COMMISSION OF THE
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Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

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Deliverable D3.3
Assessment of current practice for tank testing of small marine energy devices

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Assessment of current practice for tank testing of small marine energy devices

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Summary

At present no common practices are adopted to assess the performance and operational characteristics of conceptual and small prototype wave and tidal energy devices when tested within controlled laboratory environments. Information acquired from this early stage assessment may be used to secure development funding or promote a specific wave or tidal energy device. Since no standards exist, the data produced may be misinterpreted or inaccurately presented, which in turn may lead to failure to live up to performance expectations, as devices scale up in size.

This report aims to identify limitations of current practices adopted for tank testing of small prototype devices and the development of new methods enabling device performance assessment and benchmarking. The contents of this report will be tightly integrated with the remaining deliverables of WP 3, specifically Deliverable 3.4.

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1. Introduction

At present no common practices are adopted to assess the performance and operational characteristics of conceptual and small prototype wave and tidal energy devices when tested within controlled laboratory environments. Information acquired from this early stage assessment may be used to secure development funding or promote a specific wave or tidal energy device. Since no standards exist, the data produced may be misinterpreted or inaccurately presented, which in turn may lead to failure to live up to performance expectations, as devices scale up in size.

This report aims to identify limitations of current practices adopted for tank testing of small prototype devices and the development of new methods enabling device performance assessment and benchmarking, in accordance with Annex 1 – Description of Work of the EquiMar project, where task 3.3 is defined:

Task 3.3 Assessment of current practices for tank testing of small marine energy devices

Currently proof of concept tests for most devices are conducted at model scale. Each laboratory has its preferred procedures making equitable comparisons difficult. This task will examine the current practices. In a similar manner to that described for Task 3.1, these practices will be tested against a matrix of indicators of appropriateness, accuracy and limitations (e.g. wave/ tidal flow generation and measurement; treatment of model and scaling effects; data acquisition, verification and reduction). Again, where possible, quantitative estimates of uncertainty and error will be identified and used.

The contents of this report will be tightly integrated with the remaining deliverables of WP 3, specifically Deliverable 3.4.

The development stages for a marine energy converter can be split into 5 phases as follows, and this document is concerned with the first two:

Stage 1:	**Proof of Concept – Lab testing small models at 1:50**
Stage 2:	**Design and Feasibility Study – Lab testing models from 1:50 to 1:10**
Stage 3:	*Testing in Real Seas – 1:10 to 1:3*
Stage 4:	*Demonstrator – Sea Trials at 1:2 to full size*
Stage 5:	*Array Deployment*

The objectives of this report are primarily the identification of the limitations of current procedures being widely adopted, which are sources of the errors that pollute experimental results obtained during small scale tank tests; and then identification of the procedure described fully in Deliverable 3.4, designed to mitigate these errors. The errors are captured as limitations in current practice, however it must be understood that no *particular* practice is being critiqued here. This document seeks to draw out generic points that should inform any tank testing methodology.

Through tank testing during Stages 1 and 2, the pivotal questions being asked are those of energy capture and power performance. Outcomes of these tests are typically going to be coefficients of power, thrust, torque and so on. These coefficients, as well as being dimensionless parameters which inform scaling and allow comparison between different devices, are the output of data reduction equations (DRE). A DRE is a statement of the form (here for example the power coefficient for a tidal devive) $C_P = C_P(X_1,X_2,\ldots,X_n)$ for n measured individual variables X, such as wave period, significant wave height, or carriage velocity, blade thickness, shaft torque and so on. Therefore any errors, variability or inconsistencies in measuring the variables X propagate through the DRE into the calculated value and a lack of awareness of these will prohibit the result of a particular experiment being directly comparable to another, separate experiment, either in the same facility or elsewhere.

2. Test Management Practices, Reporting and Documentation

2.1. Context

The purpose of scale model testing is to provide information for the developer, with a view to:

- establishing values of key performance parameters;
- optimising certain aspects of the design;
- calibrating mathematical or computational performance models; or
- securing funding for further development.

Current practices mean any reports produced from a testing program remain confidential. Conference or journal publications may follow at a later date, but the format of these varies with the different testing objectives. So, as far as reporting is concerned it is difficult to establish current 'best practice' with any precision. Future best practice should of course aim to capture comprehensive and accurate data in the most cost-effective way, so that decisions on progress are well-founded and money is not wasted.

2.2. Design of test programme

In any experimental test, unless the facility owner is undertaking the testing, agents for both the developer and facility operator will be involved. Therefore, the relationship between the developer and facility operator is likely to follow one of the following patterns:

i. The developer will hire the facility, provide the test model and conduct supervised tests at the facility. The developer will be responsible for experimental design, sensors used in measurements and data collection and processing; the facility operator role will be restricted to ensuring the safety of the staff, client and facility.

ii. The developer will hire the facility, and commission the operator to construct a model and perform some experiments on it as specified by the developer. The operator will determine and implement the required experimental setup and data collection, and at the end of the experiment the developer will receive data and results, possibly without supporting contextual information.

iii. Some pattern between these two extremes, where there is shared responsibility between developer and facility operator for the planning and conduct of the test programme.

There are clearly potential pitfalls in the first two cases. The construction of the model and the implementation of the test programme might be undertaken without adequate professional oversight, leading to spurious results. And a developer presented with a set of test results may not fully understand their context, and the extent to which they may be extrapolated to other cases.

There is a further technical issue: test facilities which appear to be similar may produce significantly different results when testing the same model. This is a widely recognised problem, and will be addressed in a forthcoming EC FP VII Infrastructures programme MaRINET. Currently, results presented are likely to have a degree of uncertainty from the tolerance levels associated with experimental data and subsequent processing.

2.3. Reporting

Responsibility for reporting to the budget-holder, stakeholders or interested parties lies with the developer or his contractor. Because of confidentiality, there will be no professional scrutiny outside that which can be provided within the developer's team or appointed agents undertaking due diligence. The report will normally be used to assist in decision-making, so it is essential that the validity of the experimental process and the limitations of the results are fully understood. One of the decisions is likely to concern the securing of funds enabling progression to a larger scale, so the effects of scale (elaborated in chapter 3. below) are of particular relevance. The implementation of 'Quality Control' is essentially a matter of professional competence, and self-regulation. It is in the broad interests of all concerned that the highest standards should be attained.

3. Limitations in Similarity and the Laws of Similitude

Primary Scaling Limitations

Tidal Devices | **Reynolds Scaling Generally Unattainable** – device is normally fully submerged therefore Reynolds scaling should be used. But this is almost impossible to achieve for small-scale models. Froude scaling is not appropriate for determination of power output or structural loads.

Wave Devices | **PTO Scaling** – Generally, the hydrodynamics of the wave devices dictates the use Froude scaling, as inertia is the dominating force. However, this does not apply to the PTO of such devices. Therefore, it does not make sense to attempt to deploy a scaled version of the PTO in the scale model for tank testing. Instead, efforts should be made to ensure correct modelling of the effect of the PTO on the hydrodynamic system, as their responses are heavily linked.

In order to test a model within the confines of a test tank and produce results relevant to an up-scaled prototype, it is important to observe the Laws of Similitude. These relate various device parameters between scaled model and prototype; and ensure that the scale model reproduces as faithfully as possible the responses of the prototype. In many cases, this has not been taken into consideration, further requiring caution when reviewing post-test performance data. When defining a scale ratio there exist three levels of similarity that must all be satisfied if scale model testing is to be completely similar to the prototype:

Geometric similarity – the device geometric dimensions must be scaled;

Kinematic similarity – geometric similarity plus all (fluid and model) velocity ratios must be the same at model and prototype scale;

Dynamic similarity – kinematic similarity plus all (fluid and model) force ratios must be constant.

Analysis proceeds by identifying all parameters required to describe the system and expressing them as dimensionless groupings using well established techniques, for example the Buckingham-Π theory. This gives rise to the following groupings, which are expressed as force ratios:

Froude number = (inertial force/gravity force)$^{1/2}$ = $\frac{U}{\sqrt{g \cdot L}}$

Reynolds number = inertial force/viscous force = $\frac{\rho \cdot U \cdot L}{\mu}$

Weber number = inertial force/surface tension force = $\frac{\rho \cdot U^2 \cdot L}{\sigma}$

Cauchy number = inertial force/elastic force = $\frac{\rho \cdot U^2}{E}$

Euler number = pressure force/inertial force = $\frac{p}{\rho \cdot U^2}$

A model is said to be a similitude model if it satisfies dynamic similarity. Unfortunately **only one force ratio can be identical between full size prototype and scale model, and complete dynamic similarity is therefore impossible**. The most relevant force ratio in most hydrodynamic cases is the Froude or Reynolds number, but it has to be confirmed that scale effects due to the others are relatively small. The values of the rest of the force ratios are not identical and may result in non-negligible scaling effects. The larger the scale ratio , the more deviation will occur in these force ratios and the larger (potentially) are the scale effects. Results from a scale model up-scaled to full scale would therefore not agree exactly with the observations at full scale. However, if the scale ratio is small, scale effects may be negligible.

Froude number scaling is desirable in cases where gravity driven phenomena are to be examined: for example considering device motion at very low speeds under the effects of gravity and buoyancy, where the ratio of hydrodynamic and inertial loads to gravitational loads is important – in such situations, gravity is providing one of the forces required for equilibrium.

In conditions where the fluid velocity is such that hydrodynamic loads render the loads due to gravity insignificant, or when the device experiences severe viscous effects, Froude number scaling is inappropriate and Reynolds similarity criteria are applied.

3.1. Limitations with Scaling Laws and "Rules of Thumb"

Under certain conditions it is impossible to practically or meaningfully apply dynamic scaling laws. A particular example is the testing in a cavitation tunnel of a tidal turbine in the absence of a free surface. In this situation, the Froude number scaling as defined is meaningless, as gravity does not play a significant role unless the turbine is mounted on a horizontal cantilever and is not neutrally buoyant (and even then, Froude number is not the appropriate scaling law as the motion in concern is of a structure rather than just the fluid). Euler number matching can yield an appropriate inflow velocity and Reynolds number matching can be used to yield a corresponding rotational speed. Unfortunately in this situation, the calculated rotational speed will be exceptionally high. Normal practice in this situation is to assume that Reynolds scaling is unattainable and to use Euler (or Froude) scaling to inform inflow velocity and then use a kinematic relation, in this case the tip-speed-ratio, to specify the rotational speed. As always with engineering there is a compromise.

Accurate prediction of scale effects is complex and carries some uncertainty. Some rules of thumb are often applied in hydraulic modelling to avoid major scale effects. The following may be relevant for tidal or wave energy converters:

- Kinematic scaling is often appropriate where dynamic scaling by the obvious laws is problematic or physically impossible. This is most apparent in testing turbines in water, where it is generally impossible to Reynolds number scale. Kinematic considerations (tip-speed-ratio TSR) are applied, possibly along with Froude number scaling.
- Scale effects increase with decreasing model size.
- Wave periods in a model should not be smaller than 0.35s. Waves with smaller periods are considerably affected by surface tension and propagate as capillary and not as gravity waves.
- The depth of flowing water should not be smaller than about 0.04 to 0.05 m to avoid considerable scale effects due to surface tension and fluid viscosity. This limitation may be relevant in tidal or wave energy converters (e.g. overtopping devices).
- Phenomena involving air entrainment require scales larger than 1/8th (1:8) to avoid considerable scale effects. Air bubbles do not scale and have a similar size in the model and its prototype.

- The investigation of cavitation in a physical model is challenging. Cavitation depends on the local pressure in a fluid relative to atmospheric pressure. The correct modelling of cavitation requires a reduction of the atmospheric pressure in accordance to scale.
- Tip-speed, velocity and other kinematic ratios can provide parameter values where dynamic scaling laws fail, or are problematic.
- Due to the scale ratio of power (being the length scale factor to the power of 3.5) the length scale factor applied in laboratory tests of wave energy converters should not be too large. Limitations on the level of power which can be measured and controlled in a reliable manner will typically lead to maximum length scale factors of around 1:40 – 50.
- In cases where extreme loading/survivability are being investigated (and not power production), higher length scale factors (up to 1:80 – 100) can be appropriate.
- Turbulence intensity is measured in terms of the standard deviation (equivalent to the root mean square of the fluctuating component) of the current velocity over the mean velocity, and allows some measure (via calculation of turbulence length scale) of the flow input turbulence characteristics.

