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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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Sea Trial Manual

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Sea Trial Manual

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Content

INTRODUCTION

Technology Development: Stages 3 & 4

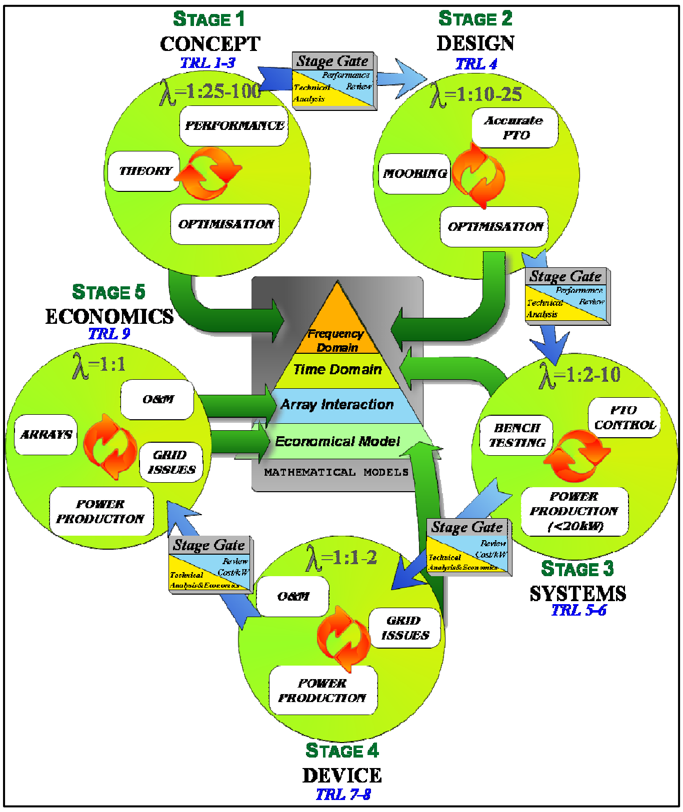
A Five Stage Device Development Programme:

The three EquiMar engineering protocols were designed in conjunction with the International Energy Agency's Implementing Agreement on Ocean Energy Systems (IA-OES) 5 Stage development programme for wave energy converters (WECS). The objective is to complement that overview document by detailing the project planning and technical requirements necessary to safely and successfully advance the design of a WEC with minimum risk and uncertainty. This manual addresses Stages 3 and 4 and introduces guidelines for the testing, monitoring and evaluating of the sea trial of solo devices.

The US Department of Energy's (DOE) Technology Readiness Assessment scheme for the development of marine hydrokinetic (MHK) devices also follows a similar format but with 9 Technology Readiness Levels (TRL). These are combined into 5 funding sub-groups that can be cross related to the 5 Stage plan as shown in the diagram below.

The device's performance monitoring, analysis and evaluation is designed in accordance with the IEC~TC114; Marine Energy technical specification; Power Performance Assessment of Electricity Producing Wave Energy Converters.

The Structured Approach: As can be seen in the overview diagram below, the programme is designed to assist the development of a WEC from its initial concept to full sized pre-commercial devices deployed in a small array. The stages are selected to minimise the engineering and fiscal risk encountered as the development moves along a path of increasing technical complexity and required investment levels.



Project technical risk is controlled by gaining required, specific knowledge at each appropriate stage to reduce the uncertainty of continuing to the next, more complex, costly stage. Stage Gate evaluation criteria are applied at the conclusion of each stage to confirm commercial viability and assist the decision to continue. Effectively, the programme has built in due diligence between each stage.

The financial risk management mitigation is based on applying the appropriate device scale at each stage, as indicated in the programme flow diagram.

Stages 3 & 4: Involves the sea trials of the WEC, initially at a scale in the region of one quarter in Stage 3, and advancing to full size pre-production prototypes in Stage 4. On conclusion of the sea trials the device design should be at the pre-commercial stage.

IMPORTANT REFERENCES

EquiMar: Technical Reports WP2, WP3, WP5);	EMEC: Standards and Guides;
IEC TC 114: Marine Energy; Device Evaluation;	DNV: Design & operation of WECS
IEA-OES-IA: Annex II & III;	PCCI(MMS): Criteria & Standards

Development Stages:

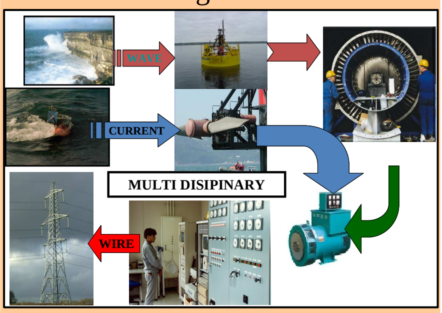
As stated in the introduction, and other sections of this document, the solo device sea trial stages (S3 & S4) of a wave energy converter development covers a wide scope. Devices must progress from the pre-prototype scale (circa 1:4) ***systems*** proving units, through ***pre-production*** full scale design and on to a ***pre-commercial*** machines, ready to be certified as fit-for-purpose and small array deployment.

The primary factor common throughout sea trials is that the tests move from the controllable and comfortable surroundings of an indoor facility, where waves can be generated on demand, to the natural outdoors where test conditions have to be accepted as they occur and test programmes adjusted to suit.

Sea Trials Scope: Stage 3 & 4 sea trial have 4 primary areas of interest:

- Technical evaluations;
- Operational proving;
- Environmental effect;
- Economic verification.

Converting wave energy from the raw resource to electricity feed into a country's distribution grid is a multi-disciplinary process, as show in the diagram.



Each energy conversion stage is covered separately but were practical the sections are dealt with in a standard format:

- Rationale & Objectives
- Data Acquisition;
- Data Analysis;
- Data Presentation;
- Data Archive;
- Data Evaluation (Stage Gates)

TEST PROGRAMMES:

There are two Stages covered in the Sea Trial section of a device development schedule, each of which is further subdivided into two phases. These are:

Stage	Section	TRL	Timetable
S3	Sub-system Bench Tests	5	6-12 months
	Full-system Sea Trials	6	6-18 months
S4	Prototype Sheltered Site	7	1-2 years
	Prototype Exposed Site	8	1-5 years

The minimum details of wave data required at each of the stages can be different without diluting the stages trials too much, although it should again be emphasised that, the more environmental information gathered at all times, the better.

- **Sub-System Bench Tests;** if control strategies are to be investigated a realistic time history of the sea surface at the test site would be an advantage.

- **Full-System Sea Trials:** although at a large, rather than full, size these trials represent the first time the device has been in a real sea environment. The primary purpose of the test schedule is to verify all the systems and sub-systems at a scale large enough to assemble a fully operational power take-off (PTO) but still small enough for the device to be reasonably easily handled. This is an extremely important stage and the final opportunity for limited design changes and modifications to be carried out economically. This means extensive met-ocean monitoring should be conducted to assist in the major data analysis that should accompany these trials. Because the wave conditions should also be appropriately scaled the acquisition rate and duration should be adjusted accordingly.

- **Prototype Sheltered Site;** following Stage 3 it is expected that a full, or approximately full, size prototype device will be constructed for sea trials. It could be anticipated that a shake-down period to prove the component, assemblies, manufacturing quality and instrumentation would be conducted at a station with a less aggressive climate than the final destination. Systems operation and control, especially fail safe and shut-down scenarios, should be practised so wave data that facilitated these commissioning trials must be included. Device performance can be verified but survival modes must be deferred until the following site sea trials.

- **Prototype Exposed Site;** once the operator is confident the pilot plant is functioning acceptably it should be transferred to a location with similar conditions to those expected at a typical power park. The sea trials are now specifically for proving rather than modification, so deployment should be for an extended duration to facilitate component lifecycle verification, full range performance verification and survival diagnosis. Met-ocean monitoring can be minimised to that required for offshore operations and may be a function of the degree of information necessary for the device PTO control.

Sea Trial Manual:

The purpose of the manual is to outline the prospective tasks to be undertaken during a sea trial, differentiating where possible from those procedures adopted during tank testing. This covers sea trialling from a quarter scale to pre-commercial prototypes and is intended to delineate the various aims, processes and outcomes expected of a series of such trials.

The rationale for sea trials are multirole, but can be broken into the 3 principal categories opposite.

Test Centres: For reason outlined at various point in the manual it is recommended that sea trials are conducted at one of the official test centres being establish in several European coastal states. Beside the permitting convenience offered by these Centres this is mainly so the expertise that will evolve around these sites can be utilized.

Sensors: losing data will be more costly that ensuring its safe acquisition. The 3 guiding principles should be:

- Build in redundancy;
- Consider duplication;
- Install alternatives from which other parameters can be obtained.

Keys to Success:

- Should not write a test plan when the device is finished. The plan should be made first, then the design should accommodate the testing process, not vice-versa.
- Developers tend to focus on design for energy production, whereas at the prototype phase, design for deployment should (may) be more important.
- Should be a sensible duration given device scale – how much data?

RATIONALE:

- **Experience Building**: It is anticipated that significant experience will be brought to bear before sea trials commence, both from scale model testing of the actual device, and also from contractors and external agents with involvement in similar situations. However it is clearly vitally important that the procedures governing the deployment – that is assembly, commissioning, maintenance, recovery and decommissioning – of the specific device are formalised and thoroughly evaluated and practised.

Experience gained in handling the device is hard won and as such it is vital that maximum benefit is derived from it, feeding into for example standard operating proceedures, safety protocols and emergency actions, and eventually the "owners manual."

- **Proving:** During sea trials the device must be proved in a number of ways. Since the device is essentially to be deployed as a sea going vessel the naval architecture must be validated, therefore verification of water-tightness, centres of gravity/buoyancy, etc should be sought. While it is not envisaged that sea-trials will test the survivability of a device by design, it is not inconceivable that an extreem storm will occur during the trial schedule, therefore the possibility of monitoring and assessing the survival modes of the device should be accounted for.

Control system/ software proving will provide opportunities to test control strategies authenticly, as it is unlikely that full control methodologies were employed at test scale. This also provides an opportunity to run-in and test software associated with SCADA.

The various component & assembly run-in, full system testing and proving will also be performed here. The objectives are to put all the components together and test the ensemble for perhaps the first time, ensuring the interoperability, compatibility and overall effectiveness of the various sub-components.

In addition to functional verification, a full suite of scientific measurements of the device performance and its effect on the locale will be performed during the sea trials.

- **Characterising Performance:** These results are the main outcome of the sea trial schedule. They are intended for the validation and verification of the various predictions made at smaller scales and computationally. The objectives here are to verify the claimed device performance at large scale (extended proof-of concept) and thus allow the validation and calibration of the various numerical models which will be run alongside the deployment during sea trials and commercialisation.

Further objectives are to provide scientific data regarding the various device characteristics and the effect of the device on the local sea conditions. These also provides validation/calibration for mathematical models as well as feeding into the knowledge base required during the transposition to commercialisation, in the form of data for environmental issues (EIA).

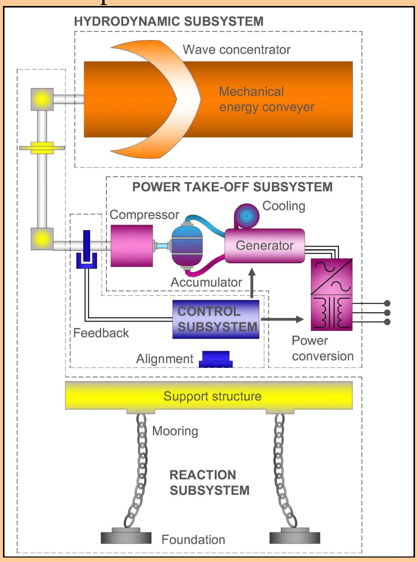
Test Plan

The test programme is obviously very device specific, with various competing requirements dictating the overall objectives and schedules and limiting the duration, data captured and so on. However, there is a common thread to all successful sea trials. The various processes are described opposite.

Sub-System Approach: to assist in the sea trial specification a device sub-system approach is adopted.

Each section of the manual address one of 5 specific sub-system, which are:

- Resource (met-ocean data);
- Hydrodynamics;
- Power Take-Off & Control;
- Reaction (position keeping);
- Operation & Maintenance.



Plan: The schematic below outlines the overall structure that should be adopted when planning sea trials in either Stage 3 or 4.

PROJECT PLANNING

- **Appoint a person with overall responsibility.**

This person is the project manager and their duty is to make clear and agree the test procedures with any vessel captains. The PM will be the sole person making critical decisions (with the exception of vessel captains whose prime concerns are the safety of their crew and vessel). The PM must ensure that everyone on the project is aware of their responsibility, and once the organisation is defined, capable of exercising their tasks in a given situation.

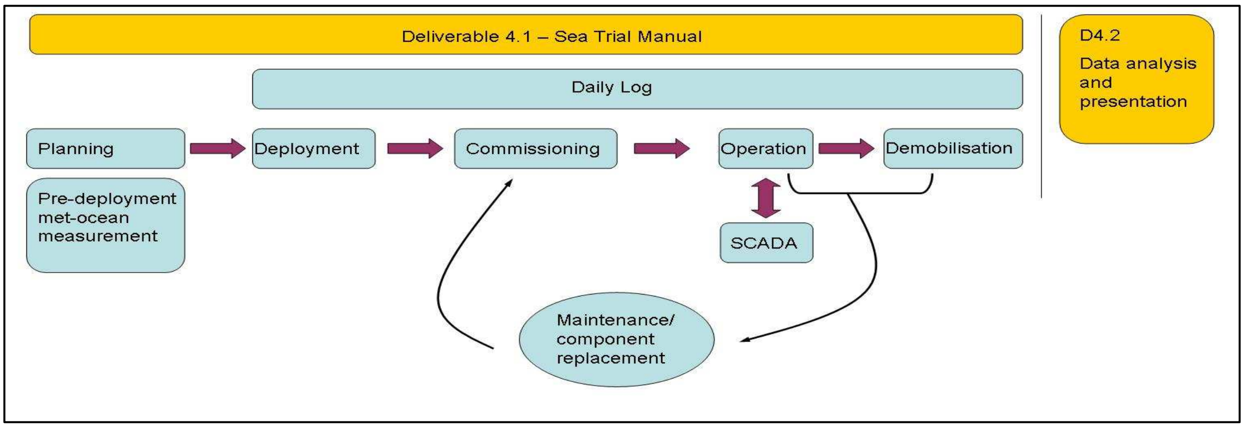
At this stage the level, type and duration of intervention capacity should be analysed for the chosen test location. Proximity to qualified personnel, safe harbour and appropriate support vessels should be analysed. The on-site requirements should be weighted against the expected met-ocean conditions at the test locale over the duration of the test schedule.

- **Ascertain and define the objectives of the test.**

This involves definition of the measurements required at desired sea states, the various proving operations required and any practical considerations such as testing a range of deployment options. Therefore, in addition to the details presented in the section about sensor choice and placement for the various subsystems, it is required to specify operational modes to be investigated

Normal running, where the device is operating in generating mode or a dormant/standby mode. The limits of normal running should be clearly defined and adhered to, for example, with cut-in and cut-out speeds, and the transition from one normal running mode to the next should be carefully examined for all the conditions expected during the schedule.

Failure modes, where the device is artificially impaired in some way representative of expected failure modes. These should be considered as a result of and selected from the various Failure Mode, Effects, and Criticality Analyses (FMECA). The desired conditions in which it is appropriate to perform such tests should be clearly defined and strictly adhered to so that a simulated failure does not result in entering operating modes from which the device cannot be extricated.



Safety procedures, differentiated from failure modes as the unplanned but controlled transition from normal running to an either dormant/standby state or to a safety state appropriate to the circumstances. The desired conditions in which it is appropriate to perform such tests should be clearly defined and strictly adhered to so that a simulated safety mode does not result in entering operating modes from which the device cannot be extricated.

- **Site selection and characterisation:** Since basic site identification is expected to have commenced well before this stage, at this point it is anticipated that sufficient data are now available in order to perform site characterisation. In addition to the qualitative analysis of the incident conditions due consideration of the sub-sea environment is required with a view to establishing reliable data on site:
    - Hydrography and physical oceanography identifying rocks, shoals, reefs, etc;
    - Bathymetry and topography of the site and the immediate environs which effect site flow/wave conditions;
    - Geotechnical data including seabed composition;
    - Constraints such as other users, ammunition dumps, etc.

The data campaign is anticipated to commence though examination of availability and accuracy of existing data and is anticipated to require a degree of tailored on site measurements, including, but not limited to, bathymetric surveys and ADCP profiling leading to production of numerical models of the site. The result is to be a set of GIS overlays representative of site conditions expected during the test schedule.

- **Pre-deployment – "cautious-steps":** By this point, the device components should be available for assembly. It is envisaged that a large amount of testing of individual components will have been undertaken already, but that this is the first opportunity for testing components in more assembled form. Therefore before actual deployment it is anticipated that the device be secured in assembled form in a safe location for initial testing for:

Dry tests – on the quayside. The assembled device will have a grid emulator connection. If possible run the device backwards (either in motor mode, or mechanically) checking for e.g. vibration. Positioning and calibration of sensors should now be verified and finalised. Watertightness should be checked by pressurising compartments. During the tests measurements should be taken giving an indication of resistance of power train mechanisms, seals, etc. Where possible these tests should be performed on the assembled device, however individual system components can be tested as required.

Wet tests **-** benign conditions at a nursery type site e.g. harbour. Once onshore system test and calibration has been undertaken, the device can be introduced to the water in a protected locale to verify safe operation in the wet. Power up, and initial operational modes should be tested, along with verification of the sensor apparatus, control system, SCADA as well as the ability to move into emergency modes. Experience should be gained here in operation, handling, connection etc. in the wet.

During these stages the device need not be grid connected, although eventually it is essential. It is possible to relatively cheaply simulate grid connection on board using power electronics. One of the failure modes which must be examined is grid loss, and the ability of the device to move to a safe state without power, and recover to generation mode when the grid becomes available again.

- **Deployment → Startup**

This stage follows naturally, and uses the experience gained in stages 1-3. By now, the device should be proven watertight, and the stability and controllability verified. Sensors and the various monitoring systems are proven working in the wet, and experience has been gained in handling, loading, unloading and manoeuvring the device.
Clearly the deployment is very device specific, and as such only general procedures are provided.

The device will be secured to the appropriate vessel and transported to the installation site, either as a complete unit in the case of smaller devices or those which can be towed, or in parts for assembly.

Once on site, the installation procedure should be verified, and performed in accordance with the planned procedures and the recommendations of the vessel captain.

> - False alarms are more common than genuine failures – provision should be made in the software system. Beware of unscheduled tests. Procedures should identify spurious signals

Control of the basic/fundamental device parameters (e.g. PTO brakes) should be verified.

Confirmation that basic electronic systems are active: SCADA, safety features, marker lights and navigation aids etc. should now be sought.

At this point the device testing can commence, and the power matrix scatter diagrams may be populated.

2 The subsystem approach: wave energy devices

Some general words about the distinction into different subsystems; DIAGRAM of wave subsystems, in addition to the MetOcean data and the system integrity & O&M schedule

MET-OCEAN DATA

Technology Development: Stages 3 & 4

Resource

Rationale:

Information on the atmospheric and oceanographic conditions occurring during sea trials should be regarded as an essential requirement. The level of detail necessary, however, can be adjusted to suit the stage of the tests. Of particular interest are the occurring ***wave fields*** at the device, against which the sub-system responses and device performance can be gauged.

Primarily empirical wave data should be obtained from direct, contact measurement. However, in the event of lost readings, or extended records being required, data can be obtained from advanced, 3rd generation prediction programs. Before use the theoretical sea state statistics must be validated against measured records at the same station.

These verified numerical models may be the only source of seaway energy spreading functions if non-directional wave gauges are used. Remotely sensed data (satellite altimeter, SAR) may also have a role in monitoring sea trials.

Objective:

There are several reasons for obtaining accurate met-ocean data at each particular test site. The main ones are:

For Wave:

- to establish the input power, short & long term;
- to determine the wave climate characteristics for operations (deployment, recovery, service etc.) at sea;
- to obtain each seaway wave frequency composition (spectral profile);
- to input into device mathematical design models;
- to cross reference with the extreme event horizons;
- to verify theoretical seaway predictions.

For Wind:

- to correlate with the concurrent waves;
- to establish the freeboard windage and general loading;
- to determine the heading control (moorings).

For Current:

- to determine the draft induced loading;
- to establish heading and current relationship;
- to qualify wave-current interactions at the site.

For Other Parameters:

- to be specified on a bespoke basis mainly with regards to environmental effects, corrosion & marine growth.

Pre-Sea Trials Requirements:

Met-ocean data for a sea trial site should be obtained prior to deployment of the device. This is to ensure the correct environmental criteria have been used during the design of the device and that deployment & recovery will be possible in a practical time frame. Maintenance and service schedules must also be accommodated.

This requirement encourages the use of established test centres where wave monitoring should have been on-going since before the site commenced operation. In the event of an ad hoc site being selected, where only limited archival records are available, mathematically predicted wave conditions can be substituted providing the results can be verified against actual in situ measurements. Such data should be used cautiously.

Extreme site forecasts are essential.

KEY ELEMENTS

- establish the correct monitoring duration and acquisition rate for each specific test programme;
- ensure the measuring instrument is free from other water perturbation effects (e.g. device radiations/reflections, topography/ bathymetry modified);
- ensure the wave gauge is calibrated and reading correctly (esp mooring & frame effects);
- locate the sensor so the appropriate wave system is monitored (up-stream of the device);
- Synchronise the time of all acquisition systems.

IMPORTANT REFERENCES

EquiMar: Resource Reports

IEC TC 114: Resource Assessment

IEA-OES-IA Annex II: Task1.1; Wave Data

Waves in Ocean Engineering, Tucker & Pitt

IAHR List of Sea State Parameters 1986

European Marine Energy Centre~Standards

Sea States:

The primary factor common throughout sea trials is that the tests move from the controllable and comfortable surroundings of an indoor facility, where waves can be generated on demand, to the natural outdoors where test conditions have to be accepted as they occur and test programmes adjusted to suit.

The level of detail of the resource required at the different stages will vary, although the underlying mantra should always be to gather as much data as practically possible. This is because wave energy. is a nascent technology so all implications of the data may not be yet appreciated. This would be similar to early off-shore engineering when wave induced fatigue of oil rig members was at first not consider. Also, the wind industry, which initially ignored gustiness to the determent of component longevity due to fluctuating loads. Both omissions stalled the respective engineering design and operational safety for some time.

Obtaining sufficient met-ocean data should remain relatively inexpensive to overall project cost. It is, however, rarely free and if gathered independently must be included in the budget. It will be advantageous to deploy pilot plants at one of the specialist test centres that are being established in several member states since these establishments should be recording all pertinent met-ocean parameters. Of particular importance at the beginning of a project is historical site data.

ENVIRONMENTAL DATA:

This manual focuses on the specification of the seaways that provide the excitation forces on wave energy devices. However, other atmospheric and oceanographic environmental parameters should also be monitored during the sea trials. Although these are required to a lesser degree than the wave field they can be very important for specific analysis routines and component design. Typical meteorological records are:

- ***Water:*** current (tidal) velocity, direction, depth profile, temperature, salinity;
- ***Wind:*** speed, gustiness, direction;
- ***Air:*** pressure, temperature, humidity.

Since test sites will be located some way off the coast it would not be satisfactory to rely on land stations to provide this information. There are two alternatives that can be considered:

- The sensors can be located on the wave energy device and calibrated to that platform. This has the added advantage that the raw data can be streamed into the on-board data acquisition system and stored in a common file.
- A proprietary met-ocean buoy can be deployed at a station close to the test berths(s). These units are specially designed for autonomous operation and would usually have a built in telemetry system to stream the raw, and on-board analysed, data to a receiving station. Once again it is possible the receiver could be housed on the device under test, or on shore. A typical commercially available buoy is shown in the adjacent photograph.

The national test centres currently being established in several countries should provide this sophistication of environmental monitoring as part of the contracted services. When developers deploying at ad hoc locations they would be encouraged to hire a buoy of this type for the early technology proving trials but would be less significant for the longer term economic proving stage.

Besides proving information for the power performance assessment of the device a well equipped met-ocean buoy will supply data to address environmental issues. These may involve organic or inorganic science.

The influence of the environment on the device, such as corrosion and bio-fouling, will be related to the properties of the surrounding water mass, should problems be encountered.

The influence of the device on the environment will equally be influenced by the properties of the water since this will influence resident species and population size. Environmental issues are an essential part of the sea trials.

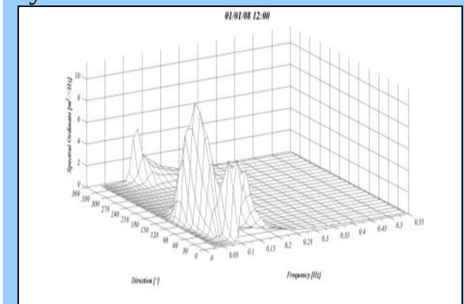
Data Acquisition:

The met-ocean data required to be gathered during sea trials will depend on three factors:

- the scale of the tests;
- the type of tests being conducted;
- the previous knowledge of the sea area.

The main parameter to be monitored will be the sea surface elevation from which all the required parameters of the wave field can be derived. Detailed descriptions of the mathematics behind these definitions are presented in the accompanying **EquiMar Resource** reports.

Because of the energy transfer mechanism of gravity waves the seas occurring at a point are often composed of more than one wave system. Any combination is theoretically possible but the usual mix are locally generated waves, known as SEA, and those from distant locations, termed SWELL. The diagram below shows a multi-system wave field.



This transfer of energy over considerable distances is one of the advantages that wave energy offers but it does make it more difficult to adequately describe the conditions easily.

The data recording requirement is the instantaneous water surface time history close to the WE device. An improvement on this is if the mean wave front approach direction is available together with the directional spreading function for each particular sea state occurring at the test site. Special sensors are required to obtain directional, 2 dimensional, spectra.

Other environmental recordings although optional are recommended.

MONITORING PARAMETERS:

Seaways: The physical processes controlling the ocean and atmosphere have been studied for a considerable time and are reasonably well understood. However, wave energy is a new technology so the level of detail needed to fully investigate and understand a device's overall performance and loadings at sea are still being discovered. This leads to the recommendation of gathering as much environmental information as possible throughout the sea trial period.

KEY Specification: For a solo WEC under test it is required that at least one wave gauge records the prevailing sea state for a prototype scale period between 20-30 minutes every hour with an acquisition rate of (circa) 2Hz. This will provide sufficient detail for the sub-system analysis comparisons outlined in this manual. It will also allow the device performance analysis to comply with the technical specifications of other agencies, i.e. IEA OES-IA and IEC TC114.

It is useful to monitor a time series length that provides a data set that can be analysed by both time and frequency domain techniques without modification.

N.B.1. **Shorter records:** can be taken but they become un-representative of the prevailing seaway and lacking in spectral resolution.

N.B.2. **Longer records:** may also be required to adequately analyse certain probabilistic parameters of the device behaviour in irregular waves. [e.g. mooring loads, overtopping rates etc].

By obtaining the time history of the water surface elevation it is possible to derive all required sea state description parameters, see Data Analysis section. Depending on the wave gauge selected this enables several different levels of device evaluation to be conducted.

Ideally a sensor that can measure the full 2 dimensional directional spectrum would be deployed to provided sufficient detail to relate the input energy flux to the device output power. This information is particularly important for directionally sensitive WECs during the early stages of the sea trials, but less critical when crest lengths are greater than the primary dimension of the device.

