-crossing period – the spectral formula to determine the period with which the surface elevation crosses the still water line (similar to the illustration in Figure 7). An attractive feature of this metric is that theoretically, there is a direction connection between this spectral zero-crossing period and that calculated from a time domain analysis (see Section 5.2.2). However, from a practical perspective, when analysing real wave data samples recorded from in-situ sensors, the usage of a higher spectral moments m_2 can introduce noteworthy instabilities in the calculations. This is due to its weighted dependency on high frequency information which is more susceptible to sensor limitations, signal-to-noise ratio issues and artificial spectral harmonic etc. Unless careful treatment of the raw data is conducted prior to analysis this metric is prone to larger errors. Thus it would not be the preferred primary metric with which to assess the period of real irregular wave conditions purely from a practical implementation perspective.

Peak period – is the wave period which carries with it the single largest portion of energy within a given sea. Although it has some use in theoretical ocean wave analysis it is of almost no practical use when analysing real ocean data. The largest drawback of this period metric is that for the most common type of ocean conditions, which tend to be fairly broad-banded in their frequency content, it has no reflection of the total energy content of the sea state. E.g. a sea state with a Bretschneider energy spectrum can have a dramatically different incident power to a sea state with a JONSWAP spectrum when the peak periods are the same. However, if the sea state has a fairly narrow-banded or peaked frequency spectrum (often described by a peakedness parameter or the Gamma parameter in the case of a JONSWAP spectrum for example), the peak period will converge closer to the other period metrics and so can be of some use.

5.2.2 Temporal Domain

As with significant wave height, the time domain wave parameter is a zero-cross based metric and can be defined as either an up-crossing (T_u) or down-crossing (T_d) parameter. Figure 7 illustrates the two scenarios, which converge to the same value for a sufficiently long surface elevation time trace.

Again an advantage of this metric is its simplicity, minimising the potential for analysis errors and possible mix up between different wave period metrics. Similar to the significant wave height, the key disadvantage is that there is no direct connection between this metric and the energy content or incident wave power of the irregular sea state. Thus further assumptions must be made to make this connection which carry with them a degree of error and imprecision.

5.3 Wave Power

The incident wave power (P_{inc}) of an irregular sea state in any water depth d can be calculated using the spectral equation:

$$P_{inc} = \frac{\rho g}{2} \sum_{n} (A_n)^2 \, C_g(f_n, d) \qquad [5]$$

where A_n and C_g are the wave amplitude and group velocity of the f_n frequency component of the sea state (ρ and g are the water density and gravitational acceleration respectively). The equation for the group velocity of a particular wave frequency in a specified water depth can be found from many standard linear wave theory text such as the coastal engineering manual (21). This is the most generic and robust formulation of incident wave power.

In the <u>deep water limit</u>, the formulation of the group velocity term can be simplified to $C_g(f_n, d) \rightarrow \frac{g}{4\pi f_n}$, and the relationship between the spectral wave amplitude and energy density is $A_n^2 = 2\,\Delta f\ S_n$. Thus, employing these relationship along with equation [3] and that of the energy period it is easy to show that

$$P_{inc} = \frac{\rho g^2}{64\pi} (H_{m0})^2 T_e \qquad [6]$$

in kW/m. This is the more industry-familiar definition of incident wave power but it must be noted that it is only valid for deep water ocean wave and also under the idealised assumptions behind H_{m0} as calculated from equation [3]. Thus it may not be an accurate assessment of the wave power in intermediate water depths and so equation [5] should be employed as the preferred calculation.