3.2. Dimensional Analysis

Writing parameters and results in dimensionless form has the following advantages:

- model results can be transferred to the prototype without scaling ratios;
- dimensionless parameters are identical between the model and its prototype whereas dimensional parameters are not;
- results of models at different scales can directly be compared in one diagram; and
- the number of output parameters reduces.

It is therefore recognised that errors will be introduced wherever dimensional parameters are used.

4. Test Facilities: Limitations Associated with Current Practice

4.1. Limitations Associated with Testing in Towing Tanks

Primary Towing Tanks Limitations

Tidal Devices

Blockage Ratio – device occupation of finite space leads to interaction with facility boundaries.

Carriage Shake – sensors on devices will potentially pick up any vibration in towing carriage motion.

Carriage Speed Tolerance and Uniformity – The accuracy of speed control and tolerance over the tow run velocity may impact on the power capture and transfer performance and will be influenced by the inertia of the turbine rotor and power take off.

Low Turbulence – wake dissipation time increased; particles for visualisation may settle out.

Carriage Driving Gear – may cause EM interference with signals; may be too low to overcome tidal device thrust.

Wave Devices

Limited Wavefields – only long crested waves can be modelled effectively.

High Aspect Ratio – mooring footprint limited by tank width.

Side Wall and Beach Reflections – device will necessarily be close to sidewalls.

Towing tanks are facilities designed originally for naval architecture work whereby a hull model for a ship would be suspended in the tank, and towed along behind or under a dolly or carriage, with measurements taken of drag, buoyancy, sideways thrust, etc. In recent times, many tow-tanks have been equipped with wave-makers, downstream energy absorbing beaches and 6DOF (degrees of freedom) sensor equipment and used for sea-keeping tests on vessel models. These capabilities, along with the significant size of some facilities and modern control capabilities on the tow carriages make these an attractive proposition when testing both tidal and wave devices.

The application of tow tanks to tidal device testing is intuitive, and towing tanks equipped with wave generation systems that can produce long crested monochromatic and panchromatic waves have three applications for wave energy trials.

For wide terminator type devices, a section of which will span the tank, (i.e. breakwater OWCs) they may provide 2 dimensional test capabilities that furnish results particularly suited for mathematical model development, calibration or validation.

For point absorbers, and in particular long attenuators (e.g. Pelamis) the larger facilities (width > 8m and length > 30m) can be useful for performance trials since they might accommodate a bigger scale device. PTO control trials might benefit from such facilities providing the sidewall effect of reflecting device-radiated waves can be tolerated. Mooring arrangements may also require modification.

Deployment and recovery techniques can be investigated, particularly the towing phase of the operation.

4.1.1. Characteristics of towing tanks

- The principal characteristic of a tow tank is a very large length to breadth ratio, a characteristic that makes the provision of 2D waves highly problematic. Furthermore, some facilities may be quite shallow relative to width, limiting the nature of devices that may be tested.

- All tanks possess a carriage mounted on rails either side of the tank along the main axis. This carriage carries the test piece(s) and any additional actuators, control and monitoring systems. Devices may be rigidly mounted to a hard-point on the carriage, literally towed behind on a flexible line, mounted to additional actuator(s) to provide various desired motions or, in the case of a self-propelled vessel, the carriage will follow the vessel along the tank.

- Towing tanks can be used to test devices without towing them, either by attaching the device to the tank itself, as in the case of mooring systems or wave device tests, or suspended from the carriage, or other suitable mounting. In these cases tow-tanks with wave-making facilities can test mooring strategies survivability, etc. only if the width allows the anchor footprint

- Wave-making and towing can be combined to model controlled wave/current (and possibly even wind) interactions, conditions that are difficult to achieve in outdoor test facilities, with significant repeatable control over the input conditions. The hydrodynamic characteristics are somewhat different from those encountered in, say, a cavitation tunnel or flume: as the fluid is notionally at rest, turbulence intensities automatically decrease after each test, ultimately meaning that very low turbulence levels can be obtained assuming one is prepared to wait a sufficient time period between runs to allow the tank to settle and wakes to dissipate. A corollary to this is that if the fluid is to be seeded for flow-visualisation purposes, or if particle based velocity measurements are required then some agitation or re-seeding will be required to achieve a thoroughly mixed particle distribution if particles have been allowed to settle out between runs or overnight.

- Due to the sometimes very large size of towing tanks, it is often problematic (i.e. expensive and time consuming) to raise or lower the fluid level. This may prove awkward if results at various depths are sought. Wave paddles may be fixed

- As the carriage speed is dictated, the effective inflow velocities for tidal devices are easy to determine.

- As the fluid is notionally stationary, there is no boundary layer development.

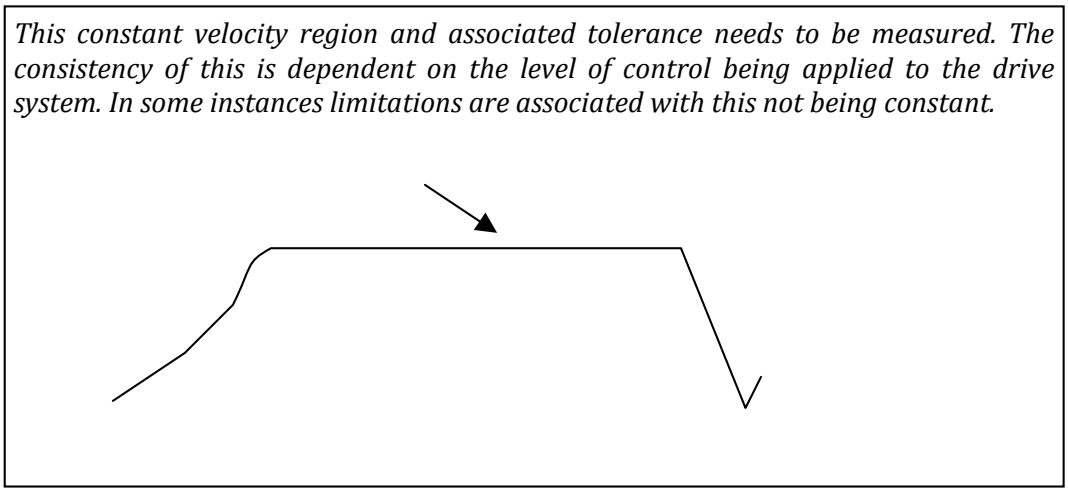

Figure 1: Diagram of typical carriage velocity characteristics along tank length.

4.1.2. Limitations with physical model effects for TECs

- **Blockage ratio**: as the channel breadth and depth are relatively short compared with the length, it is possible that a scale device will occupy a significant portion of the channel cross sectional area. In this situation, the proximity of the channel sides and bottom will alter the flow-field in the vicinity of the device as compared with a device in isolation, as a specific example fluid which would normally flow around the device may be forced through the device instead, potentially altering the power characteristics. Vertical expansion of the wake will be inhibited by close proximity to bed/water surface. This will affect rotor characteristics giving performance characteristics that cannot be attained in open sea conditions.

- **Limitations with issues of carriage shake**: it is possible that accelerometers may detect vibration from the carriage, and that vibration will be detected by instrumentation being used e.g. strain gauges, velocimeters, etc.

- **Limitations with particle settlement:** particle-based flow measurement methods are affected by settlement of particles seeded in the water during periods of settlement (usually overnight).

- **Limitations associated with ambient turbulence levels being very low**: may alter device performance through lack of energy at the top end of the energy cascade (i.e. large scale turbulent structures will not leech energy into device boundary layers); wakes may not dissipate as quickly as in more developed turbulence. Turnaround between runs may be significant if time is allowed for the tank to become quiescent if consistently low turbulence states are required.

- **Limitations associated with carriages being self-propelled**: this necessitates various high power electronics systems to be mounted on the carriage, and also large lengths of cabling being used. EMC and interference from these onto measurement systems can be an issue.

- **Carriage power**: Smaller tanks with overhead towing might not have sufficient power to tow a model tidal device at the desired towing velocities in order to overcome resistance in e.g. drag created by the test model and the drive-train.

4.1.3. Limitations with physical model effects for WECs

There are four main considerations when assessing the use of wave tanks for scale device testing:

i. Often only long crested waves can sensibly be produced so any device sensitivity to energy spreading or main approach direction will be missed.

ii. The tank may be relatively narrow with respect to the scaled device so a full mooring configuration may not be possible; however it is of course possible to model the effect of mooring systems in order to investigate appropriate compliance levels etc.

iii. Primary wave reflections from the downstream energy absorbing beach will also be present to some degree and must be accommodated in the test methodology and/or the data analysis techniques.

iv. The aspect ratio of the tank may result in transverse reflections of the radiated wave being induced from the sidewalls in narrow tanks. In essence tests can be regarded as array layouts where the adjacent device is located the width of the tank away.

4.2. Limitations Associated with Testing in Flumes and Water Tunnels

Primary Flume and Water Tunnel Limitations

Tidal Devices	**Blockage Ratio** – device occupation of finite space leads to interaction with facility boundaries. **Non-uniform Velocity Field** – velocity distribution may have variations in all spatial directions, and in time. **High Turbulence Intensity** – the turbulence intensity may be high, the turbulence may not be homogeneous and zero-mean velocity fluctuations may require long data collection runs or may not be obtainable. **Facility Characteristics** – facilities are often ex-civil engineering and have issues with, e.g. water clarity, pump performance consistency, vibrations etc. **Access Limitations to Closed Tunnels** – access restrictions to fully enclosed working sections will delay device modification during experiments.
Wave Devices	**See Towing Tank** – flumes are essentially similar to towing tanks from a wave-energy point of view.

Circulating water tunnels are a hydrodynamic extension of the wind-tunnel concept: essentially, water is pumped though a working section where the test-piece is mounted and the water is re-circulated once it reaches the end of the working section. There are two main types: open flumes and closed tunnels – the difference being that flumes possess a free surface and that closed tunnels can be run at non-atmospheric pressures to reduce or increase the incidence of cavitation (hence the term cavitation tunnel). As with wind tunnels, the fluid is pumped through a series of baffles and guide vanes, and possibly a settling chamber before re-entering the working section, in order to control turbulence to some extent. Traditionally cavitation tunnels have been used for propeller testing, thus they are typically well established for testing the turbomachinery

types associated with tidal turbines. Flumes are traditionally used in civil engineering and naval architecture, and as such may be fairly shallow. Flumes may be gravity fed or an open tunnel.

4.2.1. Characteristics of flumes

Circulating water around a static model device holds a number of advantages:

- As the device is statically mounted and flow conditions can generally be maintained for some time, tests such as wake measurements, array investigations and PIV visualisation are more easily accomplished than with a towing tank.
- Various bed and side roughnesses can be deployed allowing a range of boundary layer profiles to be developed.
- Flow measurements can be acquired quickly and with good spatial accuracy. Device measurements where steady flow conditions are required can also be gathered in an effective manner.
- A level of ambient turbulence higher than that possible in a tow tank can be maintained.

Figure 2 shows diagrammatic representation of two types of flume. Gravity-fed flumes are named based upon the effect gravity has on the water cycle. Water is lifted from a sump and deposited at the upstream end of the working section. Motor/pump arrangements are generally fixed speed with an in-line resistance valve providing flow regulation. At the end of the working section the water falls back down into the sump, generally over a weir or similar control gate. This structure provides depth control in the working section via the creation of a backwater profile. Generally indoor flumes are either entirely Perspex or have viewing windows allowing visual/laser monitoring of flow phenomena and device performance. Depending upon the nature of the inflow to the working section gravity fed flumes can have good isotropic turbulence characteristics. When inoperative the working section is drained and all water resides in the sump tanks. This tends to limit the instantaneous volume of water in the working section (or for a specific facility the working water depth) as there has to be a finite volume of water always present in the sump in order to feed the pump(s). Advantages to a gravity fed flume are that access to the working section is simplified as it can be drained down. The water depth is easily controlled via the tailgate. Gravity-fed flumes can suffer from the fact that the two desired variables, water depth and velocity, are determined by two controllable variables, pump speed and control gate height. Thus if a specific depth and velocity are needed, an iterative approach may be required when adjusting pump speed and control gate height.