The secondary approach is to monitor the 1 dimensional spectrum. In many instances this will provide sufficient information to relate to the device monitored data outlined in the sub-system sections. If the local wave prediction program results are verified against the measured records its theoretical angular distribution output can be used to supplement the practical data.

The minimal required wave input parameters must be the temporal and spatial summary statistics that describe each occurring seaway as the integrated wave height and period

Data Acquisition

There are several methods available for acquiring wave data and the one selected will relate to specific requirement. The primary sources are:

- ❍ direct measurement;
- ❍ remote sensors;
- ❍ theoretical prediction.

Sea trials can make use of all of the above but primarily will require direct, real time measurements which the other data may supplement, or support.

There are several types of wave measurement equipment that can be used, selected to suit a particular purpose, or location. The main types are:

❍ Surface buoys ~ for nearshore stations (d>25m)

❍ Acoustic sensors ~ for nearshore and inshore stations (50>d<10m)

❍ Pressure sensors ~ for inshore stations (d<15m)

❍ Radar ~ for larger coverage at inshore stations.

An advantage of conducting the sea trials at a recognised, established test centre will be that the wave climate across the whole site should already be detailed and documented. Also, the best available real time monitoring equipment should have been installed since the cost can be distributed over several projects.

In the event of gaps in the measured records they may be supplemented by validated remote & theoretical data as required. The verification process is crucial and results should only be used for basic comparisons.

Forecasting can be useful.

MEASUREMENT SENSORS

There are several wave gauges that can be used to provide direct, contact measurements.

Surface Buoys: At present the industrial standard is the directional, or non-directional, surface buoy. These have been well proven by meteorological services and offshore petroleum exploration. They are available in various sizes, which carry associated price tags. The larger met office types provide a platform for a range of other important sensors, especially atmospheric gauges. Test Centres should be based on these advanced met-ocean buoys.

It is unlikely that such platforms will be associated with solo device sea trials at ad hoc locations. Here the commercially promoted type buoys of approximately 1 metre diameter can be utilised. Several manufacturers offer these units for both 1 and 2 directional spectral records. Different measuring techniques have been used with the GPS sensor beginning to appear.

It is advantageous if the gauges supply the data as the raw time history and the analysed results.

A particular advantage of the surface buoys is that they offer real time telemetry of the data. The primary problems are:

- *They are difficult to moor in shallow water;*
- *They are less accurate in shallow water;*
- *They can often be swept away.*

These can be overcome by a different type of recorder.

Submerged Sensors: These fall into two types:

Acoustic Doppler Current Meters: ADCP signal processing can now provide water surface elevation time series from which the full 2 dimensional wave spectra can be derived. This is in addition to the water column velocity profile, which is also a useful record.

They are usually bottom standing units so can be less vulnerable in storm conditions. This means they must be autonomous, which increases the service requirement, or be hard wired to a mass storage bank. If close to shore a land station is possible otherwise a convenient platform may not be available, such as the device. They can be linked to surface telemetry buoys but then become as susceptible in extremes as the former group.

Pressure Gauges: are useful in water shallower than 20m. They measure the water surface profile remotely by pressure fluctuations caused by the waves, which provides the 1 dimensional spectrum. Directional spreading is obtained from water particle motions adjacent to the sensor passing through an electromagnetic field. Current speed and direction is also monitored. These can be exploited for on-shore device sea trials.

Data Analysis:

The data from met-ocean gauges can be provided as the raw time series of the measured parameters, for post processing, or the analysed results performed in real time on-board the instrument. Each can be useful to address different device performance issues.

In order of complexity the data formats are:

- *Water surface time history;*
- *Summary seaway statistics;*
- *1 dimensional spectrum;*
- *2 dimensional spectrum.*

Examples of the use of the data during sea trials are:

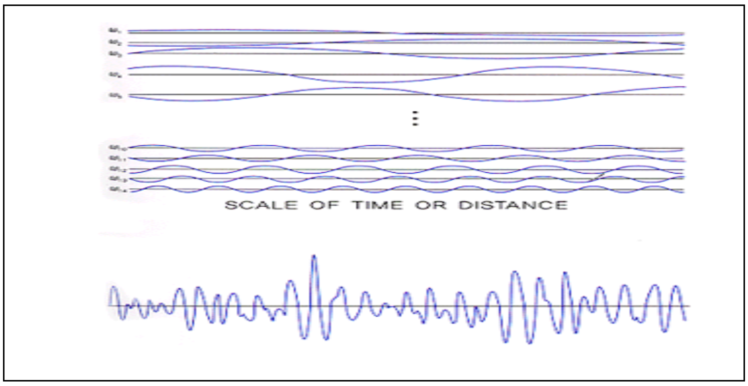
- ***Power output~*** *summary statistics & spectra;*
- ***Mooring forces~*** *time series*
- ***Hull motion RAOs~*** *spectra*
- ***O&M~*** *summary statistics & time series;*
- ***Deployment~*** *time series;*
- ***Device design~*** *all;*
- ***Control strategies~*** *time series;*
- ***Mathematical model~*** *all.*

The analysis of wave data can be conducted in the time or frequency domain, depending on the requirements of the results. In terms of the seaway summary energy flux both provide comparative values based on the variance of the water surface elevation time series. Temporal averages can similarly be computed.

However, each technique can provide unique data. The harmonic analysis reveals the wave frequency composition of each seaway in the form of the spectral profiles. Time history can be used to investigate specifics, such as weather windows.

TIME & FREQUENCY DOMAIN:

Unlike regular, single frequency waves, which can be described deterministically by two parameters (H & T), real seas are composed of the superposition of multiple frequencies that have coherent amplitudes but random phases. This produces an irregular wave train on the sea surface as shown below:



Multiple parameters are required to fully describe even a single seaway so stochastic principles are used to compress the information for convenient application.

Summary Statistics; The two principle parameters are still based on a wave height & period but that now statistically represent all the waves in a whole seaway. These can be obtained by 3 types of analysis;

- *observation = significant wave height (H_s)*
  & average wave period (T_{ave})
- *time domain = mean of highest one third wave ($H_{1/3}$)*
  & average of 1/3 waves period ($H_{1/3}$)
- *frequency domain = 4 *√ time series variance ($H_{(M0)}$)*
  & wave energy period($T_e = T_{(0,-1)}$)

These values are required for basic evaluation of the WEC under sea trials as referenced in the sub-system sections of the manual.

Each analysis method can be used for more detailed investigations as required.

- **Time Series Analysis:** is used to describe the change of the monitored signal over time. This makes it ideal for reviewing parameters such as maxima, fatigue frequencies and any grouping of waves.

Of particular merit can be the description of the seaway in terms of cumulative totals, such as wave height distributions and descriptions of the wave profiles.

From a sea trial planning perspective, and de-risking of the water based activities, analysis of the signal can be used to obtain parameters such as:

Periods & Durations when the wave height is sufficient to activate the power take-off mechanism or too extreme for its survival so requires protective measures.

Periods & Durations when the wave height is below a threshold for specific activities at sea, i.e. the weather windows when operations can be safely and efficiently conducted.

Data Analysis:

Through experience from open ocean wave measurement campaigns sea states are classified as stable for approximately 3 hours and homogeneous over many square kilometres of ocean surface. These estimates are related to storm formation and duration analysis. Recent monitoring campaigns at prospective wave energy park locations indicate high energy seaway conditions may change more quickly, both spatially and temporally. This is due to storms tracking through the area rather than being generated in it.

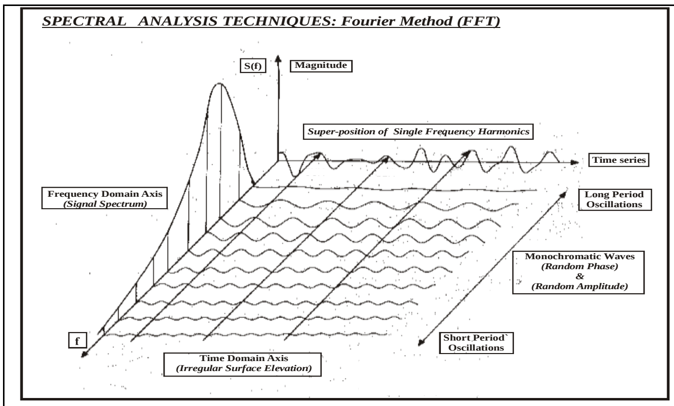
Such down-wind locations also result in the wave climates being a mix of local seas and travelling swells so can be composed of several wave systems simultaneously. Such complex conditions require powerful analysis techniques to be adequately described during WEC sea trials.

Harmonic methods can be applied to supplement the time series analysis of the water surface elevation records. A universal tool for this work is the Fast Fourier Transform, or FFT. This algorithm offers an efficient form of spectral analysis from which the wave frequency composition of the time history can be obtained.

Two factors must be accounted for:

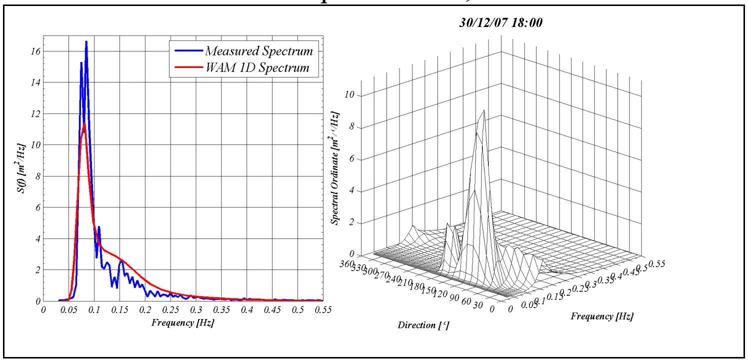
- The technique introduces periodicity where it may not exist
- FFT is based on probability so provides estimated results.

- **Harmonic Analysis:** is used to describe the monitored signal in terms of its [banded] frequency components. The figure below shows how a random time series can be deconstruction into a set of monochromatic oscillations of various frequencies and amplitudes.



The diagram also shows how the single frequency waves are represented as an energy density plot, or *spectrum*. Such in-sight into the excitation seaway is essential to the understanding of the behaviour of resonant type WEC where the seaway wave frequency composition has considerable influence on the device.

Periodicity; there are physical rules to the generation of ocean waves by wind which theoretically permit any individual frequency to be created. If the FFT is used to disassemble a seaway only harmonics are produced which introduces a repeat time for the corresponding re-constituted time series equivalent to; $T = 1/\Delta f$.



1D & 2D Spectra; The above graphs compare the non-directional, or 1D, spectrum of a seaway and the directional, or 2D, spectrum. This latter type includes the angular distribution of the wave energy flux, as shown. The corresponding frequency and direction matrix can be integrated to provide useful summary values to describe the seaway, in particular:

- Mean wave front approach angle;
- Spectral width parameters;
- Peak energy period.

Data Presentation:

As stated in the *Introduction* wave records are necessary for two fundamental purposes during WEC sea trials. (i)The evaluation of the behaviour and performance of WEC under a range of wave excitation conditions. (ii) To plan the deployment, recovery and servicing of the device during this period. Both of these requirements are aimed at de-risking the development process through the gaining of knowledge prior to incremental advances down a path of increasing technical complexity and fiscal investment.

These requirements dictate the analysis conducted and the way the results are to be presented for both convenient and detailed use by the design engineers.

Full presentation packages will be customised to a particular device and stage of the trials. However, a basic set of displays are common at all times, especially to aid the equitable comparisons of tests and devices.

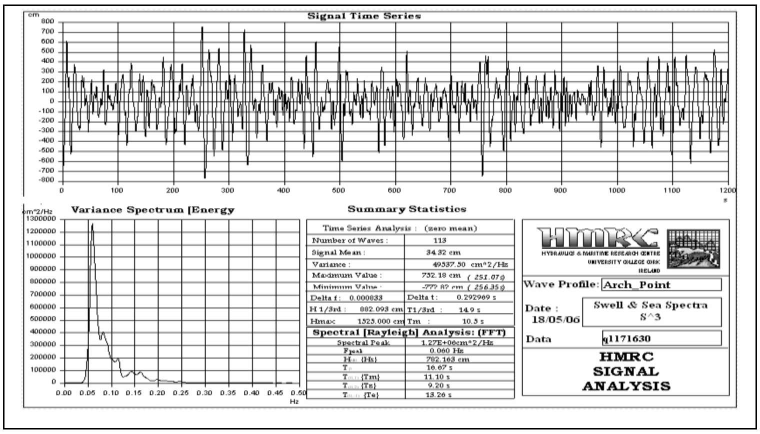
There are three aspects to the presentation of wave data measured before and during sea trials:

- ***The basic water surface elevation time history;***
- ***The summary of the seaways and waves;***
- ***The spectral details.***

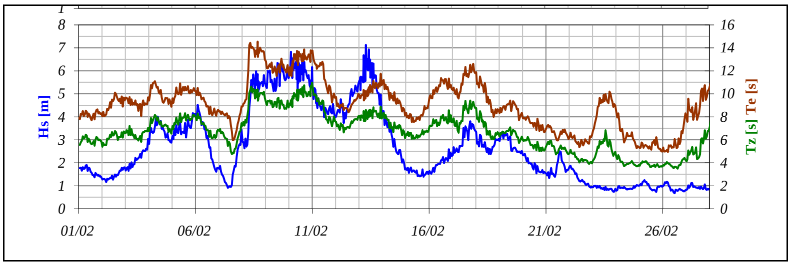
It is possible to present each of these plots on a single display for an individual seaway. To accommodate all the records that will be acquired during the sea trials reduction methods are necessary.

SEAWAY RECORDS:

As specified in the previous section a non-directional wave recorder will acquire data for 20 minutes in the form of the water surface elevation. This signal forms the basis for the time series and harmonic analysis which, together, are used to produce the summary statistics of each sea state. The figure below shows how such data can be presented in a common format.

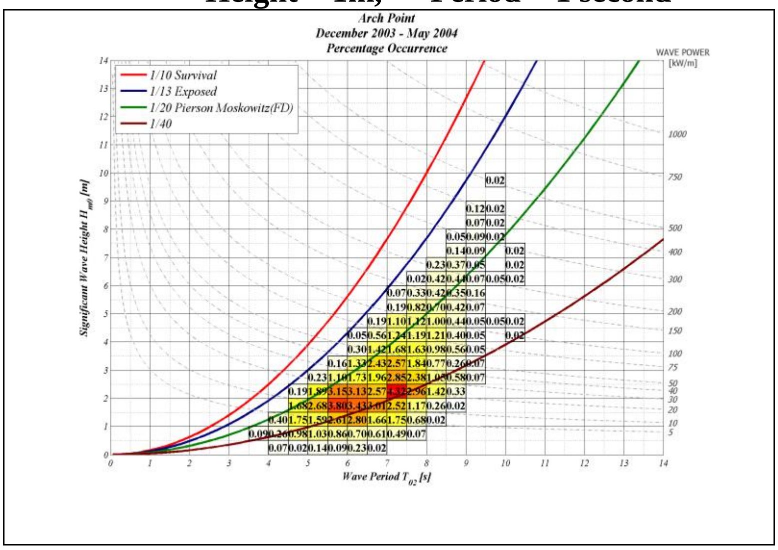


As these records amass they should be presented as the seaway summaries of height and period over appropriate time frames. These could be daily, weekly, monthly, seasonally or annually. The figure below is typical of such a plot for 1 month.



Another convenient way of presenting large amounts of seaway data is the bi-variate ***Scatter Diagram,*** as shown below. The minimum element box size should be:

Height = 1m, Period = 1 second



Data Presentation:

When presenting sea state data it can be done based on short or long term statistics.

Short Term Statistics: represent the analysis of individual seaways, as discussed so far. These criteria are the important elements for sea trials since they are gathered simultaneously with the data acquisition function on the WEC.

NB. Simultaneous recording requires that the two acquisition systems start within 15 minutes of each other at all times.

Long Term Statistics: represent the wave climate of an area and are required to predict the extremes and storm conditions that should be expected to occur at a wave energy test site or generation park.

The amount of data used in the forecasting mode reduces uncertainty in extrapolation. For official test centres this information should be accurately available. At ad hoc locations some pre-deployment wave data must be obtained to justify the confidence in the project survival estimates.

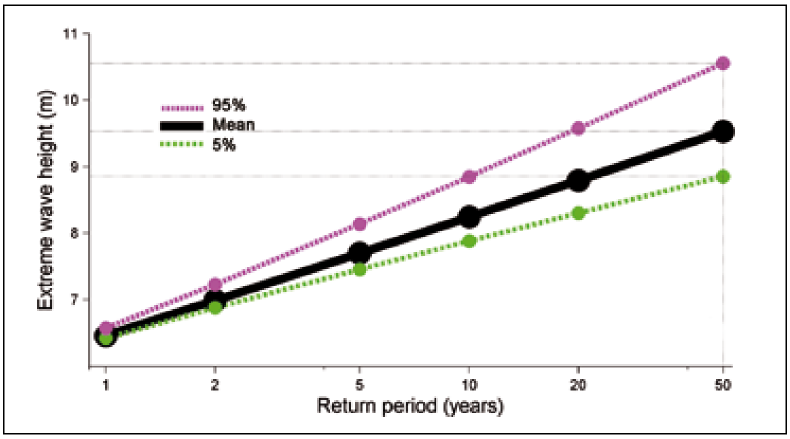
Validated, or calibrated, computer prediction packages can be used in the absence of site measurements, together with close proximity meteorological buoy data if it is available. Weibull diagrams are used to extrapolate limited wave height data to obtain, typically, the 100, 50, 10 & 1 year maximum wave. As more records are obtained the accuracy is improved.

Scatter diagrams represent the occurrence of each sub-group of seaways over a particular time period. Commonly this is for a season or a year. They are used in conjunction with the power matrix of a WEC to evaluate the overall performance during the sea trials.

Long Term Statistics: there are several methods for the prediction of the extreme waves that will occur at a test site. Basically they all operate on the same principal of probability estimations of an event exceedance in a given return period. Since this extreme prediction must be based on limited duration data, much less than the safe return period, a probabilistic model is used, such as one based on the Weibull equations.

The data is analysed to obtain the selected model coefficients which are then re-introduced into the equations to predict the extreme wave height that can be expected to be exceeded in a given time as shown in the graph below.

Alternatively the limited measurements can be graphed and the plot line extrapolated



The results can be produced for the seaway summaries, such as the significant wave height, or for the individual highest wave that would be exceeded in the same time frame. Both these values will be required for the safe design of the sea trial project.

There are two ways to reduce the uncertainty in these extreme predictions. Firstly a reasonable length of raw data is required on which to base the probabilistic model. For this exercise it is possible to resort to other sources of wave data to supplement the actual measurement. Secondly, care is required if missing data has to be accommodated. These gaps can be considered as non-measured periods or calms. This decision will influence the extrapolation.

The interpretation of the probability of non-exceedance of an extreme event in a given return period is that if it occurs on average once every 100 years then there is a 1 in 100, or 1%, chance it will be equalled in any given year. Similarly the 1 in 50 (2%) and 1 in 10 (10%) extremes can be supplied to the design team who can decide on the acceptable risk before the device is deployed.

Data Presentation:

Although energy production is an important element of sea trials they are conducted to investigate other aspects of the development of Wave Energy Devices. In particular the design's suitability for the harsh operating environment and verification that all aspects of a project, including deployment, service & recovery, can be conducted safely.

The wave data presentations for this section of the sea trials are based on both spatial and temporal information relative to set operational criteria, usually the height of the waves. The information must be compiled in three formats:

- ***Wave height exceedance;***
- ***Event duration occurrence***
- ***Event temporal spacing.***

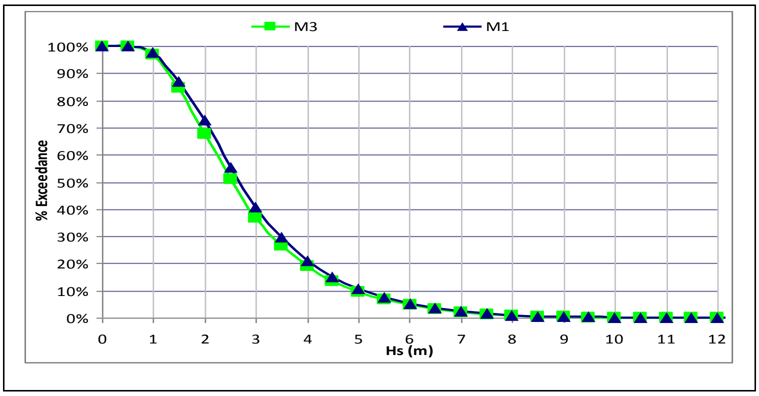
Information obtained prior to the sea trials can be used by the device design teams to modify tasks so they can be safely conducted within the time frame, or wave heights, indicated. During the trials the risk assessor can evaluate the safety of the sea based activities and adjust as required.

This information will govern the various water borne operations, both during the pre-production sea trials and, especially, the extended pre-commercial sea trials. Indeed experience has shown that they can be the main modifier to device design during full size Stage 4 proving trials.

It is recommended that these studies are regarded as an integral part of a Stage 3 programme, where the situation is more controllable.

WEATHER WINDOWS:

Exceedence plots of a parameter (i.e. wave height) are produced for a specified time period. From these the global amount of time a threshold value is exceeded is obtained, as shown below.



The next requirement is to obtain the persistence exceedance table. This shows the percentage of a year a wave height is within a window of a set time frame. In the matrix below it can be seen that seas below 1m & 12 hour duration only occur for 2% of a year (7 days). If an activity can be conducted in 1.5m waves the safety margin rises to 10% (36 days). [NB. these results will be seasonally effected]

M1 Mean Annual Windows (% Occurence)

Significant Wave Height (m) \ Minimum Length of windows (Hrs)	1	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96
2.5	45	43	41	39	38	37	36	32	31	28	26	25	23	22	21	18	17
2.4	42	39	38	36	34	33	32	29	27	26	24	22	21	20	18	17	16
2.3	38	36	34	33	31	30	28	26	25	23	22	20	19	18	17	15	14
2.2	35	32	31	29	29	26	24	23	20	20	19	18	17	15	15	13	13
2.1	31	29	27	26	25	23	22	20	18	17	16	15	14	13	12	11	11
2	28	26	24	23	21	20	18	17	15	14	14	12	11	10	9	8	7
1.9	24	23	21	20	18	17	16	14	13	12	11	9	8	7	7	6	5
1.8	21	20	19	17	16	15	13	12	11	10	9	8	6	6	6	4	4
1.7	18	17	16	14	14	12	11	10	9	8	7	6	5	5	4	3	3
1.6	16	14	13	12	11	10	9	8	7	6	5	4	4	4	3	3	3
1.5	13	12	10	10	9	8	7	6	5	5	4	3	3	3	2	1	1
1.4	11	9	8	8	7	6	5	4	3	3	3	1	1	1	1	0	0
1.3	8	7	6	5	4	4	3	3	2	2	1	1	1	1	0	0	0
1.2	6	5	4	4	3	3	2	2	2	1	1	1	0	0	0	0	0
1.1	4	3	3	2	2	1	1	1	0	0	0	0	0	0	0	0	0
1	2	2	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0

Another important met-ocean relationship that affects off-shore activity, and cost due to downtime, or stand-by penalties, is the time between acceptable wave conditions. The table below shows that at this data site for the 1.5m & 12 hr limit on average this could be approximately 16 weeks.

		Wave Height Limit (Hs)			
		1 m	1.5 m	2 m	2.5 m
Least-Mean-Most longest waiting period between windows (Weeks)	At least 6 hours long	27-30-33	9-12-15	4-7-9	3-6-9
	At least 12 hours long	27-32-36	9-16-26	4-7-9	3-6-9
	At least 24 hours long	42-44-45	19-25-36	6-11-15	4-7-9
	At least 48 hours long	150-150-150	32-34-36	18-22-30	4-11-15

Data Prediction:

Direct seaway measurements by buoys and other wave gauges, together with remote sensing from cliff-top headlands or orbiting satellites, provide real-time data for each instance in time and space. This is obviously essential information when gathered synchronously with the acquisition system on the WEC under test. Responses of the device can be convoluted with the sea states to help understand the design requirements, improvements and safety features of both the hardware and the control software required to operate wave energy machines at sea.

There are other factors in sea trials, however, that would benefit from advanced knowledge of the waves that a device will experience.

A key technical requirement is if active (predictive) control is integrated into the power take-off system. This forward projection is usually provided by deconstructing the seaway spectrum monitored by the direct wave gauge and applying dispersion algorithms to a new location.

Offshore operations, particularly for deployment, maintenance scheduling, and export predictions would also benefit from accurate forecasts of the prevailing wave systems at different time advances.

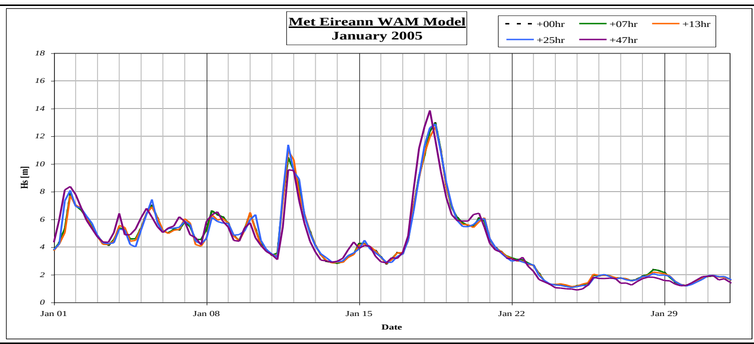
Traditionally this information was extracted from probability analysis of hindcast wave data, as described in the ***weather window*** section. A different approach is to reference the output of modern 3rd generation energy budget wave prediction models.

WAVE MODELLING:

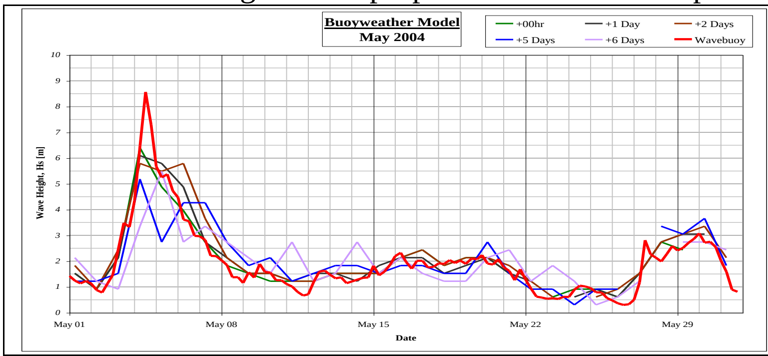
Wave prediction programs have improved considerably in recent years, although it should be noted from the outset that the quality of results can be very site specific. They can be useful during sea trials for two different time frames.

Short Term (<24 hours); Global wave prediction models are often run on a regional scale to a tight grid of a few kilometres, and up to 2 days ahead. These mathematical models can be very accurate up to this forecast period so once the accuracy of this Meteorological service has been validated for the sea trial site the data can be referenced to assist in the planning of the device test programme. In particular it can be used to specify when variables should be changed relative to the populating of the device energy matrix at different set-ups.

Also, the electricity supply market is based on predicted output from generating plants for a few hours into the future. This has usually been problematic for irregular sources such a renewables. At typical exposed wave energy generation park site wave height prediction for up to 24 hours forecast should be accurate enough to facilitate the export planning, as shown in the diagram below. This possibility should be investigated during the pre-commercial proving sea trials relative to each particular device.