Open water tunnels are fully flooded. Generally variable-speed motors are used in order to regulate flow speed. Honeycomb or other methods of flow straightening are often employed to reduce vertical motion in the water as it enters the working section. Open tunnels are often deeper than gravity fed flumes and volumetric flow rates are often greater as there are no issues with sump storage volume. Installing structures on the flume bed is more difficult (and often not used) unless the tank is drained down which can take a long period of time. To this end, varying depth experiments are also more time consuming, as water levels must be adjusted via draining/filling.

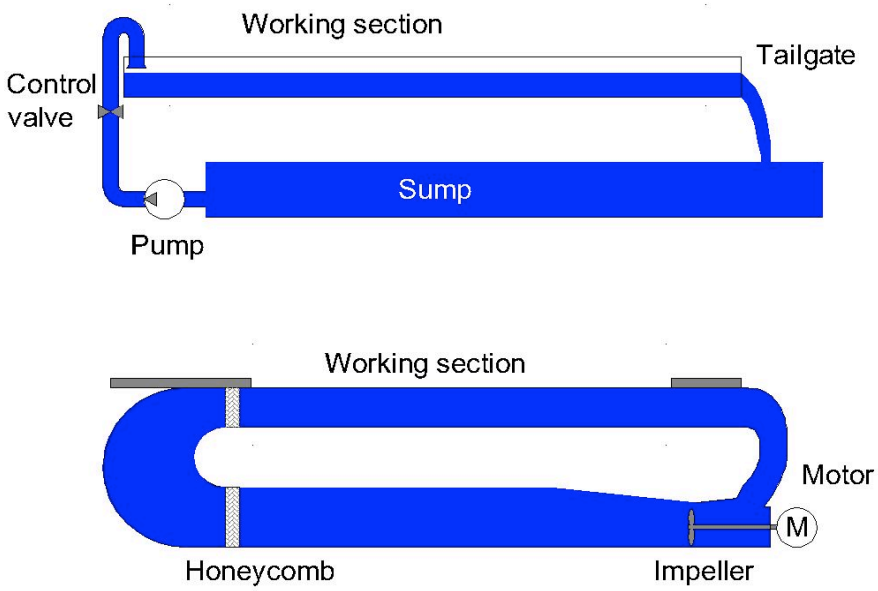

Figure 2: Schematic diagram of 2 types of flume: Gravity fed (top) and open tunnel (bottom)

4.2.2. Characteristics of enclosed water tunnels

Enclosed water tunnels have similar characteristics to open-surface tunnels described above. With airtight seals pressures in closed tunnels can be increased or decreased relative to atmospheric pressure. Historically this has been used in the maritime industry to simulate marine propeller operation at varying depths in order to study cavitation. They are perhaps less useful for tidal energy testing unless pressure-specific issues are of interest. Access to the working section is often restricted by heavily sealed panels and thus access and installation issues may be significant.

4.2.3. Limitations of model effects for TECs

- **Non-uniform velocity distribution**: for example the cross sectional velocity profile may not be symmetrical about the vertical axis, and may not necessarily have an expected vertical velocity profile.

- **Non settled working section**: There may also be variation in the cross sectional velocity profile of the flume as you travel downstream, with flow reflections off flume walls where at no point does the flow 'settle' to one profile. Obviously in real circumstances it will never settle perfectly, but a degree of consistency in the working section is desirable.

- **High turbulent intensity**: It is generally desirable to have a lower and more consistent turbulence intensity than may be encountered and the turbulence may not be homogeneous.

- **Water clarity**: required for taking pictures, videos, using LDV, or ribbons (or general visual monitoring). Often tanks have been used for civil engineering work involving suspended particulates and sediments. Generally it is a case of cleaning out the sump, and replacing the brickwork, however this may not be practical. The cleaning method for some flumes is invasive, potentially causing turbine models to become clogged.

- **Consistency of pump performance**: if the flume characteristics are being set by pump level, the pump performance must be consistent, both in the short and long terms. If pump temperature increases during use, it may be that the flow-rate varies.

- **Pump vibrations**: the pump may be located in such a way as to cause significant vibrations on the support structure of the flume, possibly affecting instrumentation and measurement devices.

- **Turbulence characteristics**: a major caveat is that full-scale turbulence is incredibly varied and site-specific, poorly understood and difficult to scale.

- **Model placement**: should ideally be where flow characteristics are stable with downstream. This should be measured/ quantified before testing, private facilities for hire may already have this information.

- **Water temperature:** can vary throughout the day due to turbulence adding heat, outdoor air temperature, etc. and can also be seasonal/ diurnal driven. This will affect water density (very small), and viscosity (more significant). These issues can be important for numerical modelling.

4.2.4. Limitations of model effects for WEC

Only deep-water (> 0.5m) wave flumes are of relevance to WEC testing. These can be similar in dimension to towing tanks but evolved from coastal engineering requirements so do not have a movable carriage. Developed principally for 2 dimensional testing they are often narrower than towing tanks to facilitate the generation of large waves for acceptable energy input requirements to the paddles. In general the comments made with respect to towing tanks are also appropriate for this type of wave facility.

4.3. Limitations Associated with Testing in Wave Basin (3D)

Primary Wave Basin Limitations

Tidal Devices	Not Applicable
Wave Devices	**Reflections** – there are *always* some reflections from the beach, thus two in phase but opposite direction wave systems at the test point in the tank. **Settling Time and Sample Length** – coherent irregular wave fields take some time to reach dynamic equilibrium; wave signal and sample lengths must be sufficiently long so all parts of the spectrum are encountered. **Facility Specific Performance** – single hinged wave paddles do not produce pure sinusoidal wave profiles.

Figure 3: Stage 1 Wave Basin

Wave basins are water tanks that are relatively wide compared to their length, indeed they can often be over square in certain establishments, perhaps when floor space has been limited. Wave generation systems are installed along one, or sometimes two adjacent, walls. Like towing tanks and wave flumes wave basins are available in a variety of sizes that can accommodate both Stage 1 (circa λ = 1:50) and Stage 2 (circa λ = 1:10) WEC scaled device test programmes. A physical size limitation factor is often the power required to generate the wave at a facility but modern, more efficient wave producing systems are alleviating this constraint.

Wave basins have several different origins, but mainly sea keeping and maneuvering tanks for the ship building industry, deep basins for the offshore engineering for the oil and gas industry and shallower facilities for coastal protection work. The depth of the basin is usually linked to the initial purpose of construction but, often, advanced facilities have either movable floors or deep pools built in.

4.3.1. Characteristics of a wave basin

- The primary purpose of a wave basin is to facilitate full 3 dimensional (or quasi 3D) scaled device testing in realistic seaways.

- To achieve this, a sophisticated wave generation system is required similar to that shown in Figure 3.5.1. A bank of separately controlled paddles (flap or piston) is installed along at least one side of the basin. These can move in unison to produce long crested monochromatic (single frequency) waves or long crested panchromatic (multi frequency) irregular seaways. They can also be controlled independently to produce short crested panchromatic wave fields. Some establishments have paddles along two adjacent walls to generate combined wave systems in the basin.

- As with all types of wave tanks an energy absorption beach is required along the downstream wall(s) to minimise the amount of reflections that contaminate the test site. Several types of beaches are available and the selection is usually dependant on the water depth. In deep tanks it is often not practical to have a beach that rises from the tank floor.

- Energy absorbing paddles are also advantageous since they prevent a build-up of primary beach reflections and also remove most of scaled device induced perturbations, in particular the radiated waves.

- For most WECs the device induced radiated wave travels away from the origin with a circle wave front. This means the wave height decreases rapidly with distance such that only small reflections from the sidewalls should be expected. However, because of the width of the tank there are many standing wave

modes that can be present in the transverse direction. These can be induced by the progressive wave frequencies and if they are found to exist that particular period must be excluded from the test programme.

- To generate deep-water progressive waves bottom hinged type paddles are preferred since the motion of the flap is more in sympathy with the water particle orbital motion. Piston type paddles have the advantage that water depths can be varied more easily providing the absorption characteristics can also be adjusted to suit

- A difficulty with most types of wave tanks is that the water depth is fixed. For floating body WEC this mainly influences the mooring arrangement that can be accommodated. If the depth is too great device scales can be adjusted to suit the water level and if it is too shallow a basin with a deep section can be engaged. There are also techniques that enable the correct stiffness of moorings to be achieved in shallow water by the use of springs. The ideal solution is to have a movable basin floor which can be found in more advanced facilities

- The effect of marine current on wave energy devices is not well documented at this time. Only a few facilities offer this option for inclusion in scaled physical test.

- As stated above most wave tank facilities have a maximum wave limit that would restrict extreme survival tests at the optimal scale for the device performance trials. This leads to either smaller scale devices during Stage 1 programmes or the transfer of the Stage 1 device to a Stage 2 facility for survival tests.

4.3.2. Model effects for TEC

Testing tidal devices in wave basins is not generally applicable at this Stage 1 scale, however for floating, moored TECs it is often useful to check response to high waves at larger scales (Stage 2) as extreme conditions are not always possible in tidal flumes/tow tanks.

4.3.3. Model effects for WEC

- Even with the most efficient energy absorbing beaches some primary reflections must occur and be present at the monitoring site. For single frequency coherent monochromatic waves this produces a longitudinal partial reflected wave envelope such that the wave height varies along the tank. Irregular wave profiles may be more complex (see 4.4.4. below).

- For floating moored devices significant surge may occur which can take the device into different wave conditions

- The coherent wave fields take some time to reach dynamic equilibrium

- Single hinged wave paddles do not produce pure sinusoidal wave profiles

- Due to beach reflections the two wave systems present at the test site will be in phase but at 180° to each other in direction.

- In shallow water tanks, particle velocities only stabilise around 3 wavelengths from the paddles.

4.4. Wave Generation

There are many forms of wave generation systems available at hydraulic test centers around Europe. The myriad of designs and functionality tends to be a product of the type of wave tank, the age of the hardware and country of origin. Most systems are now computer controlled to produce the drive signal for the system but the actuator mechanisms can vary considerably. The actual paddle drive can be hydraulic, mechanical or electrical and systems can be wet backed or dry backed with a water sealing gusset.

Most wave generators would now be capable of producing single frequency regular waves and pan frequency irregular wave trains. These latter series can be long or short crested in nature. The duration of wave production per test is a bespoke requirement but there are pragmatic rules of thumb.

Regular waves are produced for as long as required to obtain stable results, this can be in the region of 100 waves once tank stability has been achieved.

Irregular wave are usually monitored for a scaled time equivalent to the industrial standard for ocean waves of 20-30 minute. That is approximately 4 minutes at Stage 1 and 10 minutes at Stage 2. This timescale is accepted as being sufficient to measure average quantities (e.g. average power), but if it is desired to produce time histories of variations, generate distributions or include extreme loads then a minimum of around 1000 waves are required. Furthermore, methods such as calculating spectral moments can be used to determine the degree of closeness of the modelled wavefield to the input spectrum.

All wave generation systems operate on the same principal - a Biésel function which relates the paddle displacement to a water volume displacement that produces the wave. This means systems must be commissioned prior to operation to obtain the tank transfer function for each wave period that is within the range of the system.

4.4.1. Wave maker types

- Flap paddle wave maker: are flat vertical plates hinged at the bottom so when driven with an oscillatory motion they partially rotate in a fore and aft arc. They are the usual type of paddle for deeper water flumes and basins. The pitching motion about the submerged hinge is regarded as more inductive to quickly produce the correct water particle orbital profiles which also exhibit the required exponential diameter decay with depth. If water depth changes are anticipated it can be possible to mount the flap generators on a movable frame that can be raised or lowered as required.

  Some facilities have flap paddles with an additional hinge at mid-depth. Both sections can move independently such that pure sinusoidal water surface profiles can be produced. Figure 4.4.2 shows a typical flap paddle.

- Piston paddle wave maker these are also vertical surfaces but they move in a pure horizontal translatory mode. They are useful to produce shallow water waves and accommodate water depth changes more easily than flap paddles.

- Segment paddle wave maker; are relatively new and were designed to offer the advantage that the rotary motion of each segment cancels out the reverse wave so systems can be wet backed without creating chaos behind the paddles.

Figure 4: Flap type paddle

Figure 5: Piston Type Paddle

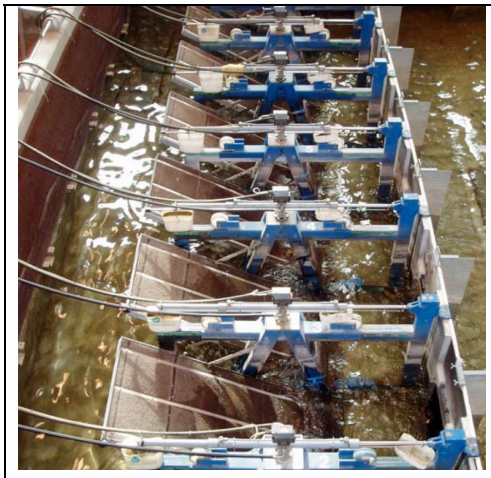

Figure 6: Segment type paddle

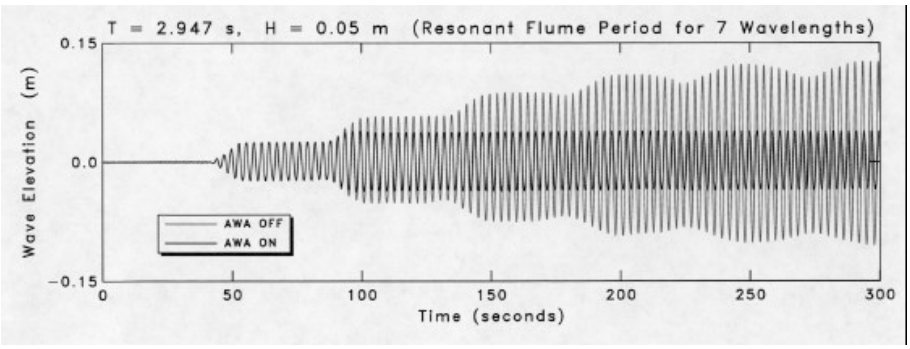

Figure 7: Time history of water surface elevation showing increasing effects of reflections and also the same signal if absorbing wave makers (active wave absorption) are used

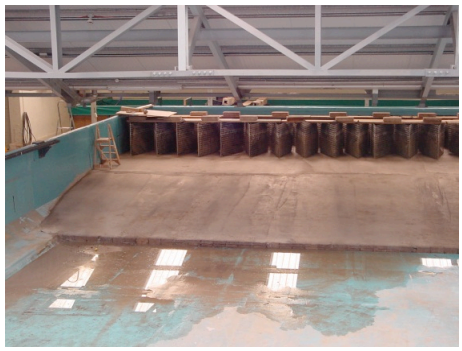

Figure 8: A typical wave absorbing beach

- Absorbing wave maker: It is standard now in most hydraulic facilities that the wave generation system will have a means by which the paddles can absorb any water disturbances travelling towards them. These may be caused by the primary beach reflections or the radiated or reflected waves emanating from the scaled device. This capability ensures the wave field produced in the tank will quickly reach a wave height equilibrium condition as shown in Figure 7. The dark inner oscillatory trace is the water surface elevation with absorbing paddles and the outer growing time series without.

  Absorbing wave makers function by comparing two signals, one representing the programmed wave and the other the actual wave at the paddle. These signals can be measured indirectly as wave induced forces on the paddle or directly as the actual water surface elevations close by the paddle. The latter method means that absorption can be retro-fitted to tank generation systems.

- Absorbing beach: as mentioned above it is inevitable that some degree of wave field contamination must be accounted for in all enclosed water tank experiments. A primary source of this is the reflection of the incident waves from the downstream end wall. To minimise such effects an energy absorbing beach is deployed along that side of the tank. There are many forms of beach depending on the type of tank in question. The ideal beach is a gentle upwards sloping plain tank bottom, circa 1:20. Unfortunately this arrangement requires a considerable length so is not often practical, even in shallow tanks. In deep water tanks it is impossible so whatever the style selected the beach will probably not extend over the full water depth. An adaptation of the plain beach in shallower tanks is to have a steeper slope, circa 1:10 to half depth then a horizontal berm on to which porous absorption material can be distributed, as shown in Figure 8. As the wave passes through this materially the kinetic energy is dissipated thus reducing the wave height.

4.4.2. Gravity Waves

There are three types of wave fields useful for WEC investigations

Wave Type	Description	Function
Regular	Single frequency, monochromatic	Fundamental understanding of the device concept Optimization of device main design variables
Irregular long crested	Multi frequency, panchromatic	Estimate device performance potential in realistic seas Validate survival in extreme conditions

Irregular short crested	Multiple frequencies and directions	Verify long crested result or identify discrepancies

4.4.3. Regular Waves

Sinusoidal waves can be generated at various frequencies and amplitudes depending on the specifications and capabilities of the facility. As in table above regular waves are used to verify and optimise device at particular frequencies – limited application as not representative of real sea states.

4.4.4. Irregular waves

Irregular waves are sea states whose stochastic nature is best described by spectra – these are a means of expressing the wave height and thus energy content in waves of a particular frequency (or period) in the frequency domain. This involves using a Fourier analysis to render an infinite time history of wave heights as a series of power amplitudes binned at different frequencies forming a power spectral density diagram. Since the shape of a wave spectrum is generally dependent on temporal and spatial fluctuations in windspeed over the fetch, determining the spectrum shape becomes an exercise in using probability density functions (such as the Rayleigh distribution) or empirical models based on parameterisation of observed sea states to specify the spectrum. Some common spectra are:

- **JONSWAP spectrum** - a two parameter (windspeed and fetch length) theoretical power spectral density function found to be suitable for fetch limited sea (North Sea)
- **Pierson-Moskowitz spectrum** - a one parameter (windspeed) theoretical power spectral density found to be suitable for fully developed (long time and fetch) sea.
- **Bretschneider spectrum** - a two parameters (significant wave height, H_s, zero crossing wave period, T_z) theoretical spectrum for long fetch sea version of the Pierson-Moskowitz spectrum.

If one observes all the caveats associated with working with signals which have undergone an FFT, specifically allowing sufficient reconstructed signal length and frequency bin phasing, it is possible to synthesize time histories of wave data using superposition of sinusoidal waves at the amplitudes and frequencies encountered in the power spectral density functions of these spectra. This signal is then processed to avoid, say, high instantaneous velocities or displacements which may damage actuators and be fed into the wave tank through the paddle actuators. As with regular waves, the success of this process in producing the desired wave field is entirely predicated upon adequate calibration of the wavemaking facilities to provide knowledge of the transfer function for wave generation.

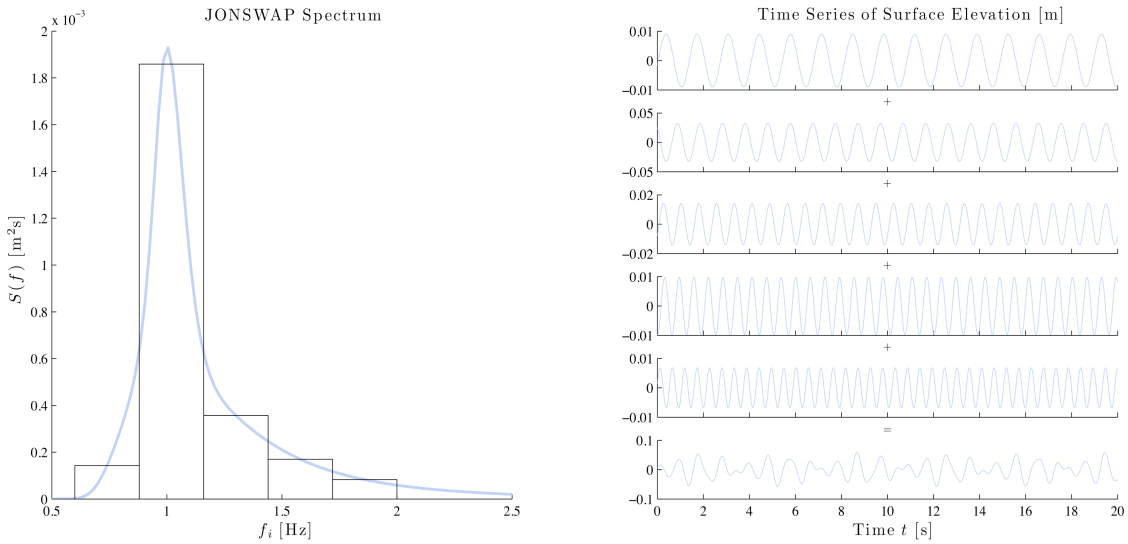

Figure 9: Synthesising of time series of surface elevation from bins of JONSWAP spectrum. This signal is that demanded of the wave makers through the wave tank transfer function(s).

Sophisticated analysis of wave generators and the dynamics of wave basins have allowed wave makers to develop sea states with an incredible degree of control – it is entirely possible to specify the location, amplitude and formation time of a wave and to have the control system generate a tailored wave train. This is useful when it is desired to include a single high amplitude wave superimposed amongst an irregular wave field for survivability assessment, etc. and optimising the wave field in this manner is possible in modern facilities.

5. Limitations with measurement systems

There are a vast number of measurement systems that can be employed during experimental trials. Whilst it is difficult to provide an exhaustive list of all possible systems this document will endeavour to provide the reader with an appreciation of typical levels of accuracy, functionality and some important issues that might not otherwise be apparent. It follows that experimental facilities vary greatly in their specification and operation and that the same measurement instrument might function differently between such locations.

5.1. Water Surface Elevation

5.1.1. Wave Gauge

Types (laser, resistance, capacitance, acoustic) These devices measure water surface displacement e.g. wave height, water level in OWC, water level in overtopping basin etc. based on a point measurement basis. These are susceptible to interference from signal noise if screened cables are not used to protect signal.

- Calibration of wave gauges (generate some waves before calibration (mix the water)); is a simple but laborious task, especially if a large number of probes are installed or they are difficult to access, such as in deep water tanks. From still water the twin wire probe is raised or lowered a fixed, metered distance and the voltage (amperage) change from the signal is noted. This process is repeated over the expected wave height range then reversed back to still water. The same inbound and outbound steps are then repeated in the opposite direction such that a calibration graph of voltage against distance can be produced. This should approximate to a linear relationship (straight line) the slope of which provides the probe calibration. The procedure would now usually be computerised via an analogue to digital converter such that the length scale is expressed as a function of a bit number. With current analogue to digital converters being between 12 - 16 bit, the resolution of wave gauges can be quite fine (i.e. $2^{12,16}$ = 4096 to 65,536 gradations).

- Laser wave probes cannot be used when there are breaking waves as bubbles due to entrained air scatter rather than reflect the laser.

5.1.2. Pressure readings

Pressure sensors can calculate fluid depths – fluid level is proportional to the static pressure. Care must be taken to ensure that the fluid is brought to a halt at the sensor location in order to measure only the static rather than dynamic head.

5.1.3. Drop-depth gauge

Generally in the form of a sharp point attached to a Vernier scale. Manual adjustment to ensure that point is just in contact with the water surface. Can be set up in arrays and only useful for steady-sate situations such as models in circulating flumes under steady flow. Despite the theoretical accuracy of up to ±0.1mm (depending upon Vernier scale) water surface deformities such as ripples will reduce the accuracy. Care must be taken to zero the gauge on the bed. Care needs to be taken to quote tolerances and the readings are heavily influenced by the water surface profile, the smoother this is the more accurate the reading. These should be used in facilities where there are constant or extremely slow moving water surface levels.