Medium Term (>7 days); The global prediction models produce forecast for as long as a week ahead. This leadtime should be sufficient to assist in the offshore activities required for deployment, maintenance and survive during the sea trials of S3 & S4. The graph below shows the time history of predicted forecasts up to 6 days in the future relative to on-station measurements. It can be seen that even at the longest forecast all major events are recorded, though the error becomes greater in proportion to the time step.



Data Archive:

There are four primary drivers to the requirement for carefully planned storage of the wave field data:

- *It is doubtful that the wave monitoring will be on the same acquisition system as the device sensors;*
- *An individual file size will not be excessive but at one record per hour over a full sea trial duration (1-5 years) a considerable number of files will be created;*
- *It will be imperative that, even after an extended delay, simultaneous wave & device record files must be recoverable from the archive;*
- *There will be many different device and environmental combinations that must be exclusively associated.*

Modern digital storage systems can accommodate the high levels of data that will produced so even raw information files should be archived.

Hardware: requirement are;

- *A storage medium that will not quickly become redundant must be selected;*
- *Data & control files can be handled separately;*
- *Direct connection to the Internet for extended distribution and remote control is available.*

Software: essential are;

- The actual sensor signal output is often not sufficient to uniquely identify single files. A project specific **metadata** nomenclature should be established.
- Real time validation & quality checks must be performed

METADATA FORMAT:

It is not required to be prescriptive on the type of archiving format that should be implemented, only that a well structured, but flexible, cataloguing arrangement covering the fundamental requirements is designed. The identification process should start with the naming of a file.

Since the met-ocean data will have an independent telemetry system the most important parameter in the identification header will be the time stamp. This one marker should allow all different data files to be cross-correlated. However, this could be laborious since several independent log files could be produced during the sea trials, such as:

- Device sensors data;
- Met-ocean data;
- Operational settings;
- Failure and service log;
- Variables & constants parameter values, etc.

If in addition to this there can be several dispersed operators who can take independent intervention actions a more detailed metadata, or heading, that registers all such parameter values settings would be useful.

These identifiers should be added at the pre-archiving stage and can have automated incrementing, or operator intrusion, as required. It is essential that all changes are registered in the master sub-directory and no contradictory files are created.

It can be advantageous if data validation and preliminary analysis algorithms are also added at this junction, including a display package, since these actions will be rote to all data sets. This would be particularly relevant to sensor calibration to ensure the correct co-efficient are not misplaced prior to use. The raw data must also always be maintained and can be presented in real time in a standard format, as shown in the example below.

REPORT NO.		LOCATION	
DATE		DEVICE	
TIME		PROJECT DURATION	

ENVIRONMENTAL CONDITIONS

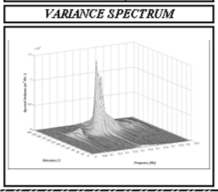
WAVE CLIMATE

INSTRUMENT	Waverider	
RECORD LENGTH	30min	
VALID RECORD	YES	NO
VERIFIED	YES	NO

STATISTICS

Hm0 [m]	2.15
T02 [s]	8.747
Te [s]	7.458
Tp [s]	12.3
Dirp [°]	132
Hmax [m]	4.05
Wave Power [kW/m]	23.88

VARIANCE SPECTRUM



WIND

INSTRUMENT	--	
RECORD LENGTH	--	
VALID RECORD	YES	NO
VERIFIED	YES	NO

STATISTICS

Mean Speed [m/s]	--
Gust Speed [m/s]	--
Mean Direction [°]	--

WIND ROSE

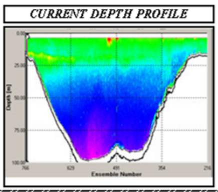
CURRENT

INSTRUMENT	ADCP	
RECORD LENGTH	60min	
VALID RECORD	YES	NO
VERIFIED	YES	NO

STATISTICS

Mean Speed [m/s]	0.12
Peak Speed [m/s]	0.2
Flood Direction [°]	17
Ebb Direction [°]	195

CURRENT DEPTH PROFILE



PROJECT LEADER	LEAD TECHNICIAN

Lessons Learned:

The recommended measured parameters together with the analysis and presentation procedures are based on the experience of pioneering wave energy device developers who have already conducted Stage 3 or Stage 4 sea trials.

Many of these suggestions have been gained from practical problems faced and solutions found so should not be ignored lightly. Difficulties encountered at sea are costly to correct, particularly when safety of personnel is a prime consideration.

It should always be acknowledged that the ocean is an unforgiving place for anyone, or anything, not equipped to be there. The greater the knowledge of the environmental conditions the less will be the risk of operation in these harsh surroundings.

Offshore engineering has advanced a long way due to the oil & gas industry which has resulted in better sensors and advanced analysis techniques. These should be adopted and adapted by the nascent ocean energy industry to reduce the levels of uncertainty in the data and minimise the risk in the required field work.

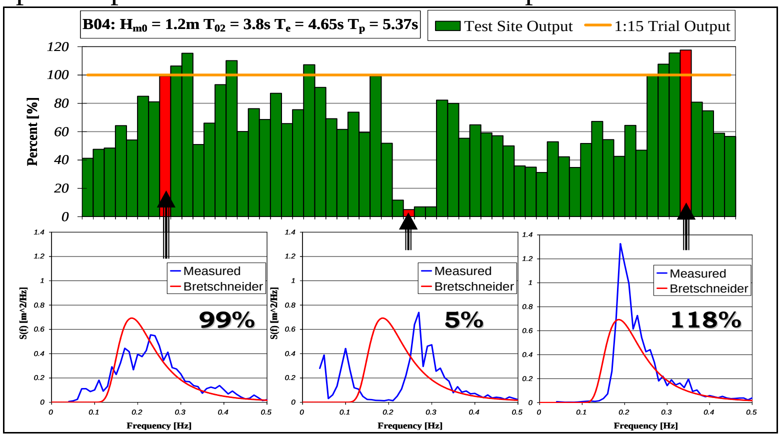
There remain many aspects to the multi-disciplinary operation that are unique to wave energy. The purpose of the sea trials is to discover these and address them, since modification and rectification is anticipated. Once a device has achieved the commercial stage change becomes more difficult. No unit to date has moved from pre-production to pre commercial without a major re-fit.

SHARED EXPERINCES:

AWS: At the start of the initial solo device sea trial Teamwork Technology (then owners of the patents) had a problem deploying the prototype scale device due to submergence instability created by the prevailing wave period. Advanced knowledge of this resonant effect would have saved considerable time at this phase.

PELAMIS: At the beginning the company's first array sea trials an unexpected problem was encountered with a previously proven mooring system. Rectification required a very tight wave height limit. There was a considerable delay in the project until these conditions occurred.

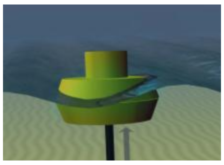
RESONANT DEVICES: The figure belows show the power output of a WEC in similar summary seaways but of different spectral profile. This is an extreme example of the



different wave frequency mix situation to emphasis the effect. The upper histogram represents the device power output. As can be seen the variability is highly significant.

OCEAN ENERGY BUOY: a ¼ scale systems testing device was deployed on station just after Christmas. By the New Year it had experienced, and survived, a 50 year storm. The company had consulted the long term wave statistics for the site during the sea trial planning stage and adjusted the mooring design and configuration to reduce failure risk to an acceptable level suggested by the certification consultants.

HYDRODYNAMIC SUBSYSTEM



Prime mover

Technology Development Stages 3 & 4

Rationale

Data on the motions of the prime mover in the water is an essential element for the hydrodynamic characterisation of a wave energy device. This represents the first step of energy conversion from wave to wire and is of particular importance for the efficiency evaluation of a wave energy technology, because the prime mover is typically the main component of distinction between technologies. Due to the different philosophies of primary energy conversion (e.g. resonant heaving buoy, overtopping, Oscillating Water Column), the characterisation of the hydrodynamic subsystem brings along different approaches from device type to device type.

Similar to the Met-ocean measurements, the level of detail necessary can be adjusted to suit the stage of the tests. The more precisely the occurring wave fields at the device are identified the better the hydrodynamic subsystem can be characterised. This step is the potentially most important item for verification of numerical simulations of the device behaviour, and is also the interface to the input for the Power-take-off (PTO) evaluation. In all cases, measurement frequency and accuracy of the hydrodynamic subsystem should be sufficient to match the target met-ocean conditions.

Objective

Monitoring the hydrodynamic subsystem can comprise the following targets, of which some are only met in rather advanced states of the sea trial schedule:

- relate the statistical properties of the sea state to absorbed mechanical/pneumatic power levels (FD-frequency domain)
- to evaluate the hydrodynamic efficiency of the device
- (advanced target): to relate the real-time body motions to the actual motion of the water surface (time-domain; TD)
- to establish the input power available to the Power-take-off (PTO), both in the time and frequency domain
- to adjust control strategies and PTO settings for safety and/or efficiency optimisation (movement restrictions)
- to determine operational limits for certain sea states (deployment, recovery, service, cut-in and cut-off wave height and period combinations, etc.); both FD and TD
- to input into device mathematical design models

Pre-Sea Trials Requirements

The hydrodynamic design, i.e. the dimensions of the prime mover, will be determined based on the existing information on predominant and extreme sea states (see met-ocean sea trial manual), in order to ensure that the sea trials serve as baseline for an extrapolation of future device generations.

The choice and location of sensors identifying the prime mover must ensure capture of extreme values, as well as maximising accuracy in most likely average operational modi.

Whereas in some devices the choice of physical quantities and respective sensors is obvious, in other cases a detailed analysis of options for identifying the energy capture of prime mover is essential.

KEY ELEMENTS

- establish the physical quantities to be measured
- ensure verifiable interface to met-ocean data and PTO measurements (redundancy of key data)
- determine acquisition rate according to met-ocean data
- choice of sensor types and locations
- time stamp of acquisition systems (synchronise with other subsystems)

IMPORTANT REFERENCES

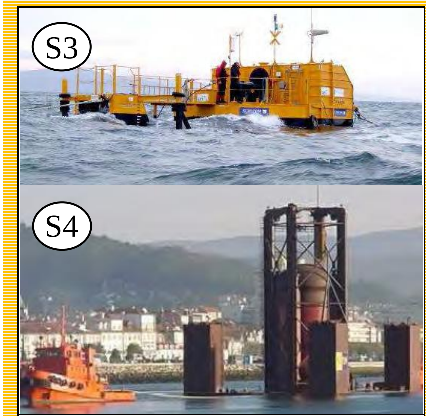
EquiMar WP3, WP8, Del 4.2	OES-IA Annex II of IEA	IEC TC 114
DECC URN 09/559	dti URN 07/808	EMEC Standards

Development Stages

The vital importance of real-sea testing of ocean energy devices is contrasted by typically very restricted funding for overcoming this phase, also as consequence of non-sufficient understanding of the factors that do distinguish ocean energy devices from other renewable energy technologies: the real sea environment.

As a consequence, a staged testing approach may be required, in order to adapt to the different priorities of each phase of a project. In the solo device sea trial stages (S3 & S4) addressed by this document, a case-to-case trade-off between monitoring system complexity and available means (both manpower and funds) needs to be done, not only distinct between wave and tidal machines, but also between different wave energy converter types.

Apart from the reaction subsystem (in particular moorings, see other reaction subsystem sea trial manual), the hydrodynamic subsystem is the major distinctive element from other technologies, stressing the importance of its proper testing in these development stages. Input hydrodynamic quantities need to be related to the movements of the outer body of the device (floater, reference body, water surface,…) with varying level of detail.



Scale tests S3 and full-scale S4

1:4-scale model of floating OWC (above; foto Ocean Energy); full-scale AWS I pilot plant (below; foto Teamwork Technology)

TEST PROGRAMMES

The present document refers to the sea trial stages S3 and S4, which according to IEA-OES-IA Annex II correspond to the Technology Readiness Levels 5-8 (see met-ocean manual), referring to specific prototype and demonstration plant testing. Primary objective of these phases is to proof technical viability and minimise technical and financial risks for the commercialisation phase.

Stage	Section	TRL	Timetable
S3	Sub-system Bench Tests	5	6-12 months
	Full-system Sea Trials	6	6-18 months
S4	Prototype Sheltered Site	7	1-2 years
	Prototype Exposed Site	8	1-5 years

Within the 2 stages of sea trials targeted by this document, the priorities can be different for each phase:

- **Sub-System Bench Tests:** typically large- or full-scale 'dry' tests of parts of the whole system with the priority of characterising the PTO characteristics, not usually straight-forward to apply to the hydrodynamic subsystem. However in particular cases special test rigs can be the last (and best) possibility to validate and calibrate 'indirect' prime mover measurements, such as determining the movement of a floating body by measuring pressure and stroke in cylinders, or the angular movement of a blade.

- **Full-System Sea Trials:** typically reduced scale (1:2 to 1:4, in some cases down to 1:10) sea testing of the complete device at a 'benign' test site. Such sites offer relatively easy accessibility as sea states do not normally interfere with boat traffic, and light equipment can be used for deployment and maintenance. However wave action is not benign with respect to the dimensions of the devices, making this phase the first seaworthiness proof, which is of particular importance to the hydrodynamic subsystem. This phase is especially important for wave energy devices, and might not be vital for tidal energy machines.

- **Prototype Sheltered Site:** sea trials of a full, or approximately full, size prototype device can be undertaken in two phases: in this first phase a sheltered site in order to allow for system functionality verification and validation of models. For wave energy hydrodynamic subsystems, in particular device performance can be verified but survival modes must be deferred until the following site.

- **Prototype Exposed Site:** as opposed to final functional verifications, this is the final proof of seaworthiness and long-term functionality. Extended performance verification and survival diagnosis are to be performed specifically for the hydrodynamic subsystem, in order to compare the prime movers' behaviour to the expected situation. Redundancy of measurements is important, both so that the motions of the prime mover can be recovered in case of loss of one system, and for verification of accuracy.

The appropriate choice of a deployment site is a key factor for stages 3 and 4, in particular with respect to the dimensions of scaled devices and the possibility of doing part of the initial seaworthiness testing in moderate conditions, before going to fully exposed sites.

Note that the dimensions of the device need to be adopted to the scale using the extensively documented Froude similitude (for 1:X scale trials):

Dimensions → scale 1:X

Time (wave period) → scale 1:√X

Shared Experiences

The behaviour in real random (and extreme) sea of the hydrodynamic subsystem has been the major challenge for wave energy projects to date, also because the environmental conditions and their interactions with the device are far more complex, severe and more difficult to predict than for other renewable energy technologies.

As presented in the next section, there are different types of power conversion, for example twin bodies, (incl. OWC), overtopping, pressure-difference, and all have important distinctive characteristics with respect to hydrodynamic subsystem and its interaction with real sea environment. In most cases, model tests and simulations have shown insufficient to reasonably predict the behaviour which makes the limited information from existing experiences crucially important for future projects.

Some shared experiences from former projects that demonstrate the importance of extensive validation of hydrodynamic subsystem motions are presented on the right-hand side.

In the last phase of stage 4 sea trials, the fundamental difference to former development steps is the necessity to deal with extreme phenomena of the Met-Ocean environment, as well as highly energetic multidirectional random seas that can have different impact on the systems from the expected one.

This trial phase is required to gather information on the extreme motions and loads exerted on the hull, power take-off, mooring lines, anchors and foundations for fixed or gravity structures. In particular, the extreme motions of the hydrodynamic subsystem as primary motion inducer are of interest, and these cannot be modelled to a realistic extent.

Further, short crested seaways can excite all the motions simultaneously, and although not tending to create maxima, unexpected interactions with the hydrodynamic subsystem can occur.

Of particular interest are moderate to high energetic sea states with well-defined energy periods in the range of the resonance frequency of the prime movers, as these typically induce the most critical forces on the Power Take Off (PTO) and the end-stops of translatary, reciprocating motion PTO systems. For this reason, floating, buoyant type WECs use hydrodynamic inefficiency as first line of survival: once the sea states become too big, the device becomes out of tune and the hydrodynamic response decreases drastically, thus avoiding excessive movements.

LESSONS LEARNT

In the recent sea trials of stage 3 and 4 devices, there have been several unexpected hydrodynamic behaviours that could not be realistically predicted through laboratory modelling and simulation techniques beforehand. Although most of these trials were properly and carefully prepared according to valid engineering standards, some typical examples of unpredicted body motions have severely jeopardised the success of the test programme:

- ✓ By 1998, the testing of the floating OWC Mighty Whale in Japan led to the conclusion that the low OWC oscillation would not allow for viable operation of that design;

Foto: JAMSTEC

- ✓ The rather large and unusual structure of the 2MW pilot plant of the Archimedes Wave Swing Technology was deployed in 2004 in Portugal, after several failed attempts due to the geometry of the 48m x 28m x 5m large support pontoon (excessive inclination and movements due to resonance with sea state)

Foto: Teamwork Technology

In general, with respect to the hydrodynamic subsystem, a number of practices of naval architecture is highly relevant to wave energy trials, in particular the recommendation to test out the pre-deployment of the device in sheltered areas (e.g harbour basin, bays), as well as device inclination tests, and free oscillation trials. Whereas the former can be vital for a smooth deployment procedure, the latter can help to assess the real-scale Response Amplitude Operators (RAOs) of the overall system: the RAOs describe the response of the body relative to the wave excitation, representing the fundamental characteristic of the resonator to harmonic excitation.


Foto: WavEC

- ✓ In the stage 3 trials in Galway Bay/Ireland, very long period components of the seaway (not in scaled proportion with respect to the device dimensions) caused excess pitch of the 1:4 scale Wavebob test device in 2007;
- ✓ In 2009, an 80 ton, 20kW rated test rig of the Trident technology capsized while being towed to the deployment site fell over on tow to station

In general, a lesson learnt from former experiences is that in particular for the S3 and S4 sea trials, failure modes and survival scenarios should be drawn up prior to commencement of the test programme, including hull breach and other unlikely situations, in order to allow for unexpected behaviour or damage, while maintaining the capacity of executing the sea trial programme.

Data Organisation

The ultimate aim for the hydrodynamic subsystem of the sea trial stages S3 and S4 is to specify the prime mover and reaction frame of the devices in relation to the complete set of environment conditions. In particular due to the random character of ocean waves, the demand is therefore to gather as much data as practically possible.

Partly because all implications of the data may not be yet appreciated, being the first test at such scale with the devices (see also met-ocean sea trial manual).

On the other hand, obtaining sufficient met-ocean data should remain relatively inexpensive, due to the typical financial restrictions of this phase mentioned before.

For the hydrodynamic subsystem, the completeness of acquired data and their appropriate organisation is of particular importance for the validation exercise of numerical models and survivability assessment.

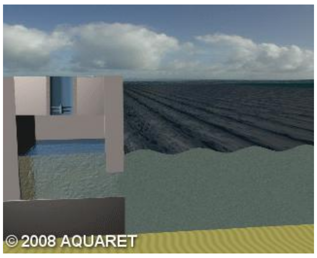
According to OES-IA Annex II, "Early prototype machines should be extensively instrumented, including duplicate and redundant sensors and dual data acquisition systems. Active operational communication should be on a separate SCADA (supervisory control and data acquisition) system to the measurement and monitoring system. The mantra should be: The cost of losing data can be more expensive than the price of obtaining it.

Duplication & Redundancy: although the cost of obtaining data during operation is high the price for not monitoring all variables will be higher. Past experience has shown that even in extended sea trials the amount of usable information, when all sensors were operational in the wave conditions and device configuration required can be limited. A measuring campaign that still leaves important

MONITORING PARAMETERS

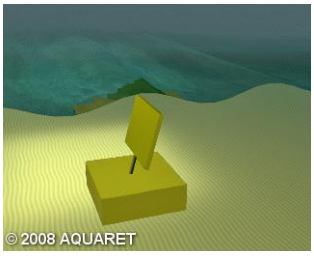
Most of the physical quantities listed in the met-ocean sea trial manual have direct relevance for the characterisation of the hydrodynamic subsystem as the first stage of energy conversion: wave height, period, directionality (principal direction and angular spreading) etc. On the other end, most relevant output quantities of the hydrodynamic subsystem are torque and/or velocity of prime mover, instantaneous absorbed power and mean power, all required inputs to evaluate the next stage of the conversion, the PTO subsystem (see PTO sea trial manual).

The identification of the physical parameters to be monitored for characterising the hydrodynamic subsystem is more complex, as there is still a variety of concepts that may be lead to deployment in the market.

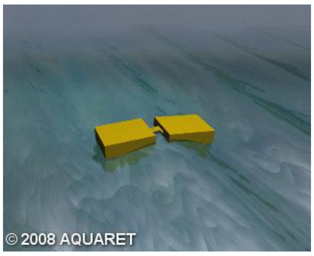


OWC (Oscillating Water Column): prime mover is the internal water column

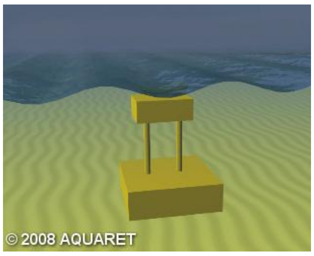
Overtopping: prime mover is combination of barge/ramp and basin surface



OWSC (Oscillating Wave Surge Converter): prime mover is a pivoting flap



Attenuator: prime mover are articulated floating bodies (relative movement)



Point Absorber (left) and Submerged Pressure Differential Device: prime mover is floater against reference body

Despite no generally accepted device classification exists, the above outlined approach delivered by the AquaRET project (www.aquaret.com) is frequently cited and used here to demonstrate the variety of prime mover characteristic. This list does not aspire completeness, and different notions/ denominations can be used. For more detailed distinction of devices presently most likely to play a relevant role in the near-decisions to extrapolation cannot be regarded as successful.

The two recommended solutions to this problem are to employ duplication of essential sensors such that the risk of failure and loss of recording is minimised. This approach is particularly useful were replacement and renewal of the transducers is not possible at sea or without a major re-fit. The less expensive approach is to adopt redundancy in the system such that indispensible physical properties can be (accurately) derived from other independently measured parameters. As with duplication, the threat of losing both sensors is considerably reduced."

Example for wave-device interaction in OWC

Data from Pico OWC: water elevation and chamber pressure records for estimation of flow rate (Graph: WavEC)

The most important data for characterising the hydrodynamic subsystem is typically related to the hull motions of floating bodies (heave, pitch, surge etc.; see right-hand side), the organisation of the separate measurements into comparable and readable records, allowing to evaluate the overall movements of all relevant bodies and components of the device.

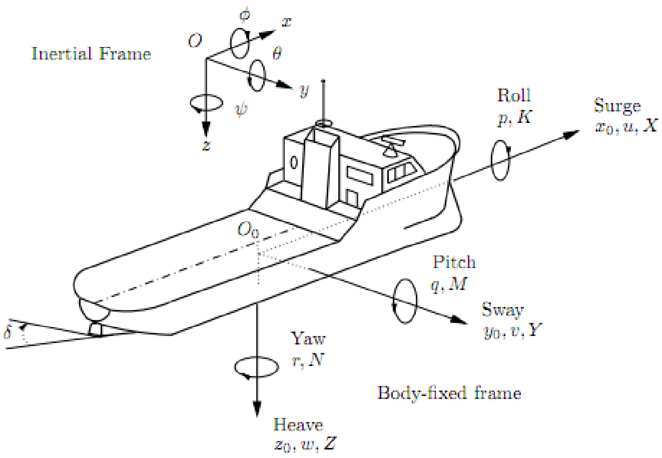
A logbook is of paramount importance. For each test period the length, input quantities, output quantities, machine control, machine status, etc. should be recorded, and additional observations/perceptions noted (e.g. general met-ocean conditions, unusual circumstances / events,…).

term market, refer to Deliverable D5.2 of the Equimar project, the 'Device classification template'.

To understand a wave energy device's overall performance at sea, the capture of the prime mover's characteristics in all instances of operation is highest priority, hence the recommendation of gathering as much following information as possible throughout the sea trial period:

- Incident wave field / wave climates at head of device, ideally also at beam and behind the device;
- 6 degree of freedom (DoF) body motion & phase / vessel motion response (velocity RAOs and motion RAOs);
- Seaworthiness of Hull & Mooring:
  - Water surface elevation abeam of devices;
  - Excessive rotations or submergence;
- PTO forces & power conversion (pressure / force) for indirect measurement of body movements

The central task for characterising the hydrodynamic subsystem is the second point, namely an as accurate a possible characterisation of the 6 DoF body motions:



Standard notation and sign conventions for ship motion description (SNAME, 1950)

According to the traditional definition of the 6 DoF of ship motions, measurements should enable to clearly identify these movements for the prime movers of wave energy converters:

- **Surge** "sliding" longitudinal motion of body;
- **Roll** motion of body about its longitudinal axis, causing the body to rock from side to side;
- **Heave** vertical, up-and-down motion of body;
- **Yaw** motion of body about its vertical axis, causing the forward and aft ends of the ship to swing from left to right repeatedly;

Further, the identification of unlikely or unphysical events, both in the frequency and time domain should be ensured, e.g. transients, level changes, etc, and statistical domain, e.g. outliers, improbable distributions etc.

For S3 and S4 sea trials, it can be summarised that the optimum is to conduct as many trials as possible, in order to yield the maximum amount of data, as well as ALWAYS HAVE A DETAILED TEST PLAN.

- **Sway** "sliding" lateral, side-to-side motion of a ship;
- **Pitch** motion of body about its transverse axis, causing the forward and aft ends of the body to rise and fall repeatedly.

Typically, for floating wave energy converters heave, surge and pitch are the primary motions for power conversion. While heave and yaw are defined along the vertical axis, the movements referring to the horizontal axes require a pre-definition of the longitudinal and transversal axis, in particular in case of axisymmetric bodies (common for point absorbers). In such a case, it is recommended to fix the longitudinal axis as the predominant line of wave propagation.

In general, the following physical quantities are likely to be most relevant for ocean energy devices:

- Level (distance);
- Pressure (dynamic/static);
- Flow (velocity);
- Valve positions (limit/percentage);
- Device position and orientation (coordinates/reference for 6 DoF motions…, floating device);
- Device (hull) angles;
- Movement, speed and/or acceleration (e.g. heaving floater vertical position, angular speed of the wing of an OWSC, acceleration of a point absorber or attenuator body).

Further, although usually not primarily required for performance assessment, the following quantities can become relevant:

- Air temperature (precision of the measurements),
- Humidity (e.g. OWC air properties),
- Salinity (e.g. corrosion risk assessment for durability of the sensors and equipment).

(lists do not aspire to be complete!)

Data Acquisition

The data acquired during the first sea trials is of fundamental importance for device assessment and the future development process, in particular with respect to the hydrodynamic subsystem. Being the first opportunity to record operational data in real sea environment, the setup of the data acquisition system of stages S3 and S4 must allow for redundant data storage and transmission strategy, in order to avoid the loss of data for any potentially relevant event (in particular extreme events).

The overall acquisition rate of the data logging equipment must be sufficient to record simultaneously all required channels with a rate sufficient to clearly relate the incident energy variation with measured physical quantities in all subsystems.