5.2. Fluid Velocity

5.2.1. Pitotstatic Probes

Used appropriately pitotstatic probes, normally called 'pitot tubes' can offer very accurate velocity measurements along a single axis notionally aligned with the flow. Measurement is based upon differentiation of static and dynamic pressures within the moving fluid. This differential is displayed on either a fluid-based manometer board (fluid pressures are read off a linear scale) or digitally via a pressure transducer. If pressure can be measured to within ±1mm water gauge then accuracy is extremely high. Fast sampling is not recommended due to the inertia of the fluid between the pitot tube and the pressure vessel which are usually linked with plastic/rubber tubing. Care must be taken to ensure that no air exists in the tubing as bubbles will distort measurements. Errors become greater for lower velocity flows as the pressure differential reduces. Ideally the manometer/pressure meter should be at a vertical height similar to the pitot tube. Most liquid and digital manometers have a number of channels so that multiple pitot tubes can be used in parallel. Digital acquisition also allows better mean averaged flow values to be resolved. The accuracy of these measurements is sensitive to pressure tappings not being blocked and tube not being deformed or bent.

5.2.2. Doppler systems

These are point-measurement methods although technically they acquire the flow characteristics volume averaged within a small volume of the flow. The principle of operation relies upon emitting a wave (light or sound) and measuring the Doppler shift of the return signal as it is deflected by small particles travelling through the measurement volume. The probe head where the emitter/receivers are located is generally situated far enough from the measurement volume that it is considered not to influence the flow within the measurement volume. Care must be taken that sufficient suspended matter exists in the water. Depending upon the internal tank surfaces and water source for any facility there may already be enough matter present. Artificial seeding material can be added to increase signal strengths that will increase instrument accuracy. Laser and acoustic systems are available. Laser systems are large and expensive but until recently were generally regarded as more accurate than acoustic systems. Laser systems are physically large, generally tied to a particular facility and have very stringent health and safety implications on usability and access during tests. In contrast acoustic systems are portable and accuracy has increased in the past years such that the performance is now almost identical to laser-based velocimeters.

Accuracy is dependent upon instrument set up and the concentration of suspended matter. Bubbly or 2-phase flows are best avoided. Regions of very high turbulence and reversing flows are also likely to produce meaningless results.

5.2.3. Hot Wire and Film Anemometers

Hot wire and hot film probes provide a point measurement of velocity. Hot film probes are used where hot wire probes would quickly break down. Hot wire probe heads consist of a number of thin wires that are electrically heated, and hot film probes replace this with a conducting film on a ceramic substrate. Fluid moving past the conductor cools them in proportion to the flow velocity and direction can be determined by including a number of angled sensors on the probe head. Other methods of operation involve the probe attempting to keep either the voltage, electrical current or temperature constant and determining velocity from the degree of regulation required. Probe heads are delicate in nature even more so for water applications where corrosion is a further complication. Hot film probes have an advantage over other measurement systems in that the sensor can be mounted flush against a surface with no physical obstruction to fluid flow. The accuracy of these is however sensitive to large changes in fluid temperature and re-calibration is required under such instances.

5.2.4. Turbine-wheel (cross flow, or propeller)

A drag-force paddle wheel or axial type propeller are rotated by the flow and a voltage output or revolution counter then gives a proportional measure of the flow velocity. Care must be taken to align the probe correctly in the water. Fouling is often an issue whereby suspended or entrained matter can restrict the rotation of the impeller. Use in turbulent flows is also not advised as this will disrupt the rate of revolution of the impeller. Generally the size of the impeller is small in order to minimise velocity shear etc. across the swept area. It follows that smaller diameter impellers are more sensitive to accurate manufacture and imperfections which might compromise accuracy or performance.

5.2.5. Flow visualisation

- Particle image velocimetry (PIV)
- Particle tracking velocimetry (PTV)
- Add tracer particles

Typically these systems require very careful configuration and setting up and require seeding of the water and are typically used for advanced R&D or academic work. This questions the relevance and practicality for general use in scale testing of marine energy converters at development Stages 1 and 2.

5.2.6. Measuring discharge

Whilst velocity is not discharge and vice-versa, both parameters are linked. For example, a 2-dimensional lateral plane of point velocity measurements could be used to estimate discharge within a flume. Similarly discharge measurements can give a value of mean velocity within a flume assuming that the cross sectional flow area is known. This method is of limited use as there will be no indication of vertical or lateral flow profiles within the flume and thus such an approach will provide limited understanding of both flow and device performance.

Discharge can be measured in a variety of ways. Electromagnetic meters can be externally mounted to supply pipes feeding the flume. Hydraulic expressions exist for estimating discharge over a weir which is often used in gravity-fed flumes as a method of downstream depth regulation. Finally, propeller or orifice meters can be internally located in supply pipes.

5.2.7. Turbulence and Shear Stress (Higher Order Flow Effects)

Higher order flow effects can be measured using Doppler systems or hot wire probes whereby velocity can be acquired at high frequency. Depending upon the number of planes that can be measured it is possible to derive expressions for turbulence intensity, turbulent kinetic energy, shear stresses etc. This document will not describe all the possible parameters; it is the responsibility of the competent persons conducting the experiment or responsible for data analysis to ensure that higher order flow effects are measured and resolved correctly.

5.3. Force

5.3.1. Strain gauges

Strain gauges can be used in isolation and are the basic component of many force-measuring instruments. The most common form is a small metallic foil sheet that is bonded to the surface of the structure where strain

measurement is required. The electrical resistance of the gauge varies with length, which will change as the structure is deformed. Gauges come in a range of different sizes, types, resistance values and quality.

Gauges can be adhered to surfaces directly or are incorporated within pre-manufacture instrument such as load cells. These can be placed between model wave/tidal device components to measure translated forces. Other types of gauges include semiconductor types that are more sensitive than foil gauges. Flexible tubes filled with a conducting liquid such as mercury can be used to measure strain on flexible surfaces such as rubber.

A key issue with strain gauges is temperature effects. The object that the gauge is adhered to will change in size as a result of thermal expansion. This will be detected as a strain by the gauge. Resistance of the gauge will also change (due to temperature), and resistance of the connecting wires will change. This can be remedied by arranging gauges in a Wheatstone bridge composed of 4 gauges. A further issue is proper adhesion of the gauge to the surface of the structure where strain is to be measured. The gauge must move perfectly with the surface as it is deformed. One final issue is amplification of strain gauge signals. Gauges are supplied at around 5V but responses can be in the order of μV. Thus signal smoothing and proper amplification are often required. Instruments such as load cells often incorporate amplification within the cell.

Signal response should observe a linear relationship with increasing strain assuming that the material is in the plastic deformation part of the stress/strain curve. User should calibrate gauged components or load cells with verified weights/ forces and zero readings should be taken during experiments. Since these are custom bonded to component surfaces of wave/tidal devices great care has to be taken to ensure structural rigidity in the bonding process and where submersed robust water proofing is essential.

5.4. Pressure

5.4.1. Static Pressure Measurement

Pressure transducers measure fluid pressures on a surface/structure via pressure tappings connected to a manometer bank or transducers. Limitations arise when trying to quantify more local effects e.g. distribution of blade surface pressure, etc. since tappings require significant external area, which limits number and proximity of taps on surfaces, and a large amount of internal tube routing. Therefore, detailed pressure distributions are only likely to be available on large scale (Stage 2 on) prototypes

5.4.2. Dynamic pressure Measurement

Dynamic pressures on blades are difficult to measure due to scale (small thin blades) for tidal device testing. Ideally, gauging/instrumentation should run inside the blade structure to maintain surface profile but generally there is not enough physical space to do this. At smaller scales this introduces limitations in measuring exactly the performance specifically associated with the blade and how much influence the instrumentation has on the performance measured. Prior to testing it is important to undertake a detailed calibration procedure that can differentiate the influence the instrumentation will have on the data being measured.

6. Aspects of physical model design

The range of devices tested at small scale is extensive and thus device architecture specific guidance cannot form part of this document. This section will offer generic guidance for design of device in order:

- To describe some of the current practices for experimental design in tank testing;
- To address some of the difficult issues e.g. how to design an experimental representation of a PTO or measure power for unusual wave energy devices;
- To highlight best practice for both model design and experimental procedure.

6.1. Subsystem approach to model design

As with other technical aspects of the guidelines the concept of device subsystems will be used to address issues surrounding model design. Figure 10 identifies the four subsystems consistent with a generic wave and tidal energy device.

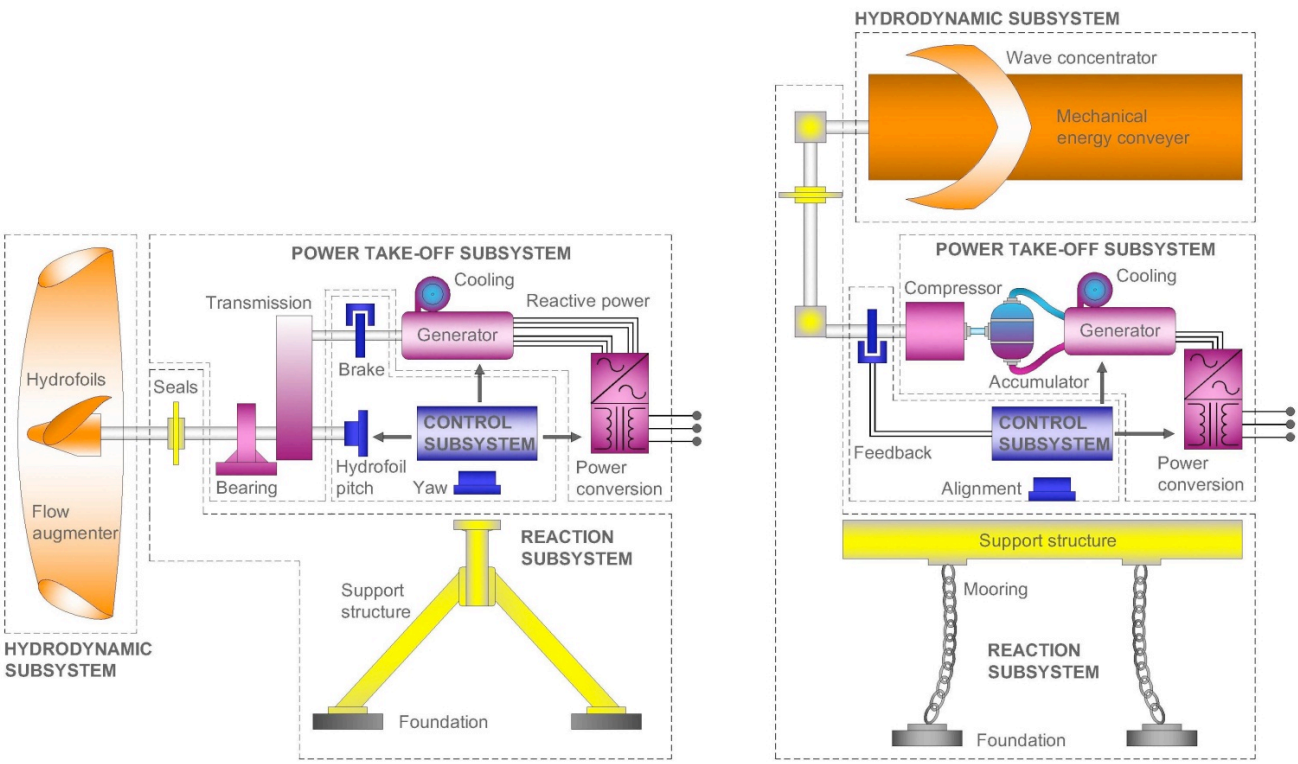

Figure 10: Identification of testing practices for generic subsystems.

6.2. Design of model hydrodynamic subsystem

In order to mitigate the limitations of current testing practices delivering limited subsystem performance assessment and limited data capture, the drivers for the design of testing practices for model scale hydrodynamic subsystem should include:

- To demonstrate proof of concept
- To validate performance characteristics predicted by a numerical model
- To iterate design of a subsystem e.g. novel blade design on a marine turbine

Inflow conditions might be different in tank testing, compared to larger or full-scale conditions. For instance:

- Towing tanks have no ambient turbulence
- Tidal energy model rotors will have much lower blade Reynolds numbers and inflow angles
- Wave tanks and basins may only offer 2D conditions or suffer from wave reflection off sidewalls
- Models may occupy a significant fraction of the hydraulic facility, artificially increasing energy capture

As the model scale hydrodynamic subsystem is far smaller than full-scale, limitations are introduced by and care must be taken with machining accuracy and tolerances. Levels of instrumentation will also be compromised by the design as the physical space provided by small-scale models which are too often limited for mounting off-the-shelf or even custom made instrumentation. In such instances compromises need to be made; this is a common aspect of small-scale model testing, and the biggest cause of limitations and inaccuracies being introduced within a testing practices.

6.3. TEC hydrodynamic subsystem

It appears that many tidal energy device concepts are taking a form close to those adopted by early wind turbines; namely axial flow or cross flow type lift-force rotors. A tidal device classification exists as part of EquiMar. Here the principal form of mechanical conversion, rotational axis and principal form of motion is described thus eliminating conventional names carried across from the wind energy industry.

Thus it is evident that for the hydrodynamic subsystem the key parameters that require quantification are forces such as lift and drag, and motion such as rate of rotation, oscillation/sweep forces and distance or angular displacement.

Lift-based rotors or straight hydrofoils are sensitive to scaling parameters such as Reynolds number. However, if stalled flow is avoided then operation at a lower Reynolds number can usually be predicted with good accuracy by computational means such as blade-element-momentum codes. Lifting surfaces should be machined with a good accuracy and small tolerances to ensure that the model profile is as close as possible to the design. This will ensure that predicted lift and drag forces are as close as possible to those predicted. Surface roughness is also important. Untreated metals such as aluminium and steel can corrode in experimental facilities, so methods such as cathodic protection should be considered to avoid degradation. Drag force rotors are less susceptible to machining tolerances but it is good practice to ensure that scaled dimensions are correct, material selection or surface coatings need to be appropriate and the model hydrodynamic subsystem functions as desired.

The purpose of the testing has implications for the level of instrumentation provided on the hydrodynamics subsystem.

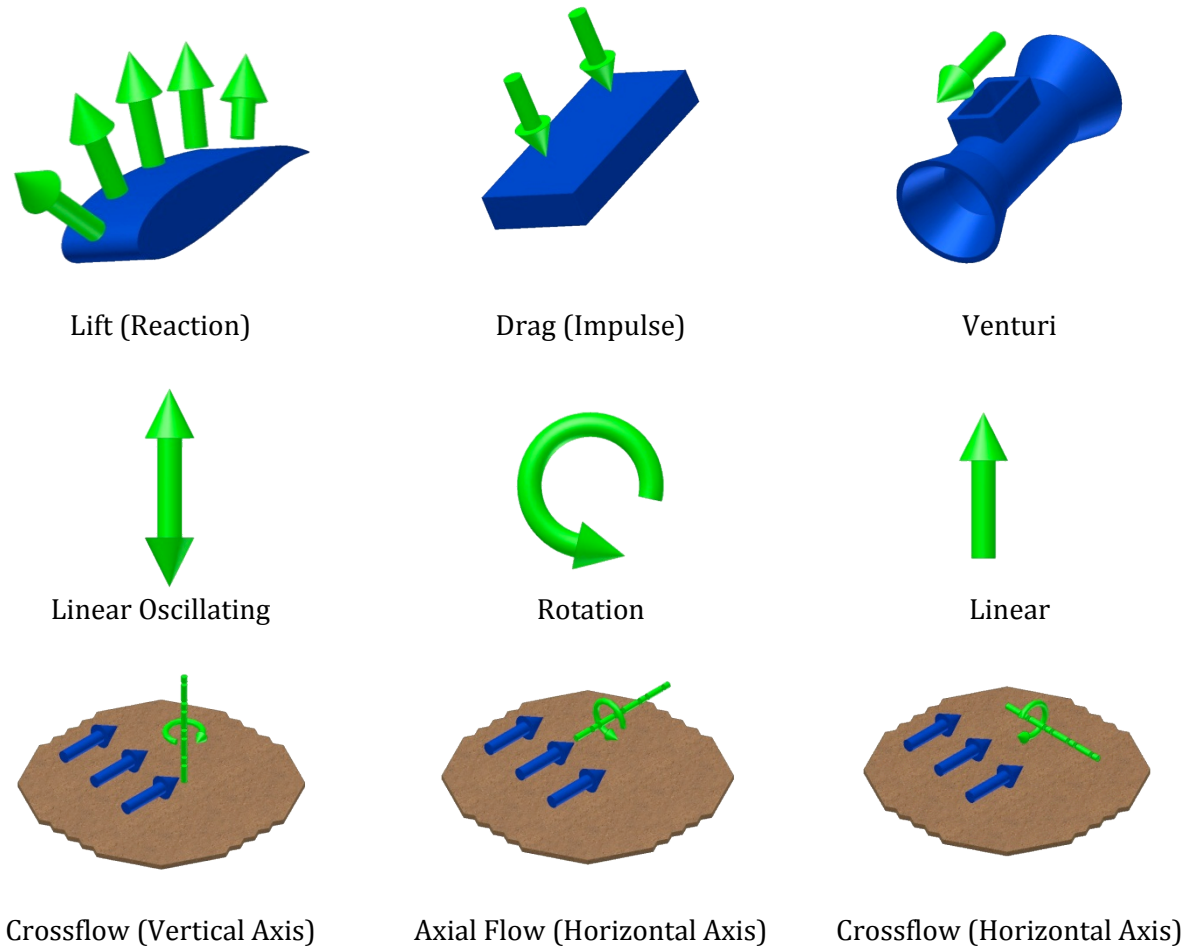

Figure 11: tidal energy hydrodynamcis subsystem characterisation showing Primary method of energy conversion (top row), Principal motion of hydrodynamic subsystem (centre) and Orientation of rotational axis (bottom)

6.3.1. Proof of concept

It is unlikely that direct measurements on the subsystem are required. Power, thrust etc. could be measured indirectly through the power take off and reaction subsystems.

6.3.2. Numerical validation of design

Here some direct measurements of forces, generated power, rotational or travel velocity will be required. Wherever possible measurements should be taken close to the point of interest with efforts made to minimise interference effects (mechanical, electrical etc.) and where possible quantify these. For example torque from a 3-bladed axial rotor should ideally be measured at the rotor hub upstream of mechanical losses (bearings, seals). This does add complexity to the design with additional sealing and waterproofing issues but with the advantage that direct measurements are obtained. Another example is the measurement of thrust upon the hydrodynamic subsystem. It could be possible to measure through the reaction subsystem but the acquired force will undoubtedly consist of the force upon the whole model device. Deductions would be required to isolate the rotor thrust and hence a degree of inaccuracy is introduced.

Static and dynamic pressures can be measured upon lift and drag surfaces but this does add complication to model design. Generally the surfaces are small at model scale and measurement equipment should not interfere with the surface profile (especially for lifting bodies). Thus the issue of miniaturisation becomes important. Custom-made measurement equipment is often required and this might be prohibitively expensive or result in an unacceptably compromised model design.

In conclusion, to mitigate limitations in the testing practices for tidal energy device hydrodynamic subsystems:

- Care should be taken with material choice, in terms of ease of machining, durability, stiffness and corrosion.
- Machining tolerances should be low especially for lifting bodies which are particularly sensitive to geometric errors.
- Direct measurements are preferable where it is practical to do so.
- If indirect measurements are taken than losses/inaccuracies/errors should be considered and quoted.
- Care should be taken to ensure that instrumentation and the acquisition of measurements does not compromise the model in such a way that the fundamental operation of the hydrodynamic subsystem is significantly altered.

6.4. WEC hydrodynamic subsystem

Due to the large number of wave device types, this section is naturally more complex than the tidal equivalent. There have been many proposals for classifying and cataloguing the wave energy conversion process. Traditionally these are attenuators, terminators, point absorbers and overtopping devices. From a fundamental physics perspective the majority of proposals fall under two types – overtopping and inertial mass devices.

6.4.1. Overtopping devices

These function on the laws governing wave run-up and over-topping that have been established in the coastal engineering and protection industry. For floating devices the hull motion is also important so naval architectural aspects must be considered in the device design.

This type of device relies on the physical capture of water from waves so Froude scaling in model tests is fundamental. Very large scale ratios (i.e. physically small models) may suffer from other scale issues (see chapter 3. above).

6.4.2. Inertial Mass

The majority of wave energy converters operate on the principle of two or more masses which move independently such that a power take-off unit can be connected between them. These can be fixed units such that the earth becomes one mass, floating devices with multiple bodies - one of which may be a water volume - such as oscillating water columns, or the hinged flap type converter which can also be fixed or floating.

Within this category we have identified 4 main subtypes of device:

- **Attenuator:** A floating device that works parallel to the wave direction and effectively rides the waves. Movements along its length can be selectively constrained to produce energy. It has a lower area parallel to the waves in comparison to a terminator (a device which operates across the wavefront, e.g. an OWC device), so the device experiences lower forces.

- **Point absorber:** A floating structure that absorbs energy in all directions through its movements at or near the water surface. The power take-off system may take a number of forms, depending on the configuration of displacers or reactors.

- **Oscillating water column:** An oscillating water column is a partially submerged, hollow structure. It is open to the sea below the water line, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. This trapped air is allowed to flow to and from the atmosphere via a turbine, which usually has the ability to rotate regardless of the direction of the airflow. The rotation of the turbine is used to generate electricity.

- **Oscillating Wave Surge Converter:** This device extracts the energy caused by wave surges and the movement of water particles within them. The arm oscillates as a pendulum mounted on a pivoted joint in response to the movement of water in the waves.

6.4.3. Other device Classes

Submerged pressure differential: these devices are typically located near the shore and attached to the seabed. The motion of the waves causes the sea level to rise and fall above the device, inducing a pressure differential in the device. The alternating pressure can then pump fluid through a system to generate electricity.

There are of course devices with a unique and very different design to the more well-established types of technology and situations where classification is difficult since information on the device's characteristics could not be determined. For example the "Wave Rotor" is a form of turbine turned directly by the waves. Flexible structures have also been suggested, whereby a structure that changes shape/volume is part of the power take-off system.

6.4.4. Operating Principles

The forces that first create the motion of the hydrodynamic sub-system can follow different principles, such as

- **Buoyancy forces:** this would be the most common driver for floating body type devices

- **Pressure difference:** has been used for submerged systems

- **Wave forces:** acting directly against hinged surge converter flaps

Whichever type of device is to be scaled for testing the requirements of the hydrodynamic sub-system are similar and revolve around the desire that the scale device is an exact dynamic replica of the full size prototype device. The Laws of Similitude that enable this are described in **Section 3** and must be followed for both Stage 1 & Stage 2 test programmes. This means that not only must component masses be correct but the distribution of that mass around the scaled device must be correct. Since it is unlikely that the model has been constructed of the prototype materials, attention must be paid to this mass distribution issue. A rule of thumb can be that the scaled device is manufactured light so that ballast can be added later in strategic locations. This approach also means the lumped ballast can be moved to change the characteristics of the device as required. Standard laboratory techniques exist to verify the physical properties of the model prior to commencing the test programme.

As outlined previously not all parameters can be scaled correctly for one set of similitude laws. This limitation must be accounted for during the model design and construction. One of the key properties that must be accommodated at smaller size is friction, either directly (as that between solid surfaces) or viscosity in the case

of fluids. The largest contributor to over-emphasised hydrodynamic damping can be vortex shedding from sharp submerged edges. Care should be taken during manufacture to minimise this possibility.

The characteristics of the Stage 1 (circa 1:50) and Stage 2 (circa 1:10) scaled devices should be checked thoroughly to verify that viscous losses have been restricted to an acceptable levels, otherwise the empirical results cannot be used to validate or calibrate mathematical models of the hydrodynamic system. Figure 12 shows the same device at Stage 1 and Stage 2 scale.