The number of recording channels and bandwidth available to the selected telemetry system will dictate some aspects of the logging and transmission protocol. For security it is advisable to log all raw variables on-board, even when they are also immediately transmitted to the shore station. Error states should be coded so that the source of the error can be quickly identified. The on-board SCADA/PLC (Programmable Logic Controller) system that is autonomously controlling the electro-mechanical parts of the power take-off can be set to record all events to the on-board logger and transmit the status marker to shore. The operational parameter recording system can file all data on board but also transmit the full time series

Since sea trials can be conducted several nautical miles off the coast the telemetry system must be selected based on the distance requirements (radio, GSM, wifi, etc.). If power is

MEASUREMENT SENSORS

For both input and output quantities, sensor redundancy is recommended in particular for the hydrodynamic subsystem, due to the lack of precedence for most measurement cases and the consequently limited confidence in accuracy. Multiple sensors, not necessarily of the same kind, should be provided, on the prime mover, or directly connected components (PTO). Sensors can also be provided elsewhere, e.g. on the reaction frame, or shore-based, such that the motions of the prime mover can be recovered. Independent data acquisition and machine control systems are recommended.

The following sensor types can be of particular use for the identification of the hydrodynamic subsystem, however this should not be a complete list, as different requirements may exist and sensing technologic progress is relatively fast:

<u>Water surface level measurement</u>

- Non-contact level measurement (level- and guided radar, ultrasonic beams, optics, video-based techniques derived from laboratory use);
- Contact level measurement (electromechanical level measuring system, capacitive level measurement, hydrostatic level measurement, differential pressure measurement, differential pressure transmitter (with ceramic and silicon sensors));
- Radiometric measurements - compact transmitter for non-contact level limit detection (including protection equipment) level, interface and density measurement; suitable for hazardous areas.

<u>Direct floater movements</u>

- Position Sensors (arrays/stacks of proximity sensors);
- Speed Sensors (utilizing magnetoresistive, variable reluctance, Hall-effect, variable inductance, and spiral technologies. Manufactured as zero speed, bi-directional, and omni-directional speed sensors);
- Accelerometers (direct pitch and roll measurements; in combination with horizontal accelerometers and a compass this forms a complete sensor unit as used in wave measurement buoys; stabilised platform sensor, performing heave and direct pitch and roll measurements combined with a 3D fluxgate compass and X/Y accelerometers);
- Motion Reference Units; gyroscopes (angular motions);
- Displacement measuring interferometers;
- Digital video cameras as useful additions to the instrument pack, or as advanced optical recognition systems (as e.g. in laboratory applications);
- GPS receiver for buoy positioning (to date precision only for verifying station-keeping, not performance).

tapped off the generation system there should not be problems with battery life but emergency back-up should still be incorporated in the circuitry. For data archiving, synchronised date/time stamps must exist for all the recorded channels.

Digital video cameras are useful additions to the instrument pack but are bandwidth consuming appliances when streamed to shore (picture quality can be reduced or time laps photography applied). They may also be placed on a separate transmission system for data safety.

Extreme emergency events, such as drifting off station, power take-off malfunction, grid loss, hull breach or survival mode failure, etc should all be on a potentially separate priority warning circuit.

<u>Floater movements through PTO flow/force/position</u>

- Position Sensors (linear distance sensors, ultrasonic sensors, SMART position sensors (most accurate linear position sensor available in the industry (0,05mm), magnetic position sensors, infrared sensors)
- electromagnetic flow measuring system, vortex flow measuring system, coriolis mass flow measuring system, ultrasonic flow measuring system, thermal mass flow measuring system
- Intelligent tank gauge with high accuracy performance liquid level, density & density profile; thermal mass flow measuring system; flow switch for safe monitoring of mass flow and temperature in industrial processes;
- Pressure transmitters (with ceramic and metal sensors), differential pressure flow measurement with orifices and deltabar differential pressure transmitter

Extreme emergency events, such as drifting off station, power take-off malfunction, grid loss, hull breach or survival mode failure, etc should all be on a priority warning circuit.

In addition to the main physical quantities indicated above, the following sensor types may be relevant:

- Fast-responding contact thermometers;
- Thermocouples,
- Temperature transmitter for resistance thermometers;
- Humidity sensors;

Instruments should be located where they can be easily calibrated and replaced during routine maintenance. Particular attention to positioning will be required if the exchange operation is to be performed at sea. The possibility of being able to exchange measurement devices during the sea trials is of particular relevance to the hydrodynamic subsystem, because

Data Analysis

It is vital for the credibility of the sea trials that the methodologies for data analysis follow common standards and are as transparent as possible. As for the other subsystems, the ultimate aim in both stages S3 and S4 is to populate the scatter diagram with relevant performance data, in order to yield a power matrix for the overall system.

On one hand, sufficient number of measured results must exist, in order to reduce the interpolation errors required to fill the blank blocks. A typical requirement of 3-5 measurements for each sea state element so that a true representation is obtained. This requirement relates to the variability in power production levels due to different spectral profiles of the seas that can occur. Deliverable 4.2 of the Equimar project offers a methodology to combine several sea states in bins for the (likely) cases that not all sea states can be satisfactorily covered by the sea trial data.

As acquisition frequency, an often used value is 2Hz, which allows to properly characterise a 5-second wave with 10 data points (see *Data Analysis*). For European West coasts open to the Atlantic waves (priority deployment areas due to resource), this has been found a typically acceptable trade-off between acquisition rate and amount of data, being 5s in the period range of the smallest wave relevant to energy production in most areas. However this value must be decided case to case, and in particular in the North Sea, generically in seas with two-peaked spectra, and in particular in S3 trials often made in sheltered areas, higher acquisition rates are required. On the one hand, an indication of a minimum of 10 data points for the shortest wave to be identified can be taken as first

DATA PRESENTATION

In order to yield a convincing statement towards technical advisors, investors and other target groups, the processed data must be presented in a clearly understandable and sufficiently commented way, with regard to the target group of the information. In general, it should be expected that two distinctive approaches are required:

(i) Commercially sensitive material for internal consultation;

(ii) Publicly available reports required to promote the device.

The decision on what information will be in which section will be conditioned by the company policy, however naturally the more data and results are published, more credibility can be triggered in the target groups.

Whereas there is no reason to publish the performance and functionality specific to the hydrodynamic subsystem (unless considered relevant for scientific articles), the commercially sensitive material to be prepared for review should include:

- Sea trial log of what proving trials were achieved and of all events requiring intervention, and particular focus on survival-relevant scenarios;
- Full “hydrodynamically absorbed” power matrix with data including estimates of uncertainty (see also Deliverable 4.2);
- Summary results comparisons and eventual design modifications for the prime mover (hull/floater/chamber etc.) identified during the sea trials

The preferable sea state parameters to be used in the scatter diagrams (hence in the “hydrodynamic power matrix”) are significant wave height (Hs) and Energy Period of the sea state (Te), according to the overall/general power matrix (input: sea state – output: active electrical power): the size of the cells delimited by the increments on the axes, can be defined as considered relevant for the concept, but as a guide a cell size of 0.1 – 0.2m/s for velocity or 1s and 0.5m for wave period and wave height appears reasonable.

In addition to the “hydrodynamic power matrix”, exemplary outputs of the sea trials should also be produced in the time domain, in order to visualise an impression of the device behaviour. An example of such a visualisation is given in the following figure, showing the evolution of incident wave and absorbed pneumatic power of an OWC column. Equally, instead of the absorbed pneumatic OWC power, there could be the mechanical power absorbed by a pivoting flap (OWSC), or by the floater of a point absorber or a submerged pressure differential device.

estimate. On the other hand, the duration of one test that can be estimated with the necessity of an approximate 3000 data points (20-30min in Atlantic Wes coast), in order to reasonably represent the spectral properties of a sea state.

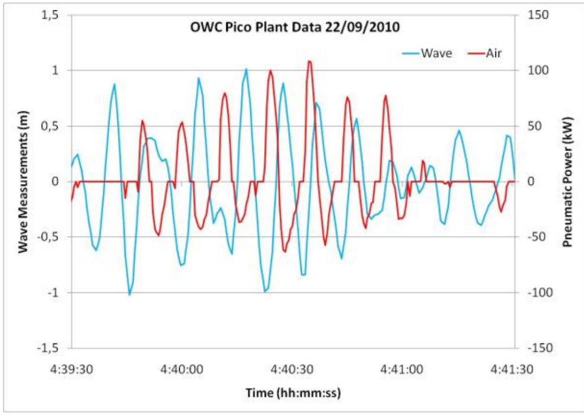
For tidal devices, each data point should have as basis the tidal velocity over a recording period of 5-10 minutes.

Further, a sensitivity analysis to be performed to establish how many readings are required for a statistically stable result to be generated and what the error bands are. Recommend appropriate techniques for data processing including the generation of summary statistics and estimates of uncertainty

Both time domain and frequency domain analysis techniques are required to investigate and summarise the data from the two phases of sea trials.

One particular difficulty for wave energy that must be accommodated during detailed analysis, particularly in the time domain, is that the incident energy measurements and device responses cannot be exactly synchronised because of the spatial separation between the two units. So, even when the two logging clocks are concurrent there will be a delay before the waves at the buoy appear at the device, at which time there may be a slight change in the water surface time series due to the multi-frequency mix of a real seaway. This means full matching from the time history is complex.

Further, with respect to the highly relevant and strongly interrelated measurements of motion, velocity an acceleration, it should be taken into account that the (double) differentiation of motion signals and/or the (double) integration of acceleration measurements is typically not a

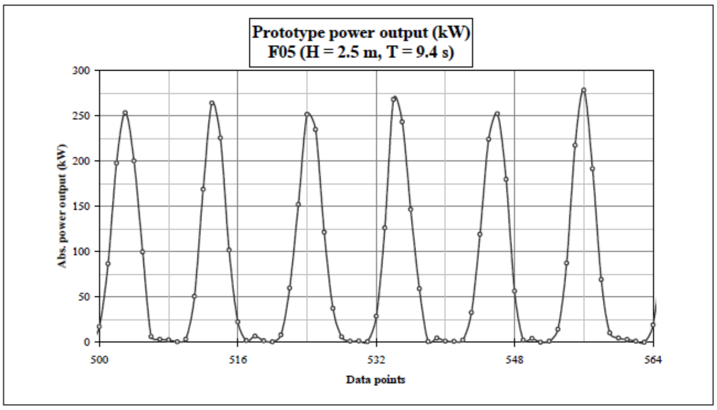


Example for time domain records of incident energy level & hydrodynamic energy absorbed: wave height measured in front of Pico OWC and absorbed power by the chamber (‘Pneumatic Power’)

Performance Assesment of the Pico Wave Energy Plant - Rated Power 400kW

		Environmental Parameters				Non-Dimensional Parameters				Performance paramete	
Zone	Hm0	Te	Pwave	Prob	Pwave*Prob	n	η(overall)	η(WP)	η(PA)	P active	P pneuma
[-]	[m]	[s]	[kW]	[%]	[kW]	[-]	[-]	[-]	[-]	[kW]	[kW]
1	1.25	7.5	155.8	6.8	11	18	0.2	0.66	0.31	32	103
2	1.75	7.5	305.4	1.6	4.8	34	0.08	0.35	0.23	24	107
3	0.75	8.5	59.88	12	7.1	11	0.39	1.4	0.28	23	81.9
4	1.25	8.5	166.3	13	21	17	0.3	1	0.3	51	171
5	1.75	8.5	326	6.3	21	16	0.11	0.39	0.27	35	127
6	2.25	8.5	538.9	2.4	13	31	0.072	0.25	0.28	39	137
7	2.75	8.5	805	0.97	7.8	12	0.077	0.29	0.27	62	232
8	1.25	9.5	174.1	5.2	9.1	16	0.23	0.81	0.28	40	142
9	1.75	9.5	341.3	6.6	23	17	0.11	0.45	0.24	37	154
10	2.25	9.5	564.1	4.4	25	11	0.1	0.44	0.23	56	248
11	2.75	9.5	842.7	1.4	12	19	0.064	0.24	0.26	54	205
12	1.25	11	180.1	3.6	6.4	11	0.21	0.9	0.23	38	163
13	1.75	11	353	3.3	12	26	0.15	0.55	0.28	54	193
14	2.25	11	583.5	1.7	9.9	14	0.086	0.31	0.28	50	181
15	2.75	11	871.7	2	17	13	0.053	0.19	0.27	46	169
16	3.25	11	1217	0.96	12	33	0.05	0.18	0.28	61	216
17	2.75	12	893.6	1.5	13	11	0.037	0.13	0.28	33	118

Example for detailed hydrodynamic subsystem (prime mover) performance matrix: available incident wave power and absorbed power by the chamber (‘Pneumatic Power’) for Pico OWC, for the chosen sea state ‘bins’ according to Del. 4.2



Example for presentation of differentiated body motion measurements (velocity), combined with Force measurements, indicating absorbed power levels (EMEC, 2009; example referring to laboratory testing, however equally applicable to S3/4 trials) straight-forward operation (see right-hand side). Also, problems associated with using smoothing/ filtering on the signals can complicate the proper data analysis and presentation.

In particular, smoothing by averaging and filtering by applying low-pass or high-pass filters to the data sets must be carefully checked, ideally compared with measurements yielding the same physical quantity but obtained by other means (signal redundancy).

To conclude, the two major issues to be addressed in S3 and S4 sea trials are:

- QUALITY assurance;
- UNCERTAINTY assessment.

There are numerous ways of how to produce usable records for analysis and presentation of sea trial data, and the exact format of how to relate hydrodynamic power capture with incident sea state will depend on the particular wave energy converter.

For uncertainty and quality control of motion, velocity and acceleration measurements in particular it should be noted that individual motion measurements can be ambiguous since the phase of the motion with respect to a reference point is not inherently known. This applies in particular when accelerometers are used, as these signals require double integration to obtain displacement, not making them very reliable or convenient.

Further, for critical components and parameters, in general dual or back-up sensors should be incorporated when possible. Another advantage of this apart from the quality control is that if the sensor will not be accessible at sea in case of maintenance requirements.

With respect to the signal quality, some decontamination is often required in field trials, and several mathematical techniques exist to improve signal quality. The most common for the cases to be expected in the context of this manual is smoothing of high frequency noise or jitter in the time domain, taking care not to introduce phase shift. A consequence of smoothing can be a reduction in the amplitude and/or a slight signal time shift in case of averaging. Further, applying high or low frequency band pass filters can be useful, however difficulties may arise when the frequency of the unwanted part and the required data information occupy the same section of the spectrum. This is often the case with low frequency noise introduced during integration of a signal such that the left hand side of the spectrum is masked by the noise. If the signal can be cleaned up prior to analysis, errors can be minimized.

Stage Gate Criteria

Device survival and system reliability are important factors that must be considered for the start of a programme. Hull seaworthiness and extreme loads can be monitored and measured in the early stages followed by full systems survival and component reliability from Stage 3 and beyond. Devices should not advance out of a stage until these issues have been fully investigated and any problems resolved.

Two key factors to success during the sea trials with particular relevance to the hydrodynamic subsystem at all stages are:

(i) to design the device incorporating reserve buoyancy that would prevent total sinking in the event of a hull breach.

(ii) to ensure safety and security of the moorings and anchors even if this requires some built in line redundancy.

Further, the following items should be considered with care when planning and during the S3 and S4 trials, in order to characterise the hydrodynamic subsystem:

- install as many useful sensors as can be technically justified (and afforded);
- ensure wave measurement is conducted simultaneously with device measurement;
- extend the sea trials until all identified operational combinations are covered, in particular survival-relevant sea states;
- ensure that sea states and device dimensions are correctly scaled.

MILESTONES TO PASS STAGES SUCCESSFULLY

<u>Stage 3 – Systems validation stage gate requirements</u>

TRL5 Sub-system Bench Tests;

TRL6 Full-system Sea Trials (scale 1:10 to 1:3)

For the transition between the two TRLs of this trial stage, it is not deemed reasonable to indicate specific requirements, as bench tests are unusual for the hydrodynamic subsystem, and there are no clear generic benchmarks for TRL5. To pass TRL6 and as such from S3 to S4, the following main targets should be met with reference to the hydrodynamic subsystem:

- ➢ Physical properties that are not well scaled analysed and performance figures validated;
- ➢ Control strategies and impact on primary power conversion presented;
- ➢ Environmental factors (i.e. the device on the environment and vice versa) identified, e.g. marine growth, corrosion, windage and current drag
- ➢ Survival conditions, mooring behaviour and hull seaworthiness quantified;
- ➢ Manufacturing, deployment, recovery and O&M (component reliability) methodologies defined;

<u>Stage 4 –Device Validation stage gate requirements</u>

TRL7 Prototype Sheltered Site;

TRL8 Prototype Exposed Site

Similar to S3, the first TRL (7) of this sea trial stage is not meaningful with respect to the hydrodynamic subsystem without terminating TRL8. It is rather a transitory phase to check the full system functionality and the generic seaworthiness of the device. The final outcome of S4 with respect to the hydrodynamic subsystem should include:

- ➢ Hull seaworthiness and survival strategies;
- ➢ Mooring and cable connection issues, including failure modes;
- ➢ Component and assembly longevity;
- ➢ Absorbed pneumatic/mechanical power (power matrix);
- ➢ Application in local wave climate conditions;
- ➢ Service, maintenance and operational experience [O&M].

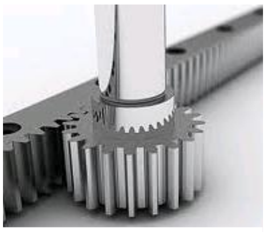
Stage 4 is a crucial phase of the development process in particular of wave energy devices, covering a solo machine pilot plant validation at sea in a scale approaching the final full size (circa 1:1). This stage is a proving programme of designs already established rather than actually experimenting with new options. By end of 2010, scarcely any device can be considered to have overcome this phase.

EMEC (2009): Tank Testing of Wave Energy Conversion Systems Marine Renewable Energy Guides

SNAME (1950). Nomenclature for treating the motion of a submerged body through a fluid. Technical Report Bulletin 1-5. Society of Naval Architects and Marine Engineers, New York, USA

Power Take Off SUBSYSTEM

Technology Development Stages 3 & 4



PTO

Rationale

The PTO subsystem is responsible for extracting the wave energy captured by the hydrodynamic sub-system and convert it into another useful form of energy, in general electricity. It usually consists of an assembly of several components of different nature (e.g. mechanical, hydraulic, pneumatic, electrical) that have to deal with highly concentrated and fluctuating flows of energy for a wide range of operating conditions. In addition, a control system is required to improve the overall sea to grid energy conversion efficiency.

The Sea trials, throughout their different stages, allow a step by step reality check of the PTO's design and assembly, concerning both its performance and reliability, under the harsh and highly dynamic conditions at which it has to operate. Furthermore, the sea trials should also be used for acquiring the first experiences with manufacturing, installation, operation, servicing and decommissioning of the PTO subsystem. Thus, beside an extensive measurement program, systematic inspection, maintenance and repair of the PTO components are an essential part of the sea trials.

All the information and experience acquired during the sea trials will be extremely valuable to feedback into the design process of the PTO sub-system, in order to further improve its construction, performance, maintainability and reliability.

Objective

The main objectives to perform sea trials with the PTO sub-system are:

- To evaluate the performance of the PTO's power conversion chain and its power output quality.
- To evaluate different control strategies to enhance the PTO's performance.
- To provide sufficient information to validate numerical models of the PTO sub-system for the full range of different operating conditions.
- To assess the endurance of the PTO components and its overall reliability, when operating in real sea conditions.
- To acquire experience with the construction, installation, operation and maintenance of the PTO subsystem.

Pre-Sea Trials Requirements

The first step, prior to carrying out the sea trials, is to perform a careful design of the PTO, its control and the data acquisition system. Although performance is an important design aspect, special care should be also given to reliability and maintainability. Neglecting these aspects may lead to long downtimes, data loss and therefore unsuccessful sea trails. The design process should be supported by: a) numerical models of the PTO dynamics, in closed loop with the hydrodynamic and control systems, for the full range of possible operating conditions expected at the test site and b) reliability analysis based on tools like FMECA (Failure Mode, Effects and Criticality Analysis) and FTA (Fault Tree Analysis).

Secondly, with the information and insight provided by the models and reliability analysis, detailed testing and maintenance plans for the sea trials should be developed, as well possible bench tests of the PTO components identified as critical.

KEY ELEMENTS

- Establish a testing plan with all physical quantities to be measured as well the testing scenarios.
- Consider reliability and maintainability in the design of both PTO and data acquisition system.
- Synchronise the time of all data logging systems.
- Extend sea trials to cover as much as possible the full range of operating conditions.
- Be prepared to accommodate major re-fit of key components.

IMPORTANT REFERENCES

IEC TC-114	EQUIMAR Del 4.2
IEA-OES-IA Annex II	Carbon Trust 2005: "Guidelines on design of WEC"

Development Stages

As stated in the introduction and other sections of this document the solo device sea trial stages (S3 & S4) of a wave energy converter development covers a wide scope. Devices must progress from the pre-prototype scale (circa 1:4) ***systems*** proving units, through ***pre-production*** full scale design and on to a ***pre-commercial*** machines ready to be certified as fit-for-purpose and small array deployment.

This progressive increase of the testing scales reduces both the technical and financial risk that would be required if the device development went straight from laboratory scale model to a full size prototype deployed at an exposed ocean location.

Development Stages S3 and S4

Stage S3 - 1:7 scale model of Pelamis and Stage S4 – full scale Pelamis prototype (photos: Pelamis Wave Power Ltd)

The primary factor common throughout sea trials is that the tests have moved from the controllable and comfortable surroundings of an indoor facility where waves can be generated on demand, to the natural outdoors were test conditions have to be accepted as they occur and test programmes adjusted to suit.

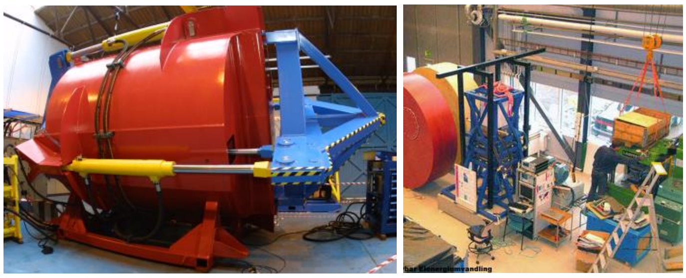
TEST PROGRAMMES

There are two stages covered in the Sea Trial section of a device development schedule, each of which is further subdivided into two phases. These are:

Stage	Section	TRL	Timetable
S3	Sub-system Bench Tests	5	6-12 months
	Full-system Sea Trials	6	6-18 months
S4	Prototype Sheltered Site	7	1-2 years
	Prototype Exposed Site	8	1-5 years

For each phase of the sea trials, the priorities can be different:

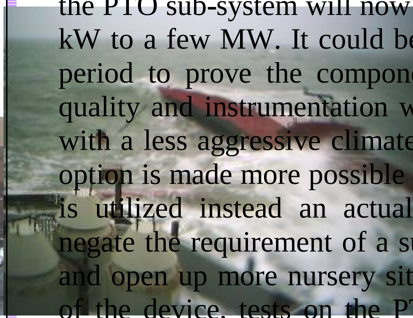
➢ **Sub-System Bench Tests:** Prior moving to the sea trials, various components (or all) of the PTO subsystem could be subject to bench tests. This could e.g. be a PTO component subjected to an accelerated fatigue test, test of auxiliary systems (pumps, valves, etc.) or tests of the full power chain conversion in closed control loop. The control strategies should be evaluated with excitation signals based on real sea records of the test site (or at least with similar characteristics).



Hydraulic Power Conversion Module Test-Rig (Left photo: Pelamis Wave Power Ltd) and Linear Generator Test-Rig (Right photo: Uppsala Univ.)

➢ **Full-System Sea Trials:** Although at a large size (typically 1:4), rather than full size, these trials represent the first time the device will be in a real sea environment and equipped with a fully operational electricity generating PTO. At this phase, the PTO subsystem will have to handle relatively small power levels (typically less than 50kW). Grid connection is therefore not a technical necessity and will depend mainly on its accessibility and cost. Focus is given to the PTO’s performance evaluation with different control laws. First insights on the PTO’s construction, installation, operation and maintenance will be also experienced.

1:4 Scale (15kW) OE Buoy Wave Prototype offshore west coast of Ireland (Left photo: OceanEnergy Ltd) and 1:4.5 Scale (20kW) WaveDragon prototype at Nissum Bredning, Denmark (Right photo: Wave Dragon ApS)



Sea Trials vs Tank testing

Wave Dragon 1:50 scale model tank testing versus Wave Dragon 1:4.5 model at sea trials (Photos: *Wave Dragon ApS*)

Another important feature of the sea trials is that the larger scale at which the tests are now conducted, compared to the ones of the previous stages (S1-S2), enables the installation of realistic and fully operational PTO sub-systems in the devices.

Hydraulic PTO of the Pelamis 1:7 scale model (Photo: Pelamis Wave Power Ltd)

Thus, sea trials will not only allow to test the performance and reliability of the PTO sub-systems in realistic conditions but also to acquire experience with all the aspects related to its manufacture, installation, operation and maintenance.

The level of detail of the data regarding the PTO subsystem required at the different stages will vary although the underlying mantra should always be to gather as much data as practically possible.

- **Prototype Sheltered Site:** following Stage 3 it is expected that a full, or approximately full, size prototype device will be constructed for sea trials. The power levels of the PTO sub-system will now range from several hundreds of kW to a few MW. It could be anticipated that a shake-down period to prove the component, assemblies, manufacturing quality and instrumentation would be conducted at a station with a less aggressive climate that the final destination. This option is made more possible if a fully certified grid emulator is utilized instead an actual grid connection. This would negate the requirement of a subsea cable for grid connection and open up more nursery sites. Prior to the offshore launch of the device, tests on the PTO and auxiliary systems (e.g. brakes, instrumentation and controls) should be conducted to assure their operability. If feasible, the PTO system should be driven by the best power input available. This may be limited for large machines (>500kW) but fundamentals can still be verified at low speeds.

Oyster – Dry Test of the PTO (Left photo: Aquamarine Power) and AWS – Test of Auxiliary Systems and instrumentation at the Harbour (Right photo: Teamwork Technology B.V.)

- **Prototype Exposed Site:** once the operator is confident the pilot plant is functioning acceptably it should be transferred to a location with similar conditions to those expected at a typical power park and grid connected. The sea trials are now specifically for proving rather than modification, so deployment should be for an extended duration to facilitate component lifecycle verification, full range performance verification and survival diagnosis. More focus is now given to condition monitoring of the PTO sub-system in contrast than at stage S3. Data for both operational and extreme conditions are here anticipated. However, extreme design conditions are not likely to be experienced during the early tests and an important element will be the extrapolation of measured peak loadings and corresponding responses to design levels. This should include calibration/validation of numerical models.

Full Scale (315kW) Osyter prototype in operation at Orkney, Scotland (Left photo: Aquamarine Power*) and Full Scale (2MW) AWS prototype during deployment operation offshore at North Portugal (Right photo: Teamwork Technology B.V.)*

Data Acquisition

One of the main objectives of the sea trials is to acquire information on the PTO performance and reliability, in realistic sea conditions. Data acquisition is the first step required to obtain this information, which can be done both automatically and manually.

Although the cost of obtaining data during sea trials is high, the price for not monitoring well all variables will be higher. Therefore data quality, reliability and maintainability of the data acquisition system are vital aspects that should be taken seriously into account in its design.

Automatic Data Acquisition

Automatic data acquisition can be performed by a variety of systems that range from specific sensors with dedicated data loggers to full SCADA systems. During the sea trials, different systems may be installed at quite separate locations like the sea (e.g. wave buoy), on-board of the device (e.g. PTO sub-system) and at land (e.g. grid connection). Experience has shown that the more separate systems are used, the higher the problems in data integration and synchronization.