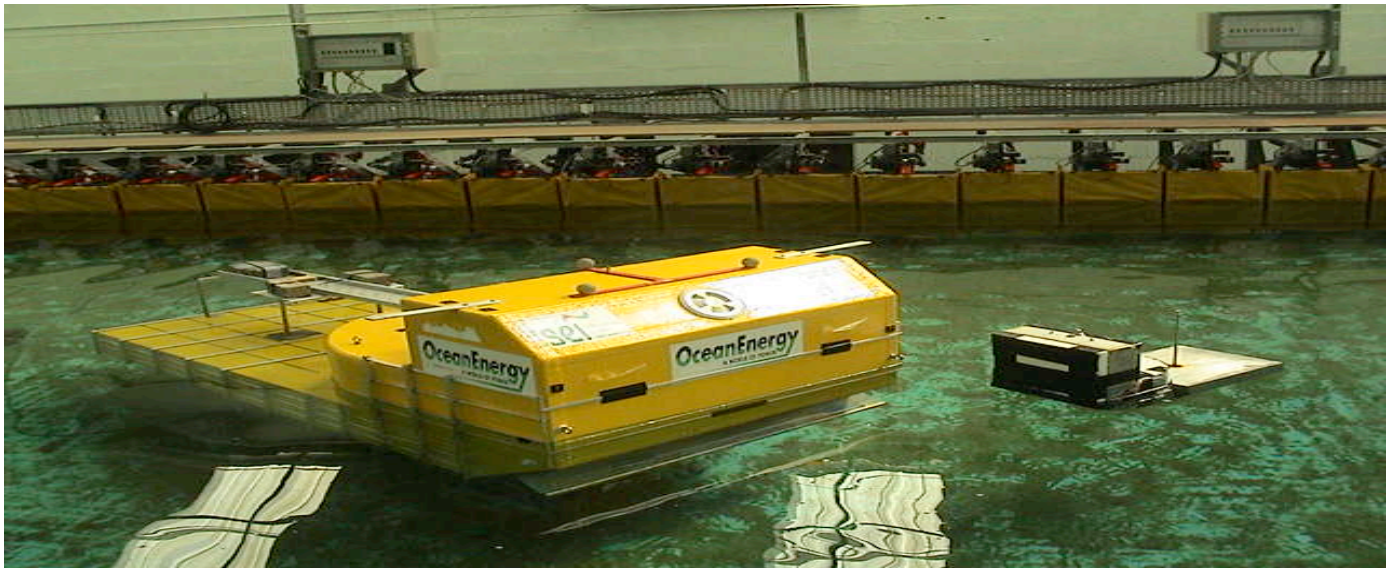

Figure 12: Tank testing of different scale devices

6.4.5. Design of model power take-off subsystem

It is unlikely that a model-scale power take off (PTO) subsystem will have the same complexity as that of a larger or full-scale device. The drivers for the design of a model scale power take-off should include:

- To convert mechanical motion from the hydrodynamic subsystem into a measureable quantity of work (electrical/mechanical power);
- To damp and/or control the performance of the hydrodynamic subsystem.

If the PTO system is integral to the model (forms part of the internal structure) then scale issues may compromise design. The alternative is to change the type and/or disposition of the PTO (relative to larger scale devices) so that more functionality is retained. Examples of each scenario are given below:

6.4.5.1. Case 1.

A horizontal axis 3-bladed tidal turbine has a PTO system housed underwater within the turbine nacelle. A permanent magnet generator has been found but in order to absorb the mechanical rotor power the nacelle is of a larger diameter than planned, such that the model nacelle/rotor diameter ratio is 1.5 times as large as the full-scale design. This could affect the downstream flow field as the nacelle provides a larger obstruction than previously envisaged.

6.4.5.2. Case 2.

A model wave energy converter is submerged at half depth. The whole device is planned to be tethered to the seabed by chains/anchor foundations and will hold its vertical position via buoyancy tanks. At small scale such

an arrangement is impractical so the device is held rigid at half depth in a wave basin. The PTO is linked to the device but positioned above the water line for ease of access.

A number of methods have been used to try to replicate PTO systems at small scale, and to generate data from which power capture can be calculated. These include:

- The use of mechanical friction brakes on rotating components;
- The use of orifices, mesh screens or porous materials to simulate turbine rotors.

Reproduction of hydraulic PTO systems is difficult, as hydraulic actuators and rotary machines are likely to suffer disproportionate frictional and viscous losses at small scale.

Errors are introduced by every power conversion – both in magnitude and response shape – and in every case it is essential that measurement are taken as early in the conversion chain as possible.

6.4.6. Design of model control subsystem

As mentioned earlier, the control system is generally inextricably linked to the PTO subsystem, especially so at the smaller scales of model testing where its primary purpose in the model test, unlike at full scale, is to ensure that the model device operates at a scaled operating point similar to that of the prototype. Moving the device from one operating point to another, controlling failure modes etc. are not key drivers whilst ascertaining the power performance of a scale model, unless such modes are core to the operating principle of the device.

In many cases there will be no active control mechanism: resistance (to mechanical force, electrical current, airflow etc.) will be fixed and the performance of the energy converter will essentially be locked into the device dynamics at that particular operating point. As a result the performance will be strongly dependant on the response (static and transient) of the PTO/control mechanism, for example, the linear range of an oleo strut force response (for say a point absorber), or the scaling of the compressive properties of a volume of air driving an approximation to a turbine (in an oscillating water column). Active control systems can be implemented by including processing apparatus remotely or within the body of the device**.** For example, a rotor whose shaft torque is reacted by an electrical generator may have its speed changed by altering the resistive load on the generator.

If an active power take-off control is envisaged for the prototype machine it is important to evaluate the contribution it can make to the device performance. This work would be conducted at Stage 2, when the model will be physically large enough to accommodate the activation equipment and monitoring sensors required, but still not too large to be deployed in a tank where conditions can be produced on demand, repeated and changed to the operator's requirements. In this way different control strategies and activation scenarios can be evaluated against each other before the system has to move to open water where conditions have to be accepted as they occur. The actual applied damping might still be provided by a power take-off simulator and not by an operational electrical generator, so it is particularly important that the equipment conforms to the specifications outlined above.

6.4.7. Design of model reaction subsystem

The design of the model-scale reaction subsystem will be driven by a number of facility and device-specific issues that should include:

- The provision of a stiff anchoring point such that the model is firmly fixed in the experimental facility
- The need for a dynamic mooring with similar compliance and degrees of freedom as in the full-scale design
- The requirement to be linearly scaled down from full-scale to study interaction with other subsystems, generally the hydrodynamic subsystem.

Manufacturing the reaction sub-system should, in most cases, prove to be a more simple task than other sub-systems. Rigid reaction frames must be able to withstand typical experimental loads but generally this is well within the capabilities of common materials. The greatest limitations arise where a dynamic mooring is to be 'represented' within the model; the combination of hydrodynamic effects and material properties which characterise the dynamic response at full scale is very hard to reproduce/ simulate.

7. Data Acquisition, Analysis and Errors

In order to attain maximum utilisation and benefit from the potentially limited time in experimental facilities, it is important to consider the performance of data acquisition (DAQ) systems not just simply in terms of their technical features, which will be limited by the facilities available at the test centre, but also in terms of acquisition capabilities and usability. Limitations occur when the capabilities of the DAS do not match the requirements of the testing practices; in terms of signal input characteristics, frequency of data collection and data signal processing requirements, prior to data storage. In order to minimise these influences, the relevant standards/guidelines adopted for the tank testing of other marine engineering applications could be referred to:

BS EN 62008:2005 (DAQ)
BS ISO TR5168-1998 (Uncertainty)
ITTC 7.5-02-01-01 (Uncertainty)

The identification of all error sources is beyond the scope of this document, and a collection of references is available below. However, the general error cascade (where errors from a previous level contaminate subsequent levels) can be written as:

A. Design → Dominant systems and their interactions.
B. Construction → Redundancy and design tolerances.
C. Experiment → Table below.
D. Data Logging → Data acquisition, handling, archiving and retrieval.
E. Post Processing → Data reduction, interpretation and correction.

In this section we are primarily concerned with levels D and E in the list above. Numerous textbooks, publications and standards are already in existence and as such the following section is intended to draw attention to some generic considerations for experimental testing and provide direction towards further reading. Guidance will be provided in D3.4.

7.1. Limitations Introduced Through Uncertainty Analysis

Throughout this document, accuracy and precision have been distinguished. In general one type of uncertainty dominates, and the work of the experimenter is focused on reducing that particular error type. Accuracy or bias uncertainty is the degree to which an experimental measurement of a mean represents the true value, and precision error is the deviation between the individual measurements and the (biased) mean value of the measurement. Given that the purpose of an experiment is to determine the values being measured, the true value is in general unknown and the error must be estimated and the measurement is stated as being within a certain confidence bound. As elementary textbooks explain, loss of accuracy results in systematic errors in measurements that can still be very precise, whereas a loss of precision results in a (random scatter) distribution of measurements around some value.

The precision uncertainty associated with a set of measurements can be determined via statistical methods of uncertainty analysis, therefore this is not covered in great detail within this document (see WP3 Deliverable 4). However, it concentrates mainly on the error sources in the "data supply chain" to include:

7.1.1. Systematic Errors - Bias

Systematic errors are *fixed* errors in, for example, instrument calibration, drift, and result in a bias uncertainty (B) or an offset in the measured mean from true value. The systematic error cannot be determined via statistical techniques, as the error lies not in the data itself but the experimental setup or underlying assumptions (i.e. a problem of accuracy not precision). For example, if an instrument such as an acoustic Doppler velocimeter (ADV) is incorrectly mounted or aligned, the data captured will have a bias.

7.1.2. Random Errors - Precision

Random or precision errors are fluctuations above and below the mean due to a large number of small, independent factors, and result in precision uncertainty (P), which is treated by statistical analysis. Statistical properties of truly random errors will generally fall in a normal distribution about the mean value of that statistical property (by the Central Limits theorem).

7.1.3. Spurious Errors

Unexpected outliers are data whose value is above some threshold deviation from the mean and these must be accounted for individually. These outliers can either be due to a measurement error or an error in the assumption of the distribution. An example of the latter would be a false assumption of normality or a false value of kurtosis.

7.1.4. Resolution Errors

Resolution errors are due to limitations in the native resolution of the sensor – i.e. the inability of the sensor or encoding apparatus to distinguish between points of similar, but distinct, value. Too small a resolution may result in a range error.

7.1.5. Range or Saturation Errors

Range errors are due to the measurement exceeding the instrument range, resulting in saturation or some other undesirable behaviour. For example a sensitive strain gauge may return flawed data if the true range is greater than the equipment range.

7.1.6. Environmental Error Sources

Environmental error sources encompass anything outside of the experimental system which influences any aspect of data capture. Signal corruption such as analogue signal degradation due to electromagnetic interference, attenuation and crosstalk may render data erroneous. The effects of temperature variations on instrumentation must also be considered; both in "warm-up" phases when beginning trials, and in causing drift (e.g. strain gauge calibration).

7.1.7. Component Reliability Error Sources

Sporadic equipment failure can result in errors such as incomplete datasets, spurious errors, signal spikes, etc.

For more discussion consult a textbook, or see BS ISO TR5168-1998 or ITTC 7.5-02-01-01.

7.2. Data Acquisition

Data acquisition is the process by which sensors are polled for data; the data is transferred from the sensor and made suitable for interrogation, usually on a computer. There are a number of common stages as per Figure 6.8.1 below, however these may be repeated, omitted or circumvented in numerous fashions depending on the DAQ system and sensor apparatus in use. Therefore, what follows is intended only as generic guidance.

For the purposes of this document, the DAQ process has been split into 3 domains: the physical domain, hardware domain and software domain however it is important that these domains be considered at all times intrinsically linked as part of the same system, and the splitting as merely a convenience to aid description herein.

7.2.1. Physical Domain

The physical domain is the real world and is a domain where physical states exist and are measured by transducers that take a physical state (energy) and represent it via some modification of an internal surrogate state. Often sensors require a driving current or input signal in order to take a measurement.