The following aspects should be given a special attention:

- **Sensors** correspond to the first step of the data acquisition process and should be therefore carefully selected, in particular their accuracy, range and bandwidth. Improper choice of one of these aspects may lead to poor data quality (e.g. low resolution, saturated signals, filtered transients). The index of protection (IP) of the sensors should be chosen in accordance to the environmental conditions at which they have to operate. Improper protection may result in early failure of the sensor.

The sensors should be installed

MONITORING PARAMETERS

The PTO sub-system consists generally of an assembly of different components, like **hydraulic** (e.g. hydraulic rams, pumps, heat exchangers), **pneumatic** (e.g. Wells turbines, valves), **mechanical** (e.g. bearings, gearboxes) and **electrical** (e.g. generators, power electronics, control systems, etc). While many components are off the shelf, others are specially designed and custom made. A few examples of typical PTO components used in marine energy devices are shown below.

Wave Dragon 2.6kW Low Head Turbines (left photo: Wave Dragon ApS), AWS 2MW Linear PM Generator (mid photo: Teamwork Tech. B.V.) and AWS Water Brake Valve (right photo: Teamwork Tech. B.V.)

McCabe Wave Pump Hydraulic Rams (left photo: Hydam Tech. Ltd) and OE buoy 15kW Wells Turbine (right photo: OceanEnergy Ltd)

Oyster – 315kW Pelton turbine, flywheel and induction generator (left photo: Aquamarine Power) and AWS - 6MVA AC/AC Converter, M.V. Switch Gear and Power Transformers (right photo: Teamwork Tech. B.V.)

Each PTO component will have its specific monitoring parameters that depend on its nature and stage of development. Hence, the set of parameters to monitor the complete PTO sub-system, during the sea trials, will be highly device dependent. However, the monitoring parameters should in general cover the following aspects:

- **Model Validation**: To calibrate the numerical model of the PTO sub-system, it’s necessary to obtain times series in accessible locations to facilitate maintenance or repair actions, while locations with high noise level should be avoided (e.g. installing pressure or flow sensors at locations where high turbulence is expected).

Cabling and grounding are also key aspects for noise reduction. Instrumentation cables should be properly shielded, grounded and installed far from strong electro-magnetic field sources (e.g. power cables and power electronics).

❍ **Data Logging** should in general happen close-by the sensors to assure that data will not be lost due to communication failure. When a reliable communication system is available, remote data logging at shore could be considered as an option.

Time stamping of recorded data should be based on a real time clock. Since different logging systems may coexist during the sea trials, it's crucial to assure time synchronization among them in order to correlate the different data sets or at least to keep track of the time shifts between the clocks of the different data logging systems.

❍ **Data Redundancy** should be implemented both at the data collection and data storage level. The first can be achieved by direct sensor duplication or by the use of other sensors from which the desired measurements can be derived (e.g. position can be obtained by integration of velocity with reset by a position switch). The second may be achieved by periodic automatic data backups done locally at each data logging system (e.g in separate hard disks) or centrally, at shore, in a redundant data storage unit (if a reliable data transmission is available).

❍ **Power Supply** of the automatic data acquisition systems should be reliable and guarantee the continuity of its operation, even if the PTO is not producing power. In absence of a cable

from its inputs, outputs and state variables. Depending on the PTO components, the variables can be for example:

- *Hydraulic/Pneumatic Components*: pressure, temperature, flow rate (mass and/or volumetric) and fluid level;
- *Linear Mechanical components*: force, displacement, velocity and acceleration;
- *Rotational Mechanical Components*: torque, angular displacement, angular velocity and angular acceleration;
- *Electrical Components*: voltage and current;

These monitoring parameters allow not only to identify the parameters of the PTO's numerical model (e.g. inertia, damping, stiffness) but also to directly evaluate the loadings, motions and the power conversion performance of the PTO sub-system. The power level at each energy conversion step can be obtained from the product of the stresses (e.g. pressure, torque, voltage) with the corresponding motions (e.g. flow, angular velocity, current).

- **Condition Monitoring**: A multitude of different phenomena like corrosion, wearing, misalignments, fatigue and fouling can degrade and eventually cause failure of the PTO subsystem. To evaluate the reliability of the PTO sub-system it's therefore of vital importance to monitor the condition of its components and assembly. This can be done automatically on-line or manually during maintenance visits. Typical examples of condition monitoring parameters acquired automatically are:
  - *temperature* (e.g. generator coils, bearings),
  - *vibration* (e.g. bearings, gearboxes),
  - *oil particle distribution and moisture* (e.g. hydraulic units, lubrication units),
  - *strains* (e.g. shaft, blades),
  - *motor current analysis* (e.g. generator, motors).

  Corrosion and fouling are on the other hand typical examples of condition monitoring parameters obtained manually by visual inspection.

- **Internal PTO Environment**: Certain parts (or all) of the PTO-subsystem are installed inside a protective case due to limitations of their operating environmental conditions. During the sea trials, these environmental conditions like e.g. temperature, humidity or pressure should be monitored to check if the protective case is performing its function well. Abnormal values of these variables are good indicators of problems like leakages, bad heat dissipation or water condensation that could potentially lead to PTO failure.

- **Power Output Quality**: The ideal voltage output of an electricity generating PTO would be a three phase balanced sinusoidal signal, with constant frequency and connection to the shore, a battery pack with sufficient capacity and possibly alternative charging options should be considered.

Manual Data Acquisition

Although automatic data acquisition systems allow collection and storage of large quantities of data at rates that would be virtually impossible to acquire manually, they're not able to collect all the relevant information to fully describe the sea trials. This additional information must be collected manually by human operators, that follow all the activities related to the sea trials, and consists generally of:

- ***Ongoing activities*** (e.g. type of test, maintenance or repair actions);
- ***Singular events*** (e.g. storm, component failures, accidents);
- ***Changes of configuration*** (e.g. PTO layout, settings, sensors, control law and gains).
- ***Condition monitoring*** (e.g. oil samples for lab analysis, visual inspection of PTO components, corrosion, leakages, fouling).

In the process of data collection, it's very useful if human operators are also able to make a correct interpretation of their observations, by using their critical sense and expert knowledge, in order to detect false alarms and correctly identify failures.

During the trial programme, all the information manually acquired should be diligently recorded on a daily basis in a logbook, together with other relevant SCADA or met-ocean data that could be useful, to give a complete account of the sea trials.

This information will be very valuable to understand the context in which the measurements were conducted and therefore vital to interpret them correctly at a later stage.

amplitude. Deviations from this reference should be monitored by tracking for e.g. the variations in the RMS value and frequency of the voltage, voltage harmonic content and phase unbalance.

- **Operational Status and Settings**: The PTO sub-system is usually supported by a set of auxiliary systems like e.g. Brakes, Cooling, Hydraulic Units, Control System. The operational status and settings of these systems (e.g. Pump on/off/tripped, Valve position/tripped, Circuit breaker on/off, Controller setpoints and gains) should be monitored for the following reasons:
    - allows the human operator to access the operational status of the PTO sub-system during the sea trials. In case of failure detection, the corresponding corrective maintenance actions can be triggered;
    - it helps to contextualize the measured data at the later stage of data analysis (model calibration, performance analysis, etc.),
    - allows to perform reliability analysis based on the failure records.

Data Analysis

Data Analysis is the process of extracting useful information from the large quantities of raw data acquired during the sea trials. The correctness of the extracted information directly depends on the quality of the data and the data processing methods to compute the information. Therefore, the first step of data analysis consists of the selection of raw data sets with good enough quality for further processing. On the other hand, the data processing methodologies used for information extraction should be based on solid scientific principles and follow common standards. These methods can be based both on time and frequency domain analysis techniques applied to signals and/or systems.

Experience shows that it's highly unlikely that during the sea trials enough quality data is acquired to fully cover all possible testing conditions. Information that cannot be obtained directly from the missing data, can still be estimated from the remaining data by extrapolation and interpolation methods (both function or model based) but of course with smaller accuracies.

<u>Data Selection</u>

The Data selection should in general take into account the following aspects:

❍ **Noise Level** should be low compared to the signal level (i.e. high SNR-signal to noise ratio). Noise with spectral content located outside the signal frequency range of interest can be filtered out with linear band-stop filters. On the other hand, gross outliers are more effectively removed, without significant signal distortion, by the use of non-linear filters (e.g. median filter).

❍ **Sampling rates** should be high enough to capture the fastest

DATA PRESENTATION

All the information and experience gathered during the sea trials is hard won and represents a substantial part of the developer's knowledge capital. It's therefore very important that all this knowledge is well documented, so maximum benefit can be derived from it for different uses like:

- **Internal consultation**, for information sharing within the developer's organization;
- **Investors due diligences**, by presenting clear and sound information that allows potential investors to perform correctly the risk assessment of their investment.
- **Device promotion**, through brochures, publicly available reports or scientific publications.

In general, at each phase of the sea trials, documentation should be produced covering the following different aspects:

<u>Commissioning</u>

➢ **Data acquisition systems reports**, which should include P&I diagrams, instrumentation and data acquisition electronics data sheets and calibration information of all instrumentation.

➢ **Control system reports,** with detail description of the different control loops (e.g. block diagrams, control laws, settings) and preliminary performance measurements.

➢ **PTO report**, with detail description of PTO components and auxiliary systems, measurements of design variables (e.g. electric isolation levels generator windings, oil pressure, vibration levels) and test results on its operability in the different modes (e.g. normal, standby, emergency stop).

<u>Operation</u>

➢ **Periodic reports**, with summary statistics of data quality, power production level, alarms, PTO downtime, etc.. These reports can be automatically generated by the SCADA system and provide to the developer a quick overview and a periodic update of how the sea trials are progressing.

➢ **Data quality check reports**, with detailed analysis of the acquired raw data quality covering aspects like sensor availability, signal coherence, noise characterization and filtering. Along the sea trials, changes in these characteristics may occur and should be promptly detected and corrected. Data selection for further processing should be well justified, with bad transients of interest. For high sampling rates, irregularities in the sampling periods can be still corrected by interpolating the signals at the desired time instants. However long sampling periods will lead to irreversible data loss.

- **Data coherence** of directly physically related measurements should be high. This can be tested by comparing measurements of duplicate sensors or of different sensors related to each other through a more complex form (e.g. velocity is the time derivative of position). A measurement with a low signal coherence with other related measurements is a strong indication of low data quality (e.g. sensor offset or damage).

Nevertheless, even incomplete data is a valuable commodity and should be archived as future analysis may possibly yield some benefit.

Data Processing

Not all information of interest can be directly measured and therefore some level of data processing is required to extract the desired information from the measured data. The complexity of the data processing can range from a simple arithmetic operation to high order non-linear regression. The information of interest to extract during the sea trials consists generally of:

- **PTO Performance** of its power conversion chain. At each energy conversion step, the power signals can be obtained from the product of the stresses and flows signals (if no direct measurement is available). This will allow the calculation of the energy conversion efficiency along the complete power train. Due to their high variability, summary statistics (e.g. average, std, max, min) should be computed for fixed periods of time, under which the data sets properly identified.

- **Data analysis reports**, covering separately topics like Power Production Performance, Control performance, Power Output Quality, Model Calibration/Validation, Condition Monitoring and Reliability. For all presented results, a clear description of their accuracy as well the raw data sets and processing methodologies used to obtain them should be made. Missing data and non-proven results should be also identified.
- **Servicing reports**, with detailed account of the maintenance and repair actions, failure identification and changes in the PTO configuration.

Demobilisation

- **Inspection report**, with detailed description of the observations made of all dismantled PTO components, with identification of developing faults (e.g. corrosion, wearing) and other reliability aspects.

After the sea trials, it's also useful if a ***final report*** is made with the overall conclusions of the trials and recommendations for further improvements of PTO sub-system, regarding its performance, maintainability and reliability. **Proven and non-proven results should be clearly identified.**

The quality of the produced documentation can be improved if the following general aspects are taken into account:

- **Document Referencing System**, should be defined prior to the sea trials. It will highly valuable for cross referencing the large number of documents expected to be produced during the complete sea trials.
- **Test phase, objectives, authors and version** of each document should be clearly identified.
- **Context information**, under which the tests occur should be provided in the documentation, since it contributes for a better interpretation and understanding of the presented results. For this purpose it's important that document production **runs parallel** with the sea trials, since risk of loosing some valuable context information is highly reduced.

Some practical examples of data presentation from sea trials are shown below.

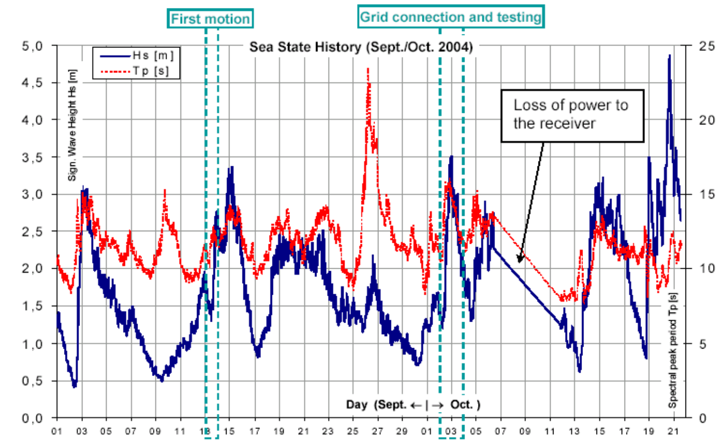
sea resource can be considered stationary. This process should be repeated for all available different measured sea conditions, see EQUIMAR Deliverable 4.2 for more details. For each PTO performance evaluation, the control law and settings should be kept fixed.

❍ **Control Performance** of the existing control loops in the PTO sub-system. For regulators, typically the control performance is characterized by the band-width (time-response), overshot and static error of the closed loop system response. This information can be obtained both in time and frequency domain by looking into the time series of the setpoints and controlled variables or at the closed loop transfer function (from setpoint to controlled variable). This analysis should be done for different operating conditions to check the control performance robustness.

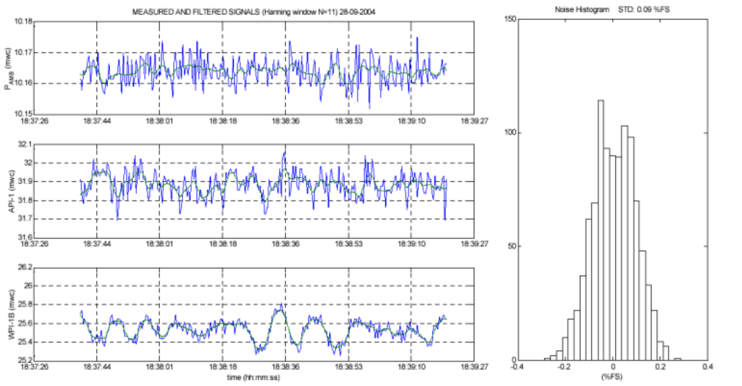
❍ **Power Quality Output**. Similarly as done for the PTO performance characterization, sum mary statistics of the different measured power quality indicators (e.g. variations in the RMS value and frequency of the voltage, voltage harmonic content) should be computed for the different sea conditions and control settings.

❍ **PTO model parameters** for calibration purposes. The estima-tion of the models parameters should be based on standard sys-tem identification techniques with input-output data sets (calibration data set) that cover as much as possible the full range of operating conditions. To simplify this pro-cess, it's recommend to perform separately system identification of the sub-models individually rather than of the complete PTO model. This will however require more input-output data available. The calibrated models should be checked by comparing measure-

Data selection Examples



Wave and device operation data availability - AWS offshore tests North Portugal 2004 (Courtesy: Teamwork Tech. B.V.)



Water and Air Pressure measurements (Times series of raw data and filtered signals) and noise histogram - AWS offshore tests North Portugal 2004 (Courtesy: Teamwork Tech. B.V.)

Power Conversion Performance Example

Performance Assesment of the Pico Wave Energy Plant - Rated Power 400kW

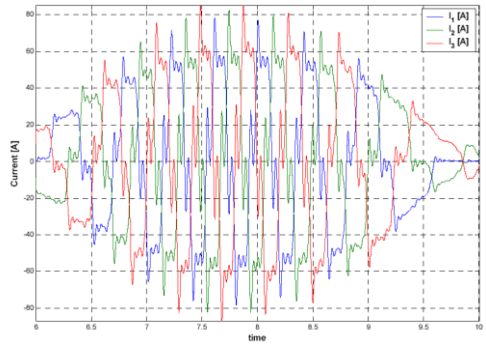
	Environmental Parameters					Non-Dimensional Parameters				Performance paramete	
Zone [-]	Hm0 [m]	Te [s]	Pwave [kW]	Prob [%]	Pwave*Prob [kW]	n [-]	η(overall) [-]	η(WP) [-]	η(PA) [-]	P active [kW]	P pneuma [kW]
1	1.25	7.5	155.8	6.8	11	18	0.2	0.66	0.31	32	103
2	1.75	7.5	305.4	1.6	4.8	34	0.08	0.35	0.23	24	107
3	0.75	8.5	59.88	12	7.1	11	0.39	1.4	0.28	23	81.9
4	1.25	8.5	166.3	13	21	17	0.3	1	0.3	51	171
5	1.75	8.5	326	6.3	21	16	0.11	0.39	0.27	35	127
6	2.25	8.5	538.9	2.4	13	31	0.072	0.25	0.28	39	137
7	2.75	8.5	805	0.97	7.8	12	0.077	0.29	0.27	62	232
8	1.25	9.5	174.1	5.2	9.1	16	0.23	0.81	0.28	40	142
9	1.75	9.5	341.3	6.6	23	17	0.11	0.45	0.24	37	154
10	2.25	9.5	564.1	4.4	25	11	0.1	0.44	0.23	56	248
11	2.75	9.5	842.7	1.4	12	19	0.064	0.24	0.26	54	205
12	1.25	11	180.1	3.6	6.4	11	0.21	0.9	0.23	38	163
13	1.75	11	353	3.3	12	26	0.15	0.55	0.28	54	193
14	2.25	11	583.5	1.7	9.9	14	0.086	0.31	0.28	50	181
15	2.75	11	871.7	2	17	13	0.053	0.19	0.27	46	169
16	3.25	11	1217	0.96	12	33	0.05	0.18	0.28	61	216
17	2.75	12	893.6	1.5	13	11	0.037	0.13	0.28	33	118

Performance matrix: available incident wave power and absorbed power by the chamber ('Pneumatic Power') of Pico OWC Power Plant, Azores, Portugal, according to Del. 4.2. (Courtesy: Wave Energy Centre) ments and model outputs, both in time and frequency domain, using a different data set (validation data set). A well calibrated PTO model is a valuable tool for supporting the design process and performance estimation.

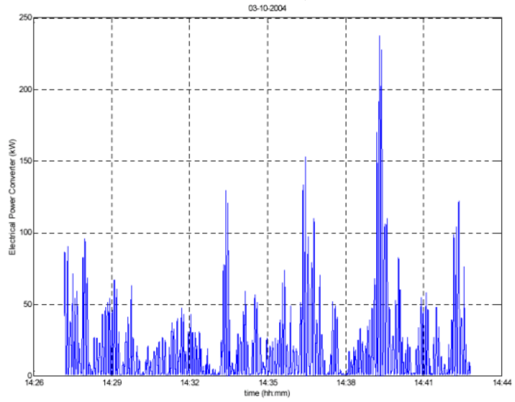
❍ **Detection of Developing Faults** for condition monitoring purposes. Feature extraction for fault diagnosis should be investigated, based on system analysis approach due to its robustness to changes in the operating conditions. For this purpose, models of the PTO sub-systems should be developed and trend analysis of the models residuals or parameters should be performed to check its applicability for early fault detection. An early detection of developing faults allows the implementation of condition based maintenance, which may significantly reduce the downtime of the device and therefore improve its economics.

❍ **Failure Rates and Modes** are essential for reliability evaluation. From the SCADA database and logbook important data related to system and component reliability (e.g. failures, downtime, repair actions, corrosion) can be used to perform statistics on the failure modes that occurred during the sea trials and also the corresponding probabilities. Due to the limited time period of the sea trials, not all possible failures will occur and therefore it be will in general difficult to acquire enough data to fully characterize the reliability of the device. During the demobilisation phase of the sea trials, careful visual inspection of the internal parts of the dismantled PTO components, may provide additional valuable information on not detected failure modes in development (e.g. sealing wearing, corrosion of electrical connections).

Power Output Quality Examples

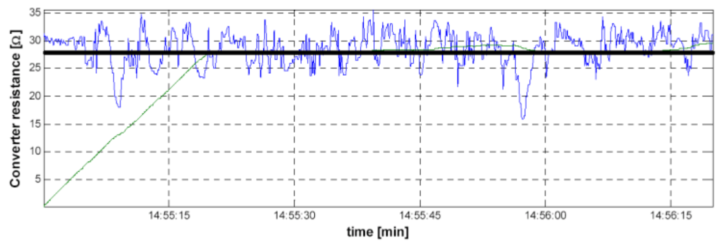


Three Phase Currents of Linear Generator in operation with AC/AC converter - AWS offshore tests North Portugal 2004 *(Courtesy: Teamwork Tech. B.V.)*



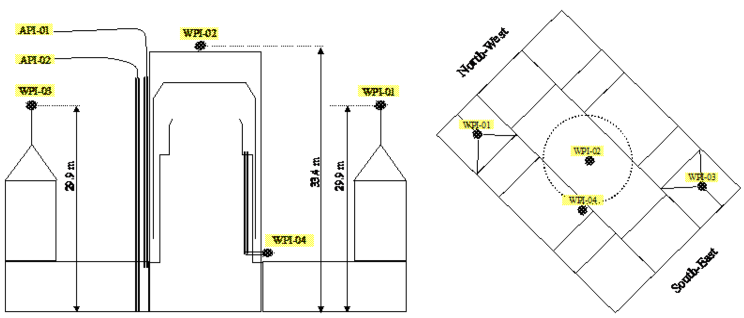
15min Irregular Power Signal at the DC link of AC/AC Converter - AWS offshore tests North Portugal 2004 *(Courtesy: Teamwork Tech. B.V.)*

Control System Performance Example



Performance of Converter's DC resistance control loop (measured DC resistance and setpoint signals)- AWS offshore tests North Portugal 2004 *(Courtesy: Teamwork Tech. B.V.)*

P&I Diagrams Example



Water and Air Pressure sensors location - AWS offshore tests North Portugal 2004 *(Courtesy: Teamwork Tech. B.V.)*

REACTION

SUB-SYSTEM

Technology Development Stages 3 & 4

Mooring

Rationale

Information on the response of the reaction subsystem occurring during sea trials should be regarded as an essential requirement. In this subsystem both anchoring and mooring arrangements, support structure and the structural elements of the device it self, is considered.

The level of detail necessary, however, can be adjusted to suit the stage of the tests. Of particular interest is response of the device in terms of forces and motions of the device in the sea, focusing in the extreme conditions (ULS), as the main concern here is the station keeping capability of the device.

However, also the responses in ‘everyday’ conditions (FLS/SLS) are of major importance, as there is likely to be a strong coupling between the response of the device and its power performance. And in addition to this, structures at sea, and in particular those activated by the waves, are prone to fatigue failures. Furthermore, observations and experiences related to marine growth / anti-fouling and corrosion protection can prove to be valuable for the further development.

Finally the structural responses measured during sea trials are of large value for the validation/calibration of numerical models describing the structure’s response to the incident resource.

Objective

There are several reasons for obtaining accurate measurements in the Reaction Subsystem at each particular test site. The main reasons are:

- To evaluate the station keeping ability of the device.
- To provide information on loadings on three different levels.
  - Global loads.
  - Cross sectional forces / internal stresses.
  - Local loads.
- To provide data for device evaluation in the various limit states – Ultimate, Accidental, Fatigue and Serviceability.
- To asses the influence of the reaction subsystem on the energy yields.
- To assess the endurance of mooring components
- To assess performance of foundations / fixing to seabed.
- To provide sufficient information to validate numerical model of structure’s reaction to incident resource

Pre-Sea Trials Requirements

Prior to carrying out any sea trials a design of the reaction subsystem components obviously needs to be carried out for the intended deployment site. For this, met-ocean data needs to be obtained prior to deployment of the device. This includes both operational and extreme conditions. Once the structure and the mooring arrangements have been designed their expected characteristics should be known. This includes the mooring characteristics in terms of force-displacement relations, dynamic response functions in all relevant DOFs for the floating body etc. The device should be instrumented to enable acquisition of the relevant data to check the design.

Furthermore, the sea trials should also be used for acquiring the first experiences with operation and maintenance of reaction subsystem. Thus, systematic in-service inspection, maintenance and repair of reaction components are essential.

KEY ELEMENTS

- Establish the correct monitoring duration and acquisition rate for each specific test programme
- Ensure the measuring instrument has sufficient resolution and range to handle the conditions that will be encountered.
- Ensure the instruments are not structurally the ‘weakest link’.
- Consider how to extrapolate measured data to events with higher return periods than events encountered during the sea trials.
- Synchronise the time of all acquisition systems

IMPORTANT REFERENCES

EquiMar WP2 & WP8	IEC TC-114: Assessment of Mooring systems for MECs
IEA-OES-IA Annex II	API-RP-2FP1

Development Stages

The station keeping system, be it fixed or flexible, to be deployed with the device for sea keeping trials should have previously been proven in medium scale (c 1:10) trials in a hydraulic facility wave tank. Failure mode physical simulations should have been conducted since it is not recommended that such trials will be attempted at sea, where the consequence of mishaps would be too risky. These empirical results should be verified by a theoretical model and both sets should include extreme conditions.

The Stage 3 sea trials, however, are the first opportunity the device design team will have to validate the structure design integrity and suitability for purpose. It is not common to scale material strength during early Stage device trials though strain gauges should have been used to measure the hull forces which are then put to the test in S3 trials, as shown photograph below.

The level of detail of the data regarding the reaction subsystem required at the different stages will vary although the underlying mantra should always be to gather as much data as practically possible, particularly relative to any failures.

One factor will be of major importance is the fact that the device most probably will not be exposed to the extreme events for which it has to be designed within the first years of testing. This means that for comparison to design data and previous physical tests results extrapolation will be need.

TEST PROGRAMMES

The two Stages covered in the Sea Trial section of a device development schedule, are as important to the reaction sub-system as to the rest of the WEC. These are:

Stage	Section	TRL	Timetable
S3	Sub-system Bench Tests	5	6-12 months
	Full-system Sea Trials	6	6-18 months
S4	Prototype Sheltered Site	7	1-2 years
	Prototype Exposed Site	8	1-5 years

The minimum details of data required at each of the stages can be different without diluting the stages trials too much, although it should again be emphasised that the more data gathered at all times the better.