7.2.1.1. Sensor Appropriateness

Are you measuring what you think you are? E.g. installing laser Doppler velocimeter (LDV) in wave tank at 120mm depth when planned for 100mm.

7.2.1.2. Sensor Alignment and Positioning

Probe alignment: any misalignment in instrumentation will cause a systematic error throughout all data. For example, if an ADV x, y, z coordinates are not aligned with tank x, y, z coordinates, the difference will contaminate all results of that test, including experimental results if unidentified errors are included and collated with “correct” data.

7.2.1.3. Instrument Interference

Some instrumentation may intrude upon the experiment. For example strain gauging an aerofoil may change its properties, or placing any measurement device within the flow will create a wake, which may impact on downstream measurements.

7.2.1.4. Calibration and Zero Setting

Without periodic calibration, values reported by transducers may drift or become more scattered – that is the bias and precision errors of the sensor will generally increase.

7.2.1.5. Drift and Environmental Sensitivity of Sensors

Sensors reported measurements may depend on, e.g. operating temperature or pressure. If these change during the course of an experiment then an incremental increase in bias caused by a drift in the zero value of the sensors will occur. Drift can also occur over time after instrument calibration for numerous reasons and should be expected.

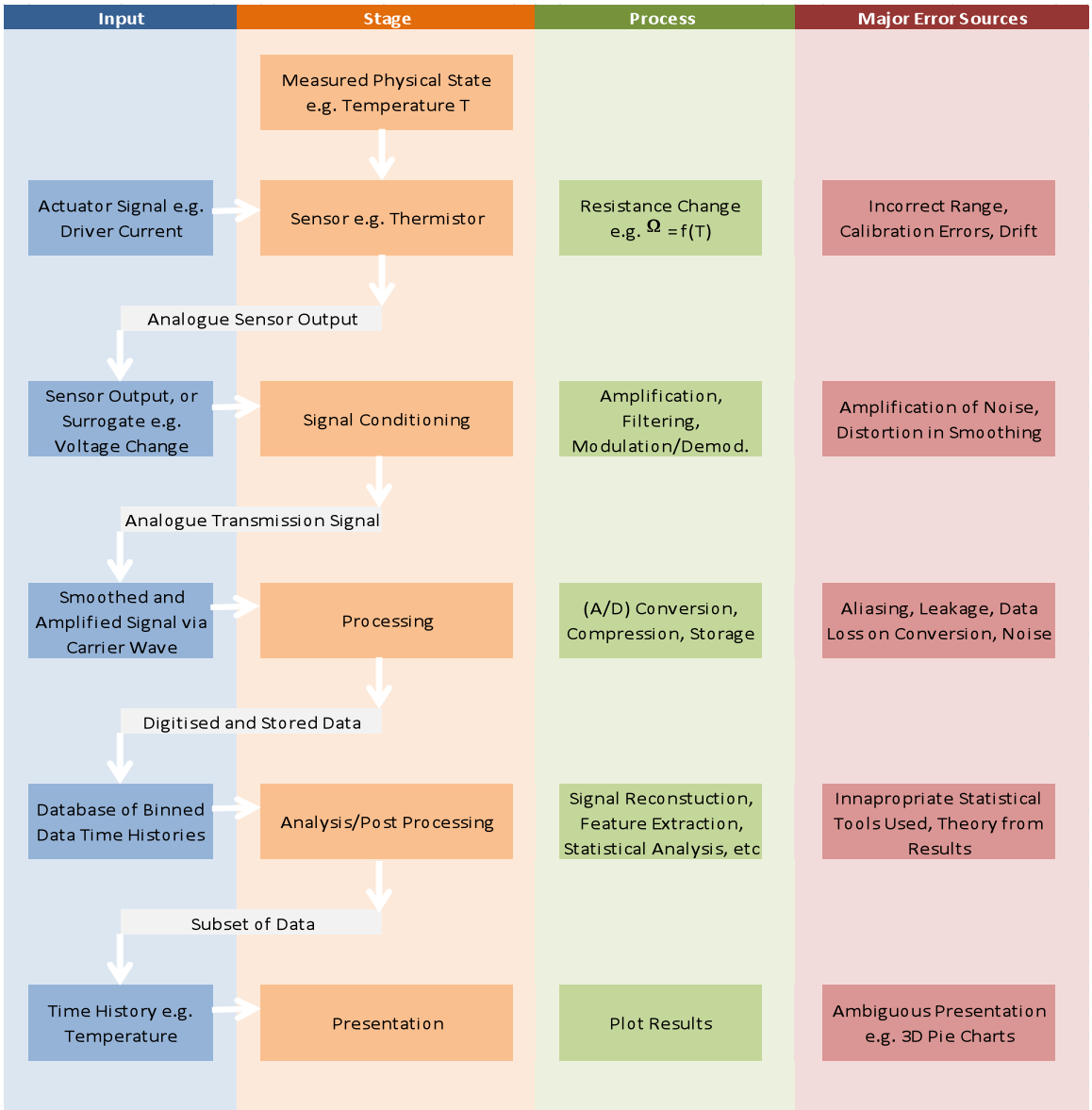

Figure 13: Data acquisition and processing procedures.

7.2.2. Hardware Domain

This is where the sensor readings from the physical domain enter the DAQ system and are made appropriate for usage (storage, analysis) in software.

7.2.2.1. Filtering (and smoothing)

Accumulation of random errors in the signal result in the appearance of "noise" in the time history of the signal. In the ideal situation, the magnitude of noise would be significantly lower than that of the underlying signal, however in many situations this is not the case, and before anything useful can be done with the signal, it must be filtered. This entails the potential loss of original data, as well as the corruption of the underlying signal.

A physical low pass filter can be used to reduce the noise from the signal. A resistor capacitor filter is commonly used in these applications; however, it can also affect the acquisition of the original signal.

Smoothing is equivalent to low pass filter, and there are two popular variations: running mean, and exponentially weighted average. It introduces a transient response whereby initial values "ramp up" in running mean. They also never quite reach (actual) steady state in exponentially weighted average.

7.2.2.2. Amplification (of noise)

In general, for safe operation in wet environments, the output signal from sensors is very small and requires amplification. Unfortunately, the signal is often quite noisy and requires filtering otherwise the amplifier will simply increase the noise and swamp the signal. Strain gauge configurations sometimes are difficult to implement for small scale testing. For example, in order to measure minor thrust loadings (i.e. 5 kg); a normal laminated plaque with a full bridge will not give the expected results due to the low output voltage (mV) even with the use of an amplifier. Other configurations can possibly measure bending instead of strain.

7.2.2.3. Analogue-Digital Conversion – Sampling

As a very minimum, the sampling frequency required is twice that of the highest frequency of interest (the Nyquist frequency condition) – any lower and there will be aliasing in re-synthesized analogue time series. In general, however, this is insufficiently low if applied to e.g. water surface elevation, as the Nyquist frequency only requires two points over each wave, and will under-resolve the peaks in water surface elevation. There is thus a requirement to compromise between the need to fully resolve certain effects, especially when generating time-series data, and the storage and processing capabilities of the equipment.

7.2.2.4. Analogue-Digital Conversion – Other Issues

AD converters can introduce noise through quantizing errors, jitter and internal crosstalk resulting in digital infiltration on analogue waveforms. There is also the possibility of drift or bias errors via non-linearity and distortion – integral/derivative effects can accumulate and swamp or attenuate the converted signal.

7.2.2.5. Transmission, Modulation/Demodulation (modem)

Interference in signal transmission is common, especially when using high voltage drivers/actuators. For example when using a stepper motor with long cables (i.e. 10 meters) care must be taken that the cables from the instrumentation and the strain gauges are not picking up the signal from the drivers. One way to solve the problem is to use screened cables and ground the entire system to a common point: if the system is not grounded, the screened cables act as an aerial. Occasionally, due to the length of the cables and the intense noise coming from the drivers, a reduction of the sampling frequency is needed. This brings difficulties in analysing experimental outcome if the tests are being carried out over short runs.

Further issues in transmission are attenuation due to resistance ($V_{in} \neq V_{out}$). These resistance/inductive losses manifest themselves in decayed low voltage signals and distorted frequency pulses over long distances. Errors are thus introduced in all stages of transcoding, modulation/quantizing for (analogue to FM or digital - PWM) transmission, transmission as analogue signal or transmission as digital signal, and demodulation.

7.2.2.6. Interfacing with Computers

Problems with interference/corruption due to shared port usage on PC can be caused by printer driver polling, otherwise errors are introduced in the same manner as with AD conversion and transmission/modem.

7.2.3. Software Domain

Here the signal is prepared for storage and retrieval.

7.2.3.1. Compression

In order to render the analysis of large datasets tractable, spectral analysis techniques such as ASD/PSD techniques using discrete or fast Fourier transforms are performed (DFT/FFT). These allow identification of periodicities in the dataset by showing how the Amplitude (energy) or "Power" in a signal time series is distributed by frequency.

7.2.3.2. Storage

Database time-stamping/synchronicity issues, incorrect retrieval, errors or assumption in dealing with huge quantities of data where missing or incorrect data may be masked, future-proofing data formats (ASCII vs. Binary) and also data format compatibility.

7.2.3.3. Analysis and Post-Processing

Interpretation of the data, correction e.g. for blockage, extrapolation, missing data (ignore, truncate, replace).

7.2.3.4. Signal Reconstruction and Multiplexing

Errors in reconstructing (or synthesizing) a finite time series from a pseudo-infinite frequency spectrum: reanalysis of spectral moments of reconstructed signals will give indication of errors associated with frequency domain work.

If measurements are taken using different instrumentation, an unsynchronized time stamp will introduce error into the data. For example, if measurements are to be taken when the rotor blade is at a certain point, the frequency of the measurement must match exactly the frequency of the rotation of the blade. Turbulent fluctuations may cause fluctuations in the rotational speed of the blade, thus knocking the measurements out of synch.

7.2.3.5. Statistical Analysis, Feature Extraction, Ensemble Averaging

Theory from results, statistical reuse of data. Incorrect assumption on correlation, bias, drift and identification of autoregressive systems will yield incorrect interpretation of results. Spectral leakage on the data that will generate false peaks on the signal. In the case of accelerometers, this will induce false harmonics in the spectrum that will lead to an incorrect system analysis.

7.2.3.6. Correction Factors

Blockage correction is required if a high blockage factor within the tank leads to hampered wake expansion and accelerated flows around the device. This means fluid behaviour in the tank will be different from that in real sea conditions. As such a number of empirical blockage correction factors are available in order to 'fudge' the data.

7.2.4. Data Presentation and Benchmarking

7.2.4.1. Data Presentation

Currently, there are no commonly applied methods in usage for the presentation of data from testing programmes. In the majority of cases, absolute data is presented at the scale of testing procedures for the specific component or system under investigation. Typical components include power capture and output (W),

pressure (Nm^{-2}), displacement (m), torque (Nm), rotational speed (rad s^{-1}), thrust loading (N), heaving loads (N), motion (dx/dt) and body forces (N). The presentation of absolute values introduces limitations in the scaling up experimental values to conditions that would be experienced at full scale. This is since the full extent of the test conditions these were measured against may not have been fully captured and reported, nor whether the measured performance parameters were instantaneous, avaraged or RMS values.

7.2.4.2. Benchmarking

Similar to ###, no common methods have been adopted cor the normalisation of performance data produced from tests undertaken. There is no standard method for benchmarking based on generic device architecture, nor a common presentation format for communicating performance to intrested parties/stakeholders. The lack of normalisation introduces limitations in the ability to reliably and consistently perform direct comparisons of device performance as they scale up within the technology evolution programme, and the impact of any changes implemmented as part of system development. The inability to benchmark performance prevents devices of similar architecture type being compared or checked against each other or a reference device.

8. Conclusions

8.1. TEC

8.2.

8.3. WEC

9. References

Voulgaris, G., Trowbridge, J.H., 1998. Evaluation of the acoustic Doppler Velocimeter (ADV) for turbulence measurements. Journal of Atmospheric and Oceanic Technology 15, 272–289.