- **Sub-System Bench Tests:** For the reaction sub-system these may be wet tests of individual components. On station anchor holding pull trials and mooring support buoy suitability should be confirm prior to use in the sea trials. The geophysical properties of the test site should be confirmed as suitable for the foundations or anchorage system.
- **Full-System Sea Trials:** The Stage 3 sea trials are the first opportunity to verify the anchoring sub-system is correctly designed and the last time to correct any issues before full scale operations. However, at this stage the structural dimensions and mooring design will not always be directly scalable compared to the intended full size device. Main focus is therefore on ensuring similitude with full scale, e.g. the mooring system might not resemble the final layout, but its response in terms of force-displacement characteristics should. Depending on choice of device size and test location, loading tests could be accelerated, e.g. if the device is sized a bit smaller than what a direct scaling based on prevailing environmental conditions would dictate. These trials should be used to full prove the reactance and structure sub-systems so adequate sensors should be incorporated and measurements made to calibrate the mathematical models.
- **Prototype Sheltered Site:** This section of test programme is less critical to the reactance sub-system development but can still provide valuable experience in deployment and recovery methods at the prototype size. The influence of moorings on body motions can be studied and the suitability of the foundation verified. Structural load monitoring is recommended. The time spend in the nursery site should be expected to vary.
- **Prototype Exposed Site:** The previous sea time experience should have resulted in a wealth of information that will de-risk the exposed site sea trials. It is still recommended that sensors are fitted to the hulls and mooring lines to further confirm the design safety margins. Here, data for both operational and extreme conditions are anticipated. However, all conditions are not likely to be experienced during the early tests, and an important element will be the extrapolation of measured loadings and responses to different levels. This should include calibration/validation of numerical models.

Data Acquisition

In general the data acquisition rate for the reaction sub-system components can be in accordance to the wave frequency monitoring. However, there are certain parameters that will require special consideration. The two primary special cases are:

- Wave slamming on the structure
- Snatch loading in the mooring lines

To ensure the short term peaks of these two parameters are not missed a fast acquisition rate is required. A multi-channel logger that can accept different rates is essential. Ideally it will offer a threshold activated cut-in facility to avoid extreme volumes of data.

Acquisition of data for the reaction subsystem is normally integrated in the overall data acquisition system on board the device. Normally, the system will be setup to handle various types of input, but often voltage or mA signals are primary types. Thus, for signals coming from strain gauges, or strain gauges based instruments such as force transducers and pressure cells, a pre-amplification prior to the data acquisition is necessary. Other instruments will by default deliver the signals as voltages in relevant measuring ranges (e.g. +/- 10 V). However, yet other measuring devices, such as e.g. “all-in-one” 6 DOF and GPS tracking systems, will deliver the measurements in digital form using some standard (or even non-standard) communication protocol (e.g. RS-485). In this case the data might not even be available with equal time intervals, which makes further pre-conditioning of the measured time series necessary prior to performance of the data analysis.

Another element of ‘data acquisition’ is registrations from inspections. Observations must be recorded in a log.

MONITORING PARAMETERS

For evaluation of loadings of the reaction subsystem a variety of sensors have to be deployed to enable measurements on three different levels:

- ***Global forces.*** Typically, these can be measured using load cells / shackles at the attachment points of the moorings on the hull of the device. Hereby the resulting total forces on the structure that the mooring system has to withstand can be established.
- ***Cross sectional forces / stress/strain levels***. For the overall structural design of the hull it is valuable to record measurements of strains/stresses in selected cross sections of the structure. This will typically be obtained through deployment of strain gauges. These should be deployed at carefully selected locations, which can represent the most loaded points of the structure. The strain gauge measurements can either be used for direct calculation of cross sectional forces and moments (in case of a well defined stress distribution) or used for validation of FEM based calculations. In any case it is important to consider what type of strain gauges to deploy. In case of a well defined stress distribution unidirectional strain gauges might be sufficient, but in more complex situations rosette type strain gauges should be deployed, as such gauges can supply all the stress components in the plan.
- ***Local pressures.*** For design of local structural details, check of numerical simulations etc. it can be valuable to investigate localized pressures on the hull/structure, e.g. wave induced pressures. This can be done by deployment of pressure transducers in the areas of interest.

Evaluation of the response of the reaction subsystem normally includes measurement of absolute and/or relative displacements in the appropriate degrees of freedom. This is aiming at evaluating the station keeping ability of the device. The types of sensors relevant for these measurements includes motion sensors, such as accelerometers, inclinometers, compass, and position sensors, often based on GPS. Recently, tailor made “all-in-on” systems, able to track 6 DOF motions assisted by GPS tracking, are becoming available.

The environmental loads acting on the structure supported by the reaction subsystem is generally constituted of contributions from wind, current and waves. If the structure is floating, the wave forces acting on the structure can be divided into constant and varying wave drift loads (second order loads) and first order wave loads. Normally, the wind, current and constant wave drift loads will determine the mean position of the floating structure. The varying wave drift force and the first order wave loads result in oscillations around a mean position. The relative magnitude of the oscillations due to varying drift forces and first order wave loads depends on the characteristics of the mooring system. If the system is stiff, the first order response will dominate If the is system is compliant (i.e. the natural period of the system is long compared to the wave periods) the varying wave drift response will dominate. It is normal practice to aim for a compliant system when designing floating structures, to limit the forces to be handled.

Data Acquisition

One of the most important factors to be considered when designing the sensor configuration for the reaction sub-system, be it fixed or flexible, is the protection of the actual sensors and cable runs. Unlike on the other sub-systems most sensors will be in exposed locations and often have to deal with awkwardly moving parts, such as the mooring load shackle shown below.

Sensors will also tend to be located on the outside of the WEC so will be exposed to the full force and harshness of the elements. The highest IP rating for each particular measuring transducer is recommended. Examples are recorded of signals being lost due to flora or fauna entering instillations as lave, growing inside the fixing and eventually causing malfunction.

Salt, grit and other small inorganic particles can become lodged in any space available and are often found on the inside of bolt treads and insufficiently protected seals.

Sensors designed to monitor the forces in the structure have fixed foundations but tend to be rather delicate instruments so require location consideration. Moving the whole device out of harms way during particular extreme storms is one strategy, as shown below. Unfortunately it is not always practical.

MEASURING SENSORS

- ***Load cell shackles in mooring lines***: Time series of the in-line forces will be recorded from load cells shackles in mooring lines. In the analysis of such data statistical parameters should be derived. Here, for each recorded time series F(t), local maxima and minima should be identified, and the statistical distribution plotted. Characteristic statistical time domain parameters, such as average of F, st. dev. of F, $F_{1/250}$, etc should be derived. In addition to analysis of the individual force time series, resulting forces and moments might be established from combining the individual time series, these too can then be analysed correspondingly. Transfer functions in the frequency domain (ratio between force and environmental (wave spectra) can be established by combining results from multiple records.
- ***Strain gauges/rosettes:*** From time series of stresses measured in the structure for sectional forces and moments and FEM calibration, various analyses can be carried out. From properly distributed strain gauges, time series of selected cross sectional forces can be calculated. In case of more complex stress conditions at the sensor point, measurements from a rosette type gauge can be used to calculate time series of principal stresses, or von Mises stresses. Then, based on the calculated time series of key forces F (or stresses), for each time series the local maxima and minima should be identified and plotted. Characteristic statistical time domain parameters, the same as described above should be produced.
- ***Pressure cells:*** from measured time series of pressures various analyses can be carried out. In cases of well defined pressure distribution and properly distributed pressure cells, time series of selected forces acting on the structure can be calculated. Then, based on the calculated time series of key forces F (or pressures), for each time series the local maxima and minima should be identified and plotted. Hydrodynamic pressure records can be analysed in the same way as the forces described above.
- ***Motion / position sensors:*** Depending on the method of measuring motions and positions, the measured time series might have to be (double) integrated (e.g. for going from an acceleration time series to a displacement time series) or otherwise pre-conditioned. The analysis of motions / positions of the various DOF will generally include both time and frequency domain analysis. For each time series a zero up or down crossing analysis should be performed and their distributions (of e.g. 'wave heights') should be plotted. Characteristic statistical parameters, such as average, st. dev., selected fractions (such as 1/3 and 1/250) should be derived. Transfer functions in the frequency domain (ratio motions in the individual DOFs and environmental (wave) spectra) can be established by combining results from multiple records.

Extreme caution is required during the double integration or singe differentiation of signals to avoid contamination of the result.

Data Analysis

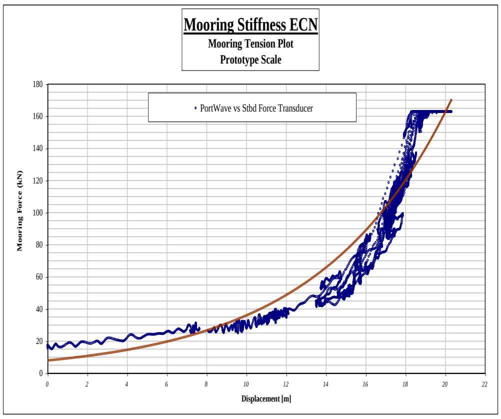
Although both frequency and time domain analysis is required for this sub-system the change of condition of parameters with respect to time, the time series, is the primary tool. Since this will involve probabilistic techniques the reaction parameters records can be required to be longer than other sub-system files. Also the signals should be reviewed to ensure the best acquisition rate is being applied to ensure no maximum peaks, or minimum troughs are missed.

➢ ***Time Domain:*** The duration of the individual recorded time series is an issue, therefore, which should be considered carefully. There are a number of items which pulls in opposite directions when the duration of the individual recorded time series is decided. In principle, it is desirable to have long time series consisting of a large amount of waves (many thousands) in order to have a stable description of the tail of the probability density functions (e.g. F1/250 based on 5-10 points), as this otherwise will give large uncertainties on the value hereof. On the other hand, it is then implicitly assumed that the wave state is stationary over the duration of the recorded time series, which in nature vary rarely will be the case. In order to get reasonable compromise it is recommended to record 500-1000 waves in each time series. For full size prototype trial, if the average wave period in the seaway under investigation is 5-6 seconds this requirement is equivalent to a duration of between 45 – 100 minutes, average 1 hour. This is twice as long as the power performance data acquisition so care is required setting up the SCADA that different channels can have different rates.

STATIC and DYNAMIC ANALYSIS

➢ ***Static:*** Before the device is left for autonomous operation, at both Stages 3 and 4, the quality of the reaction sub-system instillation should be confirmed. This is particularly important for buoyant, moored WEC. Bollard pull tests should already have been performed during the laying of the anchors to test the holding force.

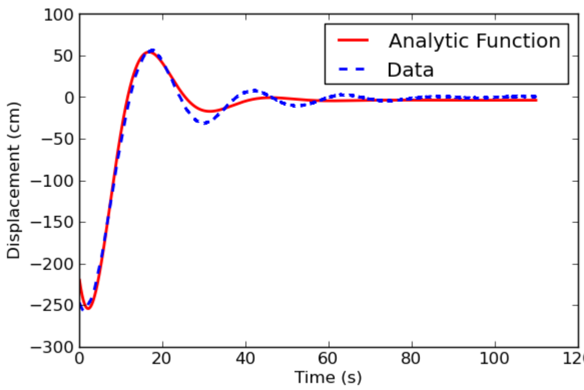
Following the connection of the WEC the pre-tension and stiffness of the mooring should be established by measuring the load – extension curve of each line, as shown in the graph left. This is done by physically displacing the WEC in a specified direction, initially along each of the mooring lines, and recording the corresponding load in the line.



The number of directions that must be verified should be advised by the mooring design company. Without this information it will not be possible to fully interpolate later results.

➢ ***Dynamic:*** If possible, it would often be valuable to also carry out decay tests of the device surge to establish the natural period of the mooring. As with the static tests the device would be displaced, held temporarily and then released. The device would then oscillate back and forth around the deployment station.

From these tests the natural oscillation frequencies and damping coefficients can be obtained by frequency domain analysis and logarithmic decrement analysis, or fitting of dynamic model to the recorded time series. As stated earlier moorings systems are usually designed to be ***soft.***



Attention needs to be given to coupling between the motions in the various degrees of freedom. Although it is desirable to avoid coupling when exciting the motion, this is often very hard, not to say impossible, when operating in large scale.

Data Analysis

In addition to the force measuring campaign there are other issues regarding the station keeping sub-system that must be considered during sea trials

- ***Environmental:***Marine growth on both structures and moorings must be monitored closely during early stages to establish the service requirements. Both fauna & flora will attach to all submerged surfaces to increase static and dynamic loading regimes.

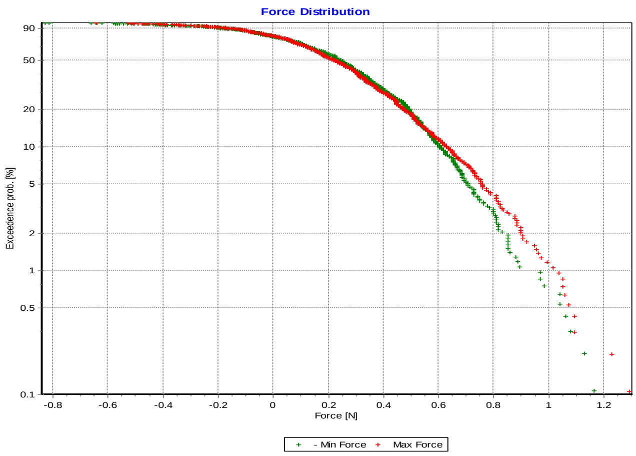
- ***Corrosion:***Particularly of moving components should be closely measured over the whole duration of the sea trials. This valuable information will be used to establish replacement maintenance schedules for later wave park operation

- ***Wear & Tare:***Besides corroding away components will also wear ways over extended use. There times must be established during sea trials.

LONG and SHORT TERM STATISTICS

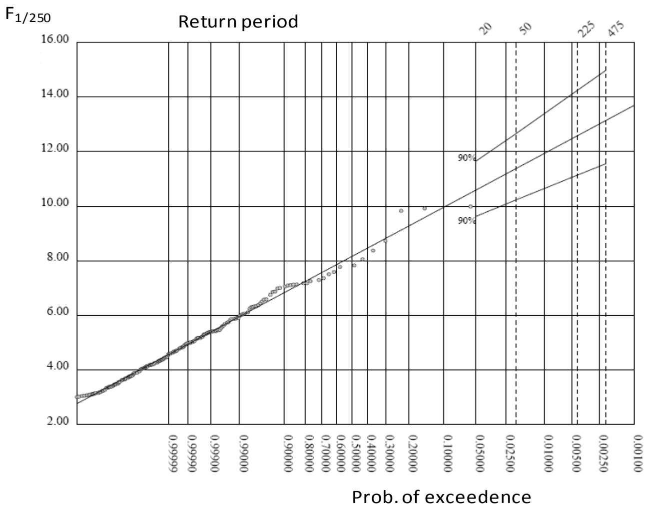
The analyses to be performed regarding measurements conducted on the reaction subsystem will be tightly linked to the specific situation and type of device under consideration. However, below are some key aspects regarding analysis of the parameters related to loads (force / stress / pressure) and motions are given. A large amount of data will be generated from the sea trials therefore, although the raw data can be revealing of force behaviour

The local minima and maxima of the parameter, e.g. measured force, can be plotted for each recorded time series, and plotted:



From each of these, key statistical characteristic parameters (e.g. F1/250) is derived and plotted as function of key environmental parameters spectral based significant wave height and mean wave period) in order to enable fatigue assessment by application of Miner's Rule (S-N or T-N approach).

A Peak Over Threshold analysis should also be performed to establish PDF for estimation of ULS loads (corresponding to e.g. 50 of 100 years events).



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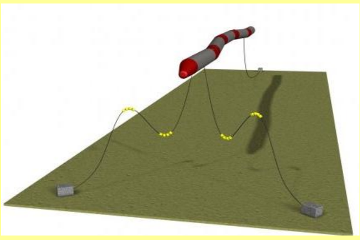
Data Presentation

Fewer sensors will be used on the reaction sub-system than other sub-systems but the amount of data generated over an extended sea trial period will be considerable.

It can also be expected that the main study of the reaction system, particularly mooring type station keeping systems, will take place in Stage 3 and the early period of Stage 4. Some monitoring will be continued into the extended proving trial period since the worse case scenario for device motion and wave loading is difficult to predict. The only safe approach is to gather as much data in as many sea states as possible and rely on reduction techniques to review the data stochastically.

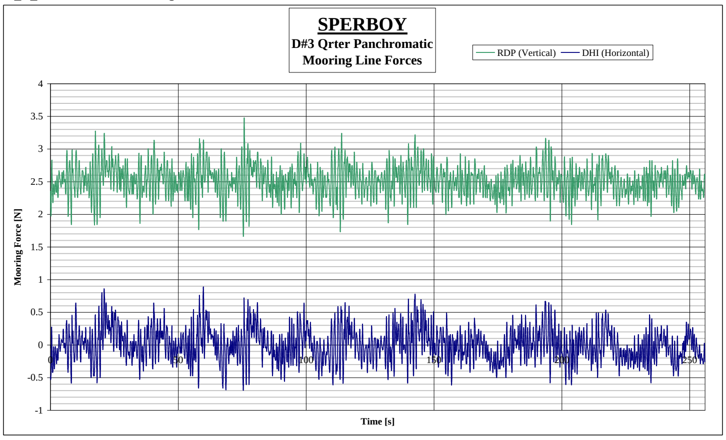
Even the question of how well the mooring will orientate the device in all environmental condition combinations must be answered.

Two different types of mooring arrangements are shown in the diagrams below. Each uses weight bearing buoys in different way to reduce the influence of the mooring lines on the device.

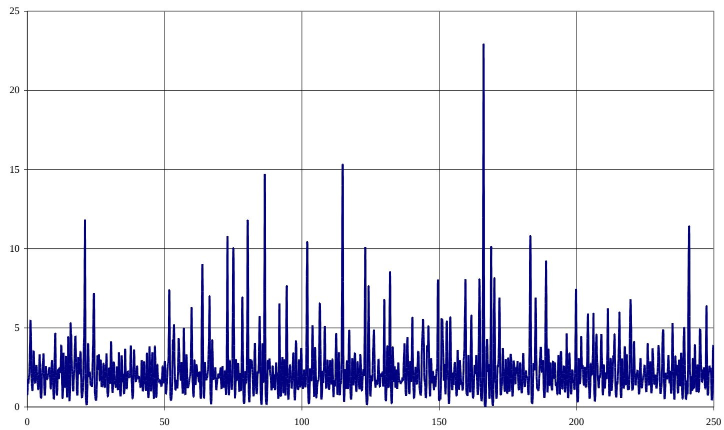


TIME SERIES

In the early stages of the sea trials it can be useful to visually inspect the mooring force load time series to obtain an overall impression of how appropriate the design is. The graphs below show such time histories of two different types of mooring. The upper plot reveals an acceptable configuration in which the first and second order wave forces created loads oscillating around a pre-tension setting. As can be seen there are no extreme peaks and the ratio of the maxima to average is approximately 1.5:1.



In the second example results from a less compliant mooring can be seen. Here the ratio of the maximum peak to average is over 10 to 1. This is due to snatching occurring in surface lines when the wave loading has surged the catenary part of the mooring tight. This level of loading ratio would not be recommended.



The latter situation can be exacerbated by wind and current causing off-sets on one or more lines. This is why it is important to monitor all relevant met-ocean data during the sea trials.

It may also become a result of one line failing so survival scenarios should have been investigated during Stage 1 and, particularly, Stage 2 test programmes since it is not recommended to conduct the at sea.

Data Presentation

➢ ***Response Amplitude Operator:*** A set of results that assist the mooring design engineer is to see how the wave energy device behaves under excitation in waves when it is attached to the mooring.

These results are often presented in a form known as the Response Amplitude Operators, (RAO), or transfer function. To obtain this diagram for each motion degree of freedom, (DoF), of interest in real seas the following process is followed.

➢ The wave energy density spectrum obtained from the met-ocean section;

➢ The response spectrum of interest is obtained from the hydrodynamic sub-system section;

➢ The quotient of the two spectra is obtained as the first part of the result, the RAO.

➢ Because of the units indices, the square root of the result can be obtained to provide the transfer function of one parameter relative to another.

This process is shown graphically to the left.

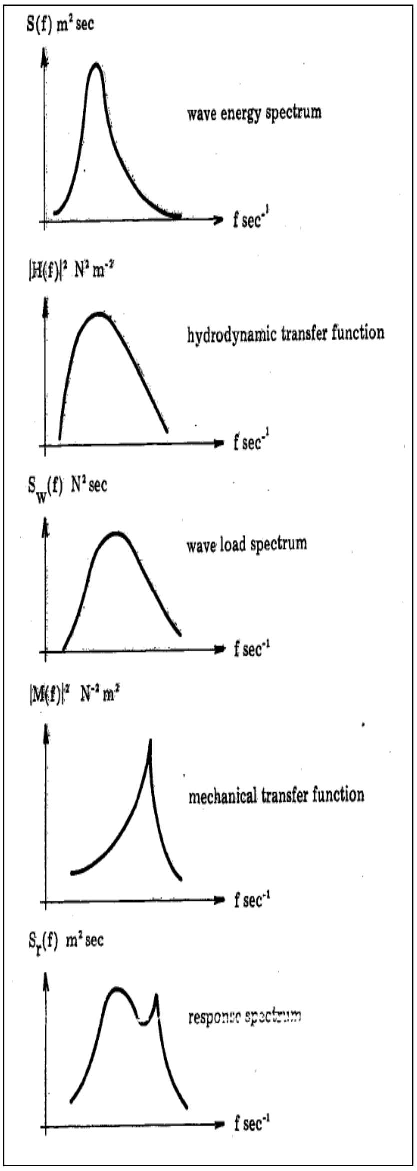
➢ ***Fatigue*** Offshore structures suffer from premature failure due to wave induced vibrations. This is exacerbated when the excitation frequency is at a natural period of structural members. Bottom standing frames will require similar analysis

HARMONIC SERIES

The spectral analysis techniques described can be used to obtain the transfer, or response, function of the mooring system during operation. This information is required by the design engineers to verify the mooring if functioning as required. Although usually generated from single frequency, monochromatic tests the same base data can be obtained from the multi-frequency irregular seaway encountered during sea trials. Hull and support structure forces can similarly be investigated to establish if vibration issue may result in fatigue concerns during extended lifetime deployment.

Based on frequency domain analyses of the excitation waves and corresponding structure/hull loads and motions the transfer function between these cause and effect parameters should be established.

This should be done by combining numerous time series covering as wide a range of seaways as possible. Attention needs to be given to the minimum amounts of energy at each individual frequency component (to avoid erroneous results arising from diving small values). The division into sub time series can be adopted in order to get sufficiently high number of spectral estimates per frequency and to reduce the uncertainty to an acceptable level. At least 30-50 sub time series (spectral estimates) should be used. This corresponds to an uncertainty of 15-25% on the individual frequency harmonics. The duration of the time series records should be sufficiently long to obtain a reasonable resolution on the frequency axis, e.g. at least 50 frequency components in the frequency range of interest (i.e. where identifiable energy in the response spectrum exists).



The transfer function is the obtained by dividing the wave energy density spectrum by the square of the load or motion response amplitude operator (RAO).

Stage Gate Criteria

The evaluation process for how acceptable and fit-for-purpose the reaction sub-system is will depend on several factors:

- The scale of the trials [S3 or S4]
- Whether the device is fixed of floating
- Has the system has been exposed to extreme conditions during the sea trials
- The amount of un-programmed service or replacement that has been required during testing
- The ease of deployment and recovery
- Other initially unknown factors that occur during the sea trials
- Will different conditions be encountered at future energy production parks

The ground conditions required for static seabed mounted devices will be as important an element for bottom mounted structures as the foundations themselves. It may be necessary to validate such anchoring techniques on a site by site, or generic seabed type, basis.

Slack moored system will be more versatile but the anchor type may require investigation at different sites.

The verification of the main structure is a task that negatives are easily proven but positives are more difficult. It is probable that the certification requirements will, as with shipping, only be proven over time.

TECHNICAL & ECONOMIC REVIEWS

The verification process for the reaction sub-system will take two primary approaches.

- The empirical data (including error logs) monitored during the sea trials must be assessed on an independent basis
- The practical results must be used to validate the mathematical models that should be progressing in parallel with the physical proving tests. This will facilitate the extension of the sea trial data for more operational and survival conditions.

Typical technical evaluation criteria will be:

- Did the sub-system perform as predicted;
- Were all forces found to be within acceptable limits and tolerances;
- Was the performance of the device unaffected by the presence of the station keeping system (structure or mooring);
- Were there any adverse environmental effects;
- Were service requirements within design statement limits;
- Does the data indicate fatigue factors must be considered and further investigated before long term deployment of multiple devices;
- Were extreme conditions encounter during the trials;
- Did any modifications and re-fits performed during the sea trials solve encountered design flaws;
- Would further trials be beneficial prior to moving to the next Stage 5;
- If at Stage 3 will the components scale up satisfactorily for Stage 4 proving trials or will modifications be required;
- Were all sensors reliable and did they provide sufficient evidence for a full due diligence examination to be performed.

Once the technical credibility of the reaction sub-system has been verified it will have to be assessed from an economical point of view. This will be particularly important in respect to the main body(s) of the device. In collaboration with the results from the hydrodynamic sub-system evaluation the hull, or structure, or frame must be in a position to be certified and insurable. The standards that will be applied will depend on which type of device it is:

- On-shore; [>15m water depth]; Static; typically civil engineering principles;
- Near-shore; [>50m water depth]; bottom standing; civil and naval engineering principals;
- Off-shore; [<50m water depth]; moored, naval architecture principles.

Lessons Learned

There are three main lessons learned regarding reaction sub-system failure:

- Most are easily avoided
- Most tend to have very visual consequences
- All are very costly to remedy

> The probability of failure should be remote but the consequences can be severe.

An interesting by-product of these miscalculations has been that new concepts and mooring designs are now being considered by various research groups. Traditional mooring techniques are, by necessity, conservative since survival has been the prime design feature. Buoyant wave energy devices must be free to move however, unhindered by the station keeping system. This has resulted in the establishment of at least on specialist test centre in Cornwall, England where fundamental studies into both the moorings and electrical umbilical can be pursued.

A second outcome of the *learning from past experiences* philosophy now undergoing review is improved, risk aversion driven, failure mode procedures. Multiple mooring lines are the first line of defence against catastrophic consequence of failure but it is important to have a pre-produces action plan document available for eventualities.

SHARED EXPERINCES

Waveplane: following successful test tank trials a full scale device was constructed and launched of Hanstholm, Denmark.

Soon after deployment a fault occurred in the mooring line which subsequently parted. Although the system was designed by accredited engineers it is not certain how much empirical data from the previous test programme was available to them. The unfortunate consequence of the failure can be seen in the photograph.

Applied Research & Technology (ART): the design team had

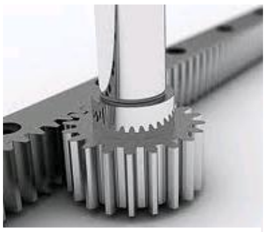
done extensive small scale device testing to validate the concept but went directly from Stage 1 to Stage 4 in the development programme. Manufacturing considerations then dictated a significant shape change was required if the prototype was to be constructed for an acceptable budget. The OWC was then launched in Scotland for deployment of the north coast. During instillation the remnants of a distant storm arrived at the site before the structure was secure to the seabed. The result was total destruction of the device.

Wave Dragon: having followed an exemplarity tank testing development programme to optimise the overtopping device the company continued with a Stage 3 device for system proving sea trials at the Danish test centre based in Nissum Bredning. The mooring design had been a major part of the latter test programme so extreme loads and fatigue statistics

were known. The plan was to verify theoretical calculations and the previous empirical results so a load shackle was fitted in the mooring line. Unfortunately, these sensors have to be placed in line in series, not parallel. Having done everything correctly up to this point someone inadvertently forgot to attach the safety line across the sensor in case of a problem Proving the adage that if *things can go wrong they will* after extended sea trials the shackle did eventually fail, a the WEC finished up on the beach. Since the company were following the 5 stage development plan the problem occurred at Stage 3 so all was recoverable and repairable.

Operations & Maintenance

Technology Development Stages 3 & 4



O&M

Rationale

Design and lab test will have produced a strategy for the operation of the device and the sea trial is the mechanism for how that can be developed and improved and this will include operation & maintenance including the phases of deployment, recovery and decommissioning. Sea trials offer the design team the first opportunity to test these categories in realistic sea states.

Objective

The main objectives to perform O&M sea trials are:

- To learn by doing.
- To prove and validate deployment procedures.
- To establish serviceability and maintenance schedules.
- To provide sufficient information to validate numerical models of the device and subsystems including components for the full range of different operating conditions.
- To give exposure to real-world costs
- To check and develop management procedures including health and safety.
- To prove and validate recovery procedures.
- To assess the endurance of the device and its overall reliability when operating in real sea conditions and identify unexpected failure modes.
- To acquire experience with the construction, installation, operation and maintenance of the device.
- Provides an opportunity to engage stakeholders at an early stage.
- Follow up environmental issues.
- Opportunity to gain experience with the supply chain.
- Finish up with a O&M procedure for a pre-commercial machine.

Pre-Sea Trials Requirements

Perform a careful reliability analysis based on tools like FMECA (Failure Mode, Effects and Criticality Analysis) and FTA (Fault Tree Analysis) and with the information and insight thereby provided, develop detailed testing and maintenance plans for the sea trials, and, if necessary, undertake bench tests of the components identified as critical.

Set H&S objectives to cover the immediate sea trials.

Establish the O&M procedures that will be followed during sea trials.

Investigate and identify the optimum site for trials, in terms of cost, logistics, supply chain, test centre facilities. Check that facilities are available nearby for required operations.

While in sheltered water, check that the maintenance operations required can be performed.

KEY ELEMENTS

- Appoint a Project Manager with overall responsibility for the sea trials, and set a budget to cover the trials and contingencies.
- Incorporate multiple redundant communication channels to the machine
- Perform a detailed reliability analysis
- Establish a logbook and logging procedure that meets the specific requirements of the machine under test.

IMPORTANT REFERENCES

DNV ???	EQUIMAR WP5, Del 5.1
IEA-OES-IA Annex II	Carbon Trust 2005: “Guidelines on design of WEC”

Sea Trial Type

There are 3 stages to implementing an appropriate O&M strategy for sea trials:

Before trials

- Experience has shown that everything that *can* be done before going to sea *must* be done

During trials

- Stick to the plan, be prepared to modify the plan appropriately to meet circumstances – and to record all changes to plan. Trials are expensive, comprehensible data is the mission goal.

After trials

- Extract as much information as possible from the trial experience and the data. Integrate the knowledge gained and update the O&M procedures and design.

A guideline checklist of the recommended activities, gained from experience, is given on the right.

Modifications to the check list will be required to suit which of 4 possible test options has been chosen; each requires different considerations:

- Established test-centre
  - grid connected
  - non grid connected
- Ad-hoc location
  - grid connected
  - non grid connected

There now exists the potential to perform "off-grid" field trials using a grid emulator. This device allows a fully operational PTO and includes all the electrical response characteristics that would occur under a full connection to the grid. Therefore the installed generator and power electronics can be as for a grid-connected machine such that the same units can be used when the unit is connected to the grid at a later stage in the trials

OPERATIONS & MAINTENANCE CHECK LIST

Before Trials

- *Draw up a trials plan*
  - *Identify and perform all tasks that can be done before deployment*
  - *Identify which maintenance can be performed wet*
  - *Develop specialist equipment if required*
  - *Define maintenance schedules*
- *Establish a condition-monitoring system*
- *Establish an automated document control and versioning*
- *Identify fatigue criticalities*
- *Prepare permissions, licenses, insurance, certification, EIA*
  - *Types of navigational aids, safety features required*
- *Identify the key problems related to deployment and recovery*
- *Determine appropriate health and safety requirements for sovereign waters*
- *Devise emergency procedures, including notification of relevant safety authorities*
- *Identify accessibility constraints*
  - *Effects of vessel availability/competition, size and type of vessel*
  - *Collision risk analysis with service vessels*
  - *Identify weather window sensitivity*
  - *Scheduling/timing*
  - *Quality of weather and sea-state forecasting & introduced uncertainty*

During Trials

- *Determine applicability of test programme to weather windows; result of severe failure modes*
- *Confirm on site access time/availability at a given Hs*
  - *Uncertainty of metocean forecast*
- *Implement trials plan, modify appropriately if required and log all changes*
- *Perform regular assessment of data and data quality and SCADA alerts*
- *Perform inspection as part of the maintenance plan*
- *On-site training of future personnel and engineers*

After Trials

- *Perform inspection at component level*
  - *Subsystems as flagged by prior failure mode analysis*
  - *Components as flagged by SCADA alerts during trials*
- *Perform detailed data analysis*
- *Feedback operation and maintenance data into the initial reliability assessment*
- *Update O&M strategy*
- *Update machine design where required to reduce or avoid O&M costs*

Test site options

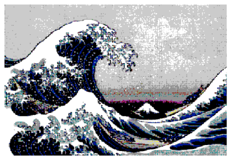
Variations on the above checklist must be considered relative to the type of test site at which the sea trials will be conducted. It would be anticipated that if an established test centre is selected then it is likely that the device will be grid connected, but not necessarily in the initial stages. It is evident from past experiences that a recognised test centre will provide the best overall support mechanisms for stage 3 and stage 4 sea trials. However circumstance may dictate that an appropriate ad hoc site will be chosen, but the developer should recognise the possible limitations and difficulties that might arise.

A grid connected site will require that the O&M strategy consider the implications of unexpected loss of connection to the operation of the machine. At an ad hoc site, should a cable be installed there will be considerable overhead and risk and the O&M should take the possibility of cable failure and damage into account.

3 The subsystem approach: tidal energy devices

MET-OCEAN DATA

Technology Development: Stages 3 & 4



Resource

Rationale:

Information on the atmospheric and oceanographic conditions occurring during sea trials should be regarded as an essential requirement. The level of detail necessary, however, can be adjusted to suit the stage of the tests. Of particular interest are the occurring ***tidal velocities*** at the device, against which the sub-system responses and device performance can be gauged.

Primarily empirical tidal data should be obtained from direct, contact measurement. However, in the event of lost readings, or extended records being required, very basic data can be obtained from admiralty charts, and more detailed data can be extrapolated from available data sets using prediction programs. Before use the theoretical sea state statistics must be validated against measured records at the same station.

Of less, but still significant importance is ***wave field*** data, which affects installation, maintenance and may impact operation for certain TE devices.

Objective:

There are several reasons for obtaining accurate met-ocean data at each particular test site. The main ones are:

For Current:

- to establish the input power;
- to establish turbulence intensity levels
- to input into device mathematical design models;
- to determine the structural induced loading;
- to establish directionality of the flow;

For Wave:

- to determine the wave climate characteristics for operations (deployment, recovery, service etc.) at sea;
- to qualify wave-current interactions at the site.
- to cross reference with the extreme event horizons;

For Wind:

- to correlate with the concurrent waves;
- to establish the freeboard windage and general loading;
- to determine the heading control (moorings).

For Other Parameters:

- to be specified on a bespoke basis mainly with regards to environmental effects, corrosion & marine growth.

Pre-Sea Trials Requirements:

Met-ocean data for a sea trial site should be obtained prior to deployment of the device. This is to ensure the correct environmental criteria have been used during the design of the device and that deployment & recovery will be possible in a practical time frame. Maintenance and service schedules must also be accommodated.

This requirement encourages the use of established test centres where tidal monitoring should have been on-going since before the site commenced operation. In the event of an ad hoc site being selected, where only limited archival records are available, mathematically predicted tidal conditions can be substituted providing the results can be verified against actual in situ measurements. Such data should be used cautiously.

Extreme site forecasts are essential.

KEY ELEMENTS

- establish the correct monitoring duration and acquisition rate for each specific test programme;
- ensure the measuring instrument is free from other water perturbation effects (e.g. weather conditions, topography/ bathymetry modified);
- ensure the data collection device is calibrated and reading correctly (esp alignment etc);
- locate the sensor so the appropriate tidal system is monitored (ideally up-stream and downstream of the device);
- Synchronise the time of all acquisition systems.

IMPORTANT REFERENCES

EquiMar: Resource Reports
IEC TC 114
IEA-OES-IA Annex II
Waves in Ocean Engineering, Tucker & Pitt
IAHR List of Sea State Parameters 1986

Development Stages:

As stated in the introduction, and other sections of this document, the solo device sea trial stages (S3 & S4) of a tidal energy converter development covers a wide scope. Devices must progress from the pre-prototype scale (circa 1:4) ***systems*** proving units, through ***pre-production*** full scale design and on to a ***pre-commercial*** machines, ready to be certified as fit-for-purpose and small array deployment.

The primary factor common throughout sea trials is that the tests move from the controllable and comfortable surroundings of an indoor facility, where velocities can be generated on demand, to the natural outdoors where test conditions have to be accepted as they occur and test programmes adjusted to suit.

The level of detail of the resource required at the different stages will vary, although the underlying mantra should always be to gather as much data as practically possible. This is because T.E. is a nascent technology so all implications of the data may not be yet appreciated. This would be similar to early off-shore engineering when wave induced fatigue of oil rig members was at first not consider. Also, the wind industry, which initially ignored gustiness to the determent of component longevity due to fluctuating loads. Both omissions stalled the respective engineering development and operational safety for some time.

Obtaining sufficient met-ocean data should remain inexpensive relative to project cost.

TEST PROGRAMMES:

There are two Stages covered in the Sea Trial section of a device development schedule, each of which is further subdivided into two phases. These are:

Stage	Section	TRL	Timetable
S3	Sub-system Bench Tests	5	6-12 months
	Full-system Sea Trials	6	6-18 months
S4	Prototype Sheltered Site	7	1-2 years
	Prototype Exposed Site	8	1-5 years

The minimum details of tidal data required at each of the stages can be different without diluting the stages trials too much, although it should again be emphasised that, the more environmental information gathered at all times, the better.

- **Sub-System Bench Tests;** if control strategies are to be investigated a realistic time history of the sea surface and velocities at the test site would be an advantage.
- **Full-System Sea Trials:** although at a large, rather than full, size these trials represent the first time the device has been in a real sea environment. The primary purpose of the test schedule is to verify all the systems and sub-systems at a scale large enough to assemble a fully operational power take-off (PTO) but still small enough for the device to be reasonably easily handled. This is an extremely important stage and the final opportunity for limited design changes and modifications to be carried out economically. This means extensive met-ocean monitoring should be conducted to assist in the major data analysis that should accompany these trials. Because the tidal conditions should also be appropriately scaled, the acquisition rate and duration should be adjusted accordingly.
- **Prototype Sheltered Site;** following Stage 3 it is expected that a full, or approximately full, size prototype device will be constructed for sea trials. It could be anticipated that a shake-down period to prove the component, assemblies, manufacturing quality and instrumentation would be conducted at a station with a less aggressive climate than the final destination. Systems operation and control, especially fail safe and shut-down scenarios, should be practised so tidal data that facilitated these commissioning trials must be included. Device performance can be verified but survival modes must be deferred until the following site sea trials.
- **Prototype Exposed Site;** once the operator is confident the pilot plant is functioning acceptably it should be transferred to a location with similar conditions to those expected at a typical power park. The sea trials are now specifically for proving rather than modification, so deployment should be for an extended duration to facilitate component lifecycle verification, full range performance verification and survival diagnosis. Met-ocean monitoring can be minimised to that required for offshore operations and may be a function of the degree of information necessary for the device PTO control.

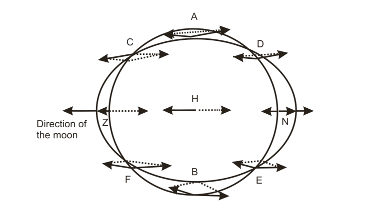
Data Acquisition:

The met-ocean data required to be gathered during sea trials will depend on three factors:

- the scale of the tests;
- the type of tests being conducted;
- the previous knowledge of the sea area.

The main parameter to be monitored will be the sea surface elevation and the velocity profile from which all the required parameters of the tidal field can be derived. Detailed descriptions of the mathematics behind these definitions are presented in the accompanying **EquiMar Resource** reports.

The ability to predict tidal patterns accurately is a fundamental advantage of the energy resource. The tide can be considered to be a series of superimposed frequencies from different sources, as mentioned in Equimar Work Package 2. Thus an accurate prediction of the resource behaviour is possible when most of these constituents are known.



Tide forces distributions

The data recording requirement is the instantaneous, 3 dimensional current velocity throughout the water column, and water surface height close to the TE device.

Other recordings are optional, such as wave data, recording surface height over a significantly shorter period of time than required for tidal heights. Wind data may also be of interest for surface piercing devices.

MONITORING PARAMETERS:

Sea State: The physical processes controlling the ocean and atmosphere have been studied for a considerable time and are reasonably well understood. However, tidal energy is a new technology so the level of detail needed to fully investigate and understand a device's overall performance and loadings at sea are still being discovered. This leads to the recommendation of gathering as much environmental information as possible throughout the sea trial period.

KEY Specification:

For a solo T.E. device under test it is required that:

- The measurement device MUST give accurate representation of inflow to the device;
- Ideally an ADCP will be positioned 2 characteristic lengths (generally rotor diameters) directly upstream;
- In many cases the ebb and flood flow velocitieis differ in magnitude, thus two measurement devices are beneficial to tquantify inflow from ebb and flood tides. This is even more important if there is a degree of 'swing' whereby the direction of the the ebb and flood tides are not directly opposed;
- A minimum ADCP ping resolution of 1 Hz for current velocity for a short period of time?
- A minimum of 5 minute resolution of water level
- A depth no more than ±10% of the intended location of the tidal device
- A bottom mounted recording device
- A maximum of 1 metre between vertical measurement points, 0.5m cells if water depth is < 20m.
- 30 days minimum data collection, where justification is required to legitimise a choice of the minimum.

It should be noted that a data set of one month is the absolute minimum amount of data required. The harmonic analysis required of such a data set will be unable to detect any constituent with a period greater than fifteen days, potentially excluding significant factors. In addition to this, a single data set is made vulnerable by the potential for unusual weather during the data collection window, which could lead to inaccurate harmonic analysis.

A much preferred method would be the positioning of at least two data capture devices (ADCPs) for a period of more than one year. However, it is recognised that this may cause an impractical delay in device development.

If the tidal energy device is installed at a location where the bathymetry is level and continuous over a large area, the case can be made for deployment of a single measurement device positioned in the same lateral plane as the device, this plane being orthogonal to the principle direction of the flow.

In all cases, the measurement systems must be positioned at such a distance that the presence of the tidal energy device does not affect the flow regime at the measuement system (i.e. the ADCP is not in the shadow of the tidal energy converter).

Data Acquisition

There are several methods available for acquiring tidal data and the one selected will relate to specific requirement. The primary sources are:

- direct measurement;
- remote sensors;
- theoretical prediction.

Sea trials can make use of all of the above but primarily will require direct, real time measurements which the other data may supplement, or support.

There are several types of tidal measurement equipment that can be used, selected to suit a particular purpose, or location. The main types are:

- Acoustic sensors ~ for
- nearshore and inshore stations (50>d<10m)
- Pressure sensors ~ for inshore stations (d<15m)
- Surface buoys ~ for nearshore stations (d>25m)
- Radar ~ for larger coverage at inshore stations.

An advantage of conducting the sea trials at a recognised, established test centre will be that the tidal climate across the whole site should already be detailed and documented. Also, the best available real time monitoring equipment should have been installed since the cost can be distributed over several projects.

In the event of gaps in the measured records they may be supplemented by validated remote & theoretical data as required. The verification process is crucial and results should only be used for basic comparisons.

Forecasting can be useful.

MEASUREMENT SENSORS

There are several instruments that can be used to provide direct, contact measurements. The purposes of deploying flow measurement sensors are:

1) To measure inflow to the tidal energy converter and
2) To measure other aspects of the flowfield of interest e.g. downstream wake.

Scale of Deployment for Measurement Devices

A large proportion of the cost for acquiring metocean data is associated with permitting/consenting and vessel mobilisation and manoeuvres. Therefore it will be more cost-effective to deploy more than one measurement system per vessel mobilisation, especially for devices operating in autonomous mode (and even more so when divers are required). It is quite possible to deploy several seabed measuremnt systems on a neap tide during slack water.

Acoustic Doppler Current Meters: ADCP signal processing can provide the time series water column velocity profile. ADCPs are also able to use water surface elevation to derive the full 2 dimensional wave spectra, which may be of use.

They are usually bottom standing units so can be less vulnerable in storm conditions. This means they must be autonomous, which increases the service requirement, or be hard wired to a mass storage bank. If close to shore a land station is possible otherwise a convenient platform may be required, such as the device. They can be linked to surface telemetry buoys, but then become as susceptible in extremes as the former group. Care must be taken when positioning the sensor to ensure its alignment does not impinge on accuracy, leading to errors in Reynolds Stress estimates.

Deployment and implementation of monitoring devices may prove problematic if bottom mounting is needed in deep water locations. Being mobile and relatively inexpensive, it is expected that ADCPs will form the bulk of measurement devices for tidal site assessments.

Pressure Gauges: are useful in water shallower than 20m. They measure the water surface profile remotely by pressure fluctuations caused by the waves, which provides the 1 dimensional spectrum. Directional spreading is obtained from water particle motions adjacent to the sensor passing through an electromagnetic field. Current speed and direction is also monitored. These can be exploited for on-shore device sea trials.

Surface Buoys: At present the industrial standard is the directional, or non-directional, surface buoy. These have been well proven by meteorological services and offshore petroleum exploration. Larger met office types provide a platform for a range of other important sensors, especially atmospheric gauges. Test Centres should be based on these advanced met-ocean buoys, but it is unlikely that such platforms will be associated with solo device sea trials. Here the commercially promoted type buoys of approximately 1 metre diameter can be utilised. Different measuring techniques have been used with the GPS sensor beginning to appear.

It is advantageous if the gauges supply the data as the raw time history and the analysed results. A particular advantage of the surface buoys is that they offer real time telemetry of the data.

Telemetry:

Ideally ADCP and other sensors will be trawler proof, and hard-wired to the shore (through device if possible). This avoids issues with autonymous operation allowing monitoring of data quality, device reconfiguration etc.

Otherwise, telemetry is achievable through underwater modems and surface transmission. If autonymous deployment is used then it MUST be supported by a system providing ‘live’ data.

Underwater data transfer, performed by divers utilising e.g. magnetic data transmission, should be avoided since opertunities for deploying divers might be restricted.

Data Analysis:

The data from met-ocean gauges can be provided as the raw time series of the measured parameters, for post processing, or the analysed results performed in real time on-board the instrument. Each can be useful to address different device performance issues.

In order of complexity the data formats are:

- *Tidal height;*
- *Instantaneous Velocity and Direction*
- *Average Velocity and Direction;*

Examples of the use of the data during sea trials are:

- ***Power output~*** *5 minute average;*
- ***Mooring forces~*** *Instantaneous record*
- ***O&M~*** *Tidal height and Tidal diamond;*
- ***Deployment~*** *Time series;*
- ***Device design~*** *all;*
- ***Control strategies~*** *5 minute average;*
- ***Mathematical model~*** *all.*

By obtaining the time history of the water surface elevation it is possible to derive all required sea state description parameters. Depending on the instrument selected this enables several different levels of device evaluation to be conducted.

Time history can also be used to investigate specifics, such as weather windows.

Data Presentation:

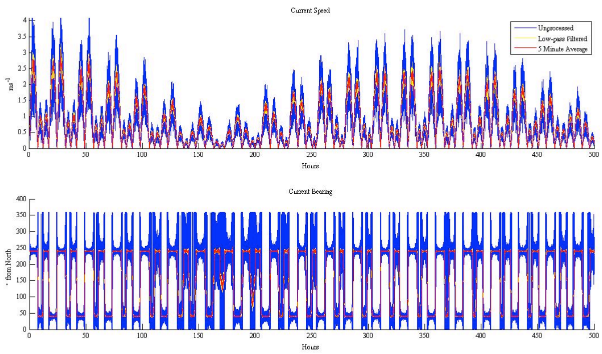
As stated in the *Introduction* wave records are necessary for two fundamental purposes during TEC sea trials. (i)The evaluation of the behaviour and

DATA FORMATS (Time Series):

Time series' are used to describe the change of the monitored signal over time. This is the primary method of analysis when considering a location for tidal energy extraction. There are several methods of data comparison and presentation, as described below.

Instantaneous record:

For applications such as mooring and blade loading, non averaged maxima are required to fully assess the nature of the location. A full time series may also allow the calculation of other parameters such as turbulence intensities. The turbulence may be visible but will require further statistical analysis to quantify it. As specified in the previous section an ADCP will acquire data for a set time in the form of the velocity, direction and tidal height raw data. This signal forms the basis for the time series and harmonic analysis which, together, are used to produce specifications for the site, including a rough indication of turbulence levels. An instantaneous record of tidal height or surface elevation will serve to capture the wave data over the period of measurement. This can then be analysed effectively using the frequency domain, as discussed below. The figure below shows how such data can be presented in a common format, plotting values for axial velocity. This method gives a representation of velocity values for a fixed point in space, varying in time.



5 or 10 Minute Average:

Instantaneous records are impractical for large periods of time, both for data capture and storage, and for processing. Time averaged analysis will form the bulk of the standard data presentation. Obviously the averaged data must be derived from the original continuous data, using the corresponding data processing techniques. A 5 or 10 minute average can be used to statistically estimate the marine flow conditions of the site. This can then be used to inform power output, control strategies, foundation design, etc. over a medium to long period of time.

performance of TEC under real sea tidal conditions. (ii) To plan the deployment, recovery and servicing of the device during this period. Both of these requirements are aimed at de-risking the development process through the gaining of knowledge prior to incremental advances down a path of increasing technical complexity and fiscal investment.

These requirements dictate the analysis conducted and the way the results are to be presented for both convenient and detailed use by the design engineers.

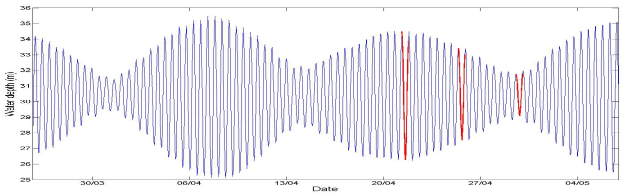
Full presentation packages will be customised to a particular device and stage of the trials. However, a basic set of displays are common at all times, especially to aid the equitable comparisons of tests and devices.

There are at least four aspects to the presentation of tidal data measured before and during sea trials:

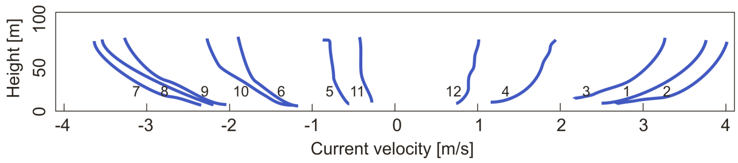
- ***The raw velocity data;***
- ***Filtered and average the raw data;***
- ***Velocity profile;***
- ***Tidal rose.***

To accommodate all the records that will be acquired during the sea trials reduction methods are necessary.

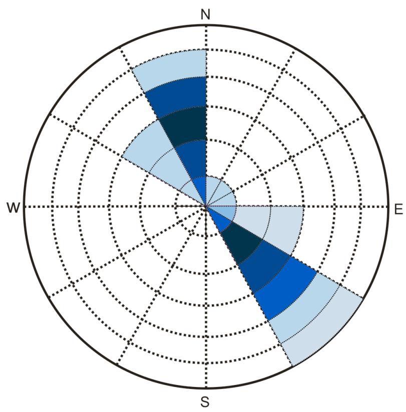
Water Surface Elevation: The most basic data form is that of tidal height, expressed in terms water depth over the tidal cycle. This information can be used to inform the power capture, mooring and installation decisions, as well as operational maintenance.



Velocity Profile: The second abstraction of data presentation displays the velocity throughout the water column. This plot becomes useful when the location of the turbine within the column is required to specify power output. Potential power output can then be calculated using the expected position of the rotor within the velocity column. It is likely that the flow velocity will not be uniform, possibly reducing performance and increasing unbalanced loading on the blades. The figure below also takes into account time variance during a single tidal cycle. If the flow is asymmetric, then multiple plots should be displayed, showing ebb and flood separately.



Tidal Rose: This method is a useful representation of the velocity magnitude and direction of a particular location over a period of time, which is commonly employed within the wind energy industry. Velocity values are assigned to bins, which are placed on a polar coordinate system and defined by a series of colours stating the magnitude.



Data Analysis:

Harmonic methods can be applied to supplement the time series analysis of the water surface elevation records. A universal tool for this work is the Fast Fourier Transform, or FFT. This algorithm offers an efficient form of spectral analysis from which the wave frequency composition of the time history can be obtained.

Two factors must be accounted for:

- The technique introduces periodicity where it may not exist
- FFT is based on probability so provides estimated results.

An analysis of the turbulence present in the flow will go some way to making turbulence prediction possible, which is essential for issues such as blade loading. Turbulence occurs when viscosity breaks the flow into irregular 3D eddies of varying scale. Turbulence intensity can be defined as the ratio of the velocity fluctuations to the mean velocity. As waves also create eddies close to the surface, turbulence measurement can be contaminated by waves.

Harmonic Analysis:

As mentioned in Data Acquisition, tidal data can be broken into separate constituent parts._These constituents are distributed in a few narrow frequency bands, and the number of constituents found will increase with the length of observation [2]. Some constituents will be location specific, especially in shallow waters. Over 1140 constituents are suggested in Qiwen 1987 [(2)]. Obviously the majority of these constituents are very small, and can be neglected whilst retaining a sufficient degree of accuracy. It is estimated that the largest 60 constituents account for about 99.97% of the tidal energy [2].

The tidal height can is given as

$$Y(t) = A_0 + \sum_{i=1}^{N} h_i \cos(\omega_i t + \varepsilon_i)$$

Where A_0 is the mean tidal height, N the total number of constituents, h the amplitude, ω the frequency and ε the phase of the constituent.

An example list of some common constituents is taken from Equimar Work Package 2.7. A minimum of twenty constituents is normally required for effective prediction [4-EMEC].

Common name	Desc iption	Pe i d hrs)	Rank
M2	Principal l nar semidiurnal	12.42	1
S2	Principal solar semidiurnal	12.00	2
N2	Larger lunar elliptic semi diurnal	12.66	3
K1	Lunisolar diurnal constituent	23.93	4
M4	Lunar quarter-diurnal shallow water overtide	6.21	5
O1	Lunar diurnal	25.82	6
M6	Lunar sixth-diurnal shallow water overtide	4.14	7
MK3	Terdiurnal shallow water compound tide	8.18	8
S4	Solar fourth-diurnal shallow water overtide	6.00	9
MN4	Quarter –diurnal shallow water compound tide	6.27	10

Turbulence Spectrum

The turbulence present can also be analysed in the frequency domain. An expected spectrum (the Batchelor Spectrum) represents the cascade of energy from large, low frequency eddies to small, high frequency eddies.

A harmonic analysis of turbulence present in the flow allows vibration analysis to provide critical information on issues such as structural and blade loading on T.E. devices.

Data Presentation:

Even if the tidal constituent parts have been obtained, uncertainty will exists with regards to unpredictable natural phenomena such as wave. This data can be presented using short or long term statistics.

Short Term Statistics: represent the analysis of individual seaways. Taken 5 minutes every hour, they will provide a brief overall picture of the wave spectrum.

Long Term Statistics: represent the wave climate of an area and are required to predict the extremes and storm conditions that should be expected to occur at a test site or generation park.

The amount of data used in the forecasting mode reduces uncertainty in extrapolation. For official test centres this information should be accurately available. At ad hoc locations some pre-deployment wave data must be obtained to justify the confidence in the project survival estimates.

Validated, or calibrated, computer prediction packages can be used in the absence of site measurements, together with close proximity meteorological buoy data if it is available. Weibull diagrams are used to extrapolate limited wave height data to obtain, typically, the 100, 50, 10 & 1 year maximum wave. As more records are obtained the accuracy is improved.

Waves and Wave Current Interaction

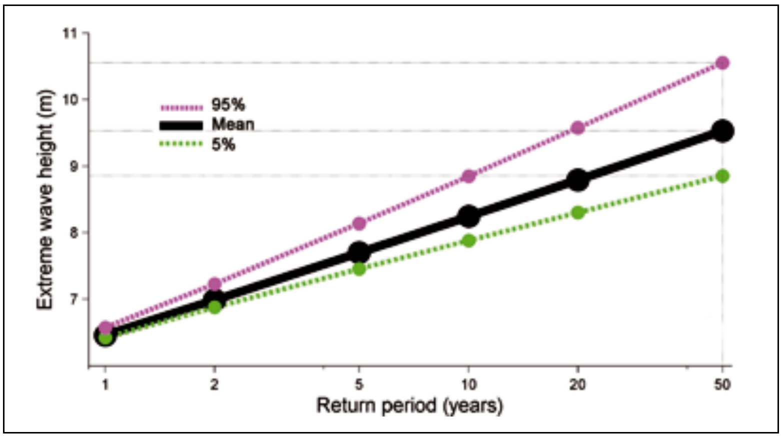
Due to the Stokes Drift process, waves will impact the velocity of current. The depth of effect on the current will be proportional to the wave height, therefore the influence of the wave environment may extend to the power extraction area. Of most critical importance are the horizontal component of the velocity perturbation, however the vertical component may also be important and should also be accounted for.

The wave climate will also be of interest to developers as they assess suitable weather windows for deployment and maintenance, as well as examining extreme conditions.

Long Term Statistics: there are several methods for the prediction of the extreme waves that will occur at a test site. Basically they all operate on the same principal of probability estimations of an event exceedance in a given return period. Since this extreme prediction must be based on limited duration data, much less than the safe return period, a probabilistic model is used, such as one based on the Weibull equations.

The data is analysed to obtain the selected model coefficients which are then re-introduced into the equations to predict the extreme wave height that can be expected to be exceeded in a given time as shown in the graph below.

Alternatively the limited measurements can be graphed and the plot line extrapolated



The results can be produced for the seaway summaries, such as the significant wave height, or for the individual highest wave that would be exceeded in the same time frame. Both these values will be required for the safe design of the sea trial project.

There are two ways to reduce the uncertainty in these extreme predictions. Firstly a reasonable length of raw data is required on which to base the probabilistic model. For this exercise it is possible to resort to other sources of wave data to supplement the actual measurement. Secondly, care is required if missing data has to be accommodated. These gaps can be considered as non-measured periods or calms. This decision will influence the extrapolation.

The interpretation of the probability of non-exceedance of an extreme event in a given return period is that if it occurs on average once every 100 years then there is a 1 in 100, or 1%, chance it will be equalled in any given year. Similarly the 1 in 50 (2%) and 1 in 10 (10%) extremes can be supplied to the design team who can decide on the acceptable risk before the device is deployed.

Data Presentation:

Although energy production is an important element of sea trials they are conducted to investigate other aspects of the development of Tidal Energy Devices. In particular the verification that all aspects of a project, including deployment, service & recovery can be conducted safely. To this end, wave and tidal data exceedance are key parameters in conducting successful deployment and maintenance.

The data presentations for this section of the sea trials are based on both spatial and temporal wave information relative to set operational criteria, usually the height of the waves. The information must be compiled in three formats:

- ***Wave height exceedance;***
- ***Event duration occurrence***
- ***Event temporal spacing.***

In addition, slack water times must be considered. Information obtained prior to the sea trials can be used by the device design teams to modify tasks so they can be safely conducted within the time frame. During the trials the risk assessor can evaluate the safety of the sea based activities and adjust as required.

This information will govern the various water borne operations, both during the pre-production sea trials and, especially, the extended pre-commercial sea trials. Experience has shown that they can be the main modifier to device design in full size Stage 4 proving trials.

It is recommended that these studies are an integral part of a Stage 3 programme, where the situation is more controllable.

WEATHER WINDOWS:

It is recommended that installation and retrieval procedures take place in slack water if possible. If the period is too brief, then the neap tide cycle is recommended. Many locations with strong currents have short slack water periods (i.e. sometimes as short as 15 minutes).

Exceedence plots of a parameter (i.e. wave height) are produced for a specified time period. From these the global amount of time a threshold value is exceeded is obtained

The next requirement is to obtain the persistence table. This shows the percentage of a year a wave height is within a window of a set time frame. In the matrix below it can be seen that seas below 1m & 12 hour duration only occur for 2% of a year (7 days). If an activity can be conducted in 1.5m waves the safety margin rises to 10% (36 days). [NB. these results will be seasonally effected]

M1 Mean Annual Windows — % Occurence

Significant Wave Height (m) \ Minimum Length of windows (Hrs)	1	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96
2.5	45	43	41	39	38	37	36	32	31	28	26	25	23	22	21	18	17
2.4	42	39	38	36	34	33	32	29	27	26	24	22	21	20	18	17	16
2.3	38	36	34	33	31	30	28	26	25	23	22	20	19	18	17	15	14
2.2	35	32	31	29	29	26	24	23	20	20	19	18	17	15	15	13	13
2.1	31	29	27	26	25	23	22	20	18	17	16	15	14	13	12	11	11
2	28	26	24	23	21	20	18	17	15	14	14	12	11	10	9	8	7
1.9	24	23	21	20	18	17	16	14	13	12	11	9	8	7	7	6	5
1.8	21	20	19	17	16	15	13	12	11	10	9	8	6	6	6	4	4
1.7	18	17	16	14	14	12	11	10	9	8	7	6	5	5	4	3	3
1.6	16	14	13	12	11	10	9	8	7	6	5	4	4	4	3	3	3
1.5	13	12	10	10	9	8	7	6	5	5	4	3	3	3	2	1	1
1.4	11	9	8	8	7	6	5	4	3	3	3	1	1	1	1	0	0
1.3	8	7	6	5	4	4	3	3	2	2	1	1	1	1	0	0	0
1.2	6	5	4	4	3	3	2	2	2	1	1	1	0	0	0	0	0
1.1	4	3	3	2	2	1	1	1	0	0	0	0	0	0	0	0	0
1	2	2	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0

Another important met-ocean relationship that affects off-shore activity, and cost due to downtime, or stand-by penalties, is the time between acceptable wave conditions. The table below shows that for the 1.5m & 12 hr limit this would be approximately 16 weeks.

		Wave Height Limit (Hs)			
		1 m	1.5 m	2 m	2.5 m
Least-Mean-Most longest waiting period between windows (Weeks)	At least 6 hours long	27-30-33	9-12-15	4-7-9	3-6-9
	At least 12 hours long	27-32-36	9-16-26	4-7-9	3-6-9
	At least 24 hours long	42-44-45	19-25-36	6-11-15	4-7-9
	At least 48 hours long	150-150-150	32-34-36	18-22-30	4-11-15

Data Archive:

There are four primary drivers to the requirement for carefully planned storage of the location data:

- *It is doubtful that the wave and tidal monitoring will be on the same acquisition system as the device sensors;*
- *An individual file size will not be excessive but at one record per hour over a full sea trial duration (1-5 years) a considerable number of files will be created;*
- *It will be imperative that, even after an extended delay, simultaneous files must be recoverable from the archive;*
- *There will be many different device and environmental combinations that must be exclusively associated.*

Modern digital storage systems can accommodate the high levels of data that will produced so even raw information files should be archived.

Hardware: requirement are;

- *A storage medium that will not quickly become redundant must be selected;*
- *Data & control files can be handled separately;*
- *Direct connection to the Internet for extended distribution and remote control is available.*

Software: essential are;

- The actual sensor signal output is often not sufficient to uniquely identify single files. A project specific **metadata** nomenclature should be established.
- Real time validation & quality checks must be performed

METADATA FORMAT:

It is not required to be prescriptive on the type of archiving format that should be implemented, only that a well structured, but flexible, cataloguing arrangement covering the fundamental requirements is designed. The identification process should start with the naming of a file.

Since the met-ocean data will have an independent telemetry system the most important parameter in the identification header will be the time stamp. This one marker should allow all different data files to be cross-correlated. However, this could be laborious since several independent log files could be produced during the sea trials, such as:

- Device sensors data;
- Met-ocean data;
- Operational settings;
- Failure and service log;
- Variables & constants parameter values, etc.

If in addition to this there can be several dispersed operators who can take independent intervention actions a more detailed metadata, or heading, that registers all such parameter values settings would be useful.

These identifiers should be added at the pre-archiving stage and can have automated incrementing, or operator intrusion, as required. It is essential that all changes are registered in the master sub-directory and no contradictory files are created.

It can be advantageous if data validation and preliminary analysis algorithms are also added at this junction, including a display package, since these actions will be rote to all data sets. This would be particularly relevant to sensor calibration to ensure the correct co-efficients are not misplaced prior to use. The raw data must also always be maintained and can be presented in real time in a standard format, as shown in the example below.

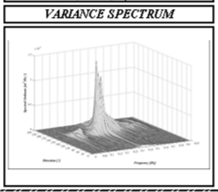
REPORT NO.		LOCATION	
DATE		DEVICE	
TIME		PROJECT DURATION	

ENVIRONMENTAL CONDITIONS

WAVE CLIMATE		WIND		CURRENT	
INSTRUMENT	Waverider	INSTRUMENT	--	INSTRUMENT	ADCP
RECORD LENGTH	30min	RECORD LENGTH	--	RECORD LENGTH	60min
VALID RECORD	YES / NO	VALID RECORD	YES / NO	VALID RECORD	YES / NO
VERIFIED	YES / NO	VERIFIED	YES / NO	VERIFIED	YES / NO

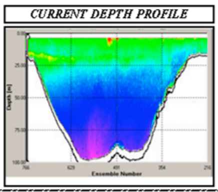
STATISTICS		*STATISTICS*		*STATISTICS*	
Hm0 [m]	2.15	Mean Speed [m/s]	--	Mean Speed [m/s]	0.12
T02 [s]	8.747	Gust Speed [m/s]	--	Peak Speed [m/s]	0.2
Te [s]	7.458	Mean Direction [°]	--	Flood Direction [°]	17
Tp [s]	12.3			Ebb Direction [°]	195
Dirp [°]	132				
Hmax [m]	4.05				
Wave Power [kW/m]	23.88				

VARIANCE SPECTRUM



WIND ROSE

CURRENT DEPTH PROFILE



PROJECT LEADER	LEAD TECHNICIAN

Check List:

The recommended measured parameters together with the analysis and presentation procedures are based on the experience of pioneering tidal energy device developers who have already conducted Stage 3 or Stage 4 sea trials.

Many of these suggestions have been gained from practical problems faced and solutions found so should not be ignored lightly. Difficulties encountered at sea are costly to correct, particularly when safety of personnel is a prime consideration.

It should always be acknowledged that the ocean is an unforgiving place for anyone, or anything, not equipped to be there. The greater the knowledge of the environmental conditions the less will be the risk of operation in these harsh surroundings.

Offshore engineering has advanced a long way due to the oil & gas industry which has resulted in better sensors and advanced analysis techniques. These should be adopted and adapted by the nascent ocean energy industry to reduce the levels of uncertainty in the data and minimise the risk in the required field work.

There remain many aspects to the multi-disciplinary operation that are unique to wave energy. The purpose of the sea trials is to discover these and address them, since modification and rectification is anticipated. Once a device has achieved the commercial stage change becomes more difficult. No unit to date has moved from pre-production to pre commercial without a major re-fit.

EXAMPLES of TIDAL DATA USE:

OPENHYDRO: Openhydro was the first pile foundation mounted turbine to be tested at EMEC. The redesign of the device took place after the use of such large monopiles caused the failure of one of the barges [2-example]. The redesigned device consisted of a gravity based foundation, and was deployed in the Bay of Fundy. However, the device needed to be retrieved from its location due to a blade and a sensor failure [3-example]. Retrieval proved time consuming due to seasonally short weather windows.

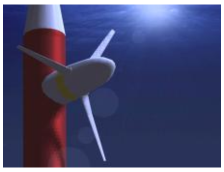
SEAGEN: Seagen was the second device to be installed by MCT. Due in part to deployment in an Area of Special Scientific Interest, a very thorough programme of environment data collection was undertaken, contributing to successful device testing. Although a rotor failure was announced, this was due to control mechanism problems as opposed to a structural failure. [6-example].

CoRMaT: The device underwent initial testing in the Sound of Islay as a complete scaled model with a flexible mooring. Due to lack of site test mapping, the first installation of the device was a failure due to the existence of an eddy at the location. The device was relocated and it was possible to proceed with the deployment. This experience serves as a reminder to the fundamental importance of carrying out a substantial investigation of the site before deployment [1-examples].

Unfortunately many developers are hesitant to reveal their failures while testing their devices. If more developer were to discuss this information, the technological growth would accelerate as common problems would be foreseen and avoided.

HYDRODYNAMIC SUBSYSTEM

Technology Development Stages 3 & 4



Prime mover

Rationale

Data on the motions of the prime mover in the water is an essential element for the hydrodynamic characterisation of a tidal energy device. This represents the first step of energy conversion and is of particular importance for the efficiency evaluation of a tidal energy technology, because the prime mover is typically the main component of distinction between technologies. Due to the different philosophies of primary energy conversion (e.g. axial or cross flow turbines, oscillating hydrofoil systems, etc.), the characterisation of the hydrodynamic subsystem brings along different approaches from device type to device type.

Similar to the met-ocean measurements, the level of detail necessary can be adjusted to suit the stage of the tests. The more precisely the incident flowfields at the device are identified, the more accurately the hydrodynamic subsystem can be characterised. This step is the potentially most important item for verification of numerical simulations of the device behaviour, and is also the interface to the input for the Power-take-off (PTO) evaluation. In all cases, measurement frequency and accuracy of the hydrodynamic subsystem should be sufficient to match the target met-ocean conditions.

Objective

Monitoring the hydrodynamic subsystem can comprise the following targets, of which some are only met in rather advanced states of the sea trial schedule:

- to evaluate the hydrodynamic efficiency of the device
- relate the real-time body motions to the incident flow conditions (time-domain; TD)
- relate the statistical properties (e.g. turbulence, wave interactions) of the sea state to absorbed mechanical/ pneumatic power levels (FD-frequency domain)
- to establish the input power available to the Power-take-off (PTO), both in the time and frequency domain
- to adjust control strategies and PTO settings for safety and/or efficiency optimisation (movement restrictions)
- to determine operational limits for certain sea states (deployment, recovery, service, cut-in and cut-out flow velocities, etc.); both FD and TD
- to input into device mathematical design models

Pre-Sea Trials Requirements

The hydrodynamic design, i.e. the dimensions of the prime mover, will be determined based on the existing information on predominant and extreme sea states (obtained via the met-ocean sea trial manual), in order to ensure that the sea trials serve as baseline for an extrapolation of future device generations.

The choice and location of sensors identifying the prime mover must ensure capture of extreme values, as well as maximising accuracy in most likely average operational modi.

Whereas in some devices the choice of physical quantities and respective sensors is obvious, in other cases a detailed analysis of options for identifying the energy capture of prime mover is essential.

KEY ELEMENTS

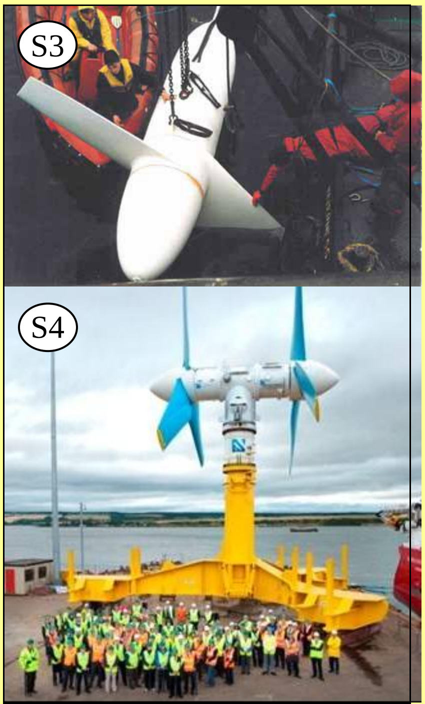
- establish the physical quantities to be measured
- ensure verifiable interface to met-ocean data and PTO measurements (redundancy of key data)
- determine acquisition rate according to met-ocean data
- choice of sensor types and locations
- time stamp of acquisition systems (synchronise with other subsystems)

IMPORTANT REFERENCES

EquiMar WP3, WP8, Del 4.2	OES-IA Annex II of IEA	IEC TC 114
DECC URN 09/559	dti URN 07/808	EMEC performance protocol

Development Stages

The vital importance of real-sea testing of ocean energy devices is contrasted by typically very restricted funding for overcoming this phase, also as consequence of non-sufficient understanding of the factors that do distinguish ocean energy devices from other renewable energy technologies: the real sea environment.



Scale tests S3 and full-scale S4

Stage S3 - ≈ 1:4 scale model of MCT (top photo: Marine Current Turbine Ltd) and Stage S4 – full scale Atlantis prototype (Bottom photo:Atlantis Resource Corp.)

As a consequence, a staged testing approach may be required, in order to adapt to the different priorities of each phase of a project. In the solo device sea trial stages (S3 & S4) addressed by this document, a case-to-case trade-off between monitoring system complexity and available means (both manpower and funds) needs to be done, not only distinct between wave and tidal machines, but also between different tidal energy converter types.

Apart from the reaction subsystem (in particular moorings, see Reaction Subsystem sea trial manual), the hydrodynamic subsystem is the major distinctive element from other technologies, stressing the importance of its proper testing in these development stages. Input hydrodynamic quantities need to be related to the movements of the outer body of the device (floater, reference body,

TEST PROGRAMMES

The present document refers to the sea trial stages S3 and S4, which according to IEA-OES-IA Annex II correspond to the Technology Readiness Levels 5-8, referring to specific prototype and demonstration plant testing. Primary objective of these phases is to proof technical viability and minimise technical and financial risks for the commercialisation phase.

Stage	Section	TRL	Timetable
S3	Sub-system Bench Tests	5	6-12 months
	Full-system Sea Trials	6	6-18 months
S4	Prototype Sheltered Site	7	1-2 years
	Prototype Exposed Site	8	1-5 years

Within the 2 stages of sea trials targeted by this document, the priorities can be different for each phase:

- **Sub-System Bench Tests:** typically large- or full-scale 'dry' tests of parts of the whole system with the priority of characterising the PTO characteristics, can be straight-forward to apply to the hydrodynamic subsystem of turbines, but less so to e.g. venture or oscillating foil type devices. However in particular cases special test rigs can be the last (and best) possibility to validate and calibrate 'indirect' prime mover measurements, such as determining the movement of an oscillating body by measuring pressure and stroke in hydraulic cylinders, or the angular movement of a blade.

- **Full-System Sea Trials:** typically reduced scale (1:2 to 1:4, in some cases down to 1:10) sea testing of the complete device at a 'benign' nursery test site. Such sites offer relatively easy accessibility as sea states do not normally interfere with boat traffic, and light equipment can be used for deployment and maintenance. However, conditions such as wave action and turbulence are not benign with respect to the dimensions of the devices, making this phase the first seaworthiness proof, which is of particular importance to the hydrodynamic subsystem. This phase is especially important for wave energy devices, and is recommended for tidal energy machines.

- **Prototype Sheltered Site:** sea trials of a full, or approximately full, size prototype device can be undertaken in two phases: in this first phase a sheltered site in order to allow for system functionality verification and validation of models. In particular device performance can be verified but survival modes must be deferred until the following site.

- **Prototype Exposed Site:** as opposed to final functional verifications, this is the final proof of seaworthiness and long-term functionality. Extended performance verification and survival diagnosis are to be performed specifically for the hydrodynamic subsystem, in order to compare the prime movers behaviour to the expected situation. Redundancy of measurements is important, both so that the motions of the prime mover can be recovered in case of loss of one system, and for verification of accuracy.

turbine blades) with varying levels of detail.

Data Organisation

The ultimate aim for the hydrodynamic subsystem of the sea trial stages S3 and S4 is to specify the prime mover and reaction frame of the devices in relation to the complete set of environment conditions. In particular due to the random character of metocean conditions, and also partly because all implications of the data may not be yet appreciated, being the first test at such scale with the devices (see also met-ocean sea trial manual) the demand is therefore to gather as much data as practically possible.

On the other hand, obtaining sufficient met-ocean data should remain relatively inexpensive, due to the typical financial restrictions of this phase mentioned before.

For the hydrodynamic subsystem, the completeness of acquired data and their appropriate organisation is of particular importance for the validation exercise of numerical models and survivability assessment.

According to OES-IA Annex II, "Early prototype machines should be extensively instrumented, including duplicate and redundant sensors and dual data acquisition systems. Active operational communication should be on a separate SCADA (supervisory control and data acquisition) system to the measurement and monitoring system. The mantra should be: The cost of losing data can be more expensive than the price of obtaining it.

Duplication & Redundancy: although the cost of obtaining data during operation is high the price for not monitoring all variables will be higher. Past experience has shown that even in extended sea trials the amount of usable information, when all sensors were operational in the [metocean] conditions and device configuration required can be limited. A measuring campaign that still leaves important decisions to extrapolation cannot be regarded as successful.

The two recommended solutions to this problem are to employ duplication of essential sensors such that the risk of failure and loss of recording is minimised. This approach is particularly useful were replacement

MONITORING PARAMETERS

Most of the physical quantities listed in the met-ocean sea trial manual have direct relevance for the characterisation of the hydrodynamic subsystem as the first stage of energy conversion: wave height, period, directionality (principal direction and angular spreading) etc. for wave energy converters, and current speed, direction, vertical/lateral current profile etc for marine current converters (plus quantification of spatial/temporal unsteadiness because of complex and possibly unknown effects on the turbine). On the other end, most relevant output quantities of the hydrodynamic subsystem are torque and/or velocity of prime mover, instantaneous absorbed power and mean power, all required inputs to evaluate the next stage of the conversion, the PTO subsystem (see PTO sea trial manual).

For tidal energy devices, there are a number of different concepts, however with respect to the hydrodynamic subsystem the distinction of the prime mover is usually less complex than with wave devices. With the exception of the oscillating hydrofoils, which are reciprocating devices, typically tidal stream technologies use axial (or crossflow) axis tidal rotors under quasi-static or quasi-periodic loading. Effects of turbulence and other unsteady flow characteristics are common to all devices.

To understand a tidal energy device's overall performance at sea, the capture of the prime mover's characteristics in all instances of operation is highest priority, hence the recommendation of gathering as much following information as possible throughout the sea trial period:

- Incident inflow conditions, upstream and downstream of the device. The assumption of bidirectional flow may be used to limit the number of ADCP deployments (see METOCEAN Subsystem), however it is expected that e.g. turbulence characteristics will depend on flow direction, and more sensors deployed is better. Suitable levels of redundancy are ADCPs deployed both up and downstream of the power capture area, plus additional direct (e.g. anemometer/Pitotstatic) and indirect (pressure) measurements at or near the centroid of the power capture area;
- For floating or compliantly moored structures, 6 degree of freedom measurements including body displacement, rates and accelerations (and if the device is acting as a vessel, velocity RAOs and motion RAOs);
- Seaworthiness of Hull & Mooring:
    - Water surface elevation abeam of devices if they are surface piercing;
    - Excessive rotations or submergence;
- PTO forces & power conversion (pressure / force) for indirect measurement of body movements;
- Incident wave conditions, either via central beam on bottom mounted ADCP, or via floating AWACS/Waverider type buoys.

and renewal of the transducers is not possible at sea or without a major re-fit. The less expensive approach is to adopt redundancy in the system such that indispensible physical properties can be (accurately) derived from other independently measured parameters. As with duplication, the threat of losing both sensors is considerably reduced."

A logbook is of paramount importance. For each test period the length, input quantities, output quantities, machine control, machine status, etc. should be recorded, and additional observations/perceptions noted (e.g. general met-ocean conditions, unusual circumstances or events, operator/observer name,...).

For S3 and S4 sea trials, it can be summarised that the optimum is to conduct as many trials as possible, in order to yield the maximum amount of data, as well as ALWAYS HAVE A DETAILED TEST PLAN.

Measurement of Device Flowfield

- Downstream centre-line wake measurements will inform array design (Ref. Part IIC of protocol). Measurements should be at least 5 characteristic lengths downstream.
- Increasing distances from the device might not suit hard-wired measurement systems. As these measurements are not essential for device performance assessment, autonomous operation is both most practical and cost-effective.
- Depending on site and device characteristics, the intensity of the wake will vary. It sis suggested that simultaneous deployment of multiple measurement devices is preferential. An example might be at 5, 7 and 9 characteristic lengths downstream deployed for 1 month or 4 spring-neap cycles. Results would the inform redeployment of further measurement devices.

In general, the following physical quantities are likely to be most relevant for ocean energy devices:

Level (distance), pressure (dynamic/static), flow (velocity), valve positions (limit/percentage), device position (6DOF for floating device), device attitude angles (3 axis), device velocity (6DOF for floating device), Euler angles and rates, etc.

Further, although usually not primarily required for performance assessment, the following quantities can become relevant: air temperature (precision of the measurements), humidity (e.g. air properties), salinity (e.g. corrosion risk assessment for durability of the sensors and equipment).

For both wave and current, identification of unlikely or unphysical events, both in the time domain should be ensured, e.g. transients, level changes, etc., and statistical domain, e.g. outliers, improbable distributions etc.

For detailed distinction of devices presently most likely to play a relevant role in the near-term market, refer to Deliverable D5.2 of the EquiMar project, the 'Device classification template'.

Data Acquisition

The data acquired during the first sea trials is of fundamental importance for device assessment and the future development process, in particular with respect to the hydrodynamic subsystem. Being the first opportunity to record operational data in real sea environment, the setup of the data acquisition system of stages S3 and S4 must allow for redundant data storage and transmission strategy, in order to avoid the loss of data for any potentially relevant event (in particular extreme events).

The overall acquisition rate of the data logging equipment must be sufficient to record simultaneously all required channels with a rate sufficient to clearly relate the incident energy variation with measured physical quantities in all subsystems.

The number of recording channels and bandwidth available to the selected telemetry system will dictate some aspects of the logging and transmission protocol. For security it is advisable to log all raw variables on-board, even when they are also immediately transmitted to the shore station. Error states should be coded so that the source of the error can be quickly identified. The on-board SCADA/PLC (Programmable Logic Controller) system that is autonomously controlling the electro-mechanical parts of the power take-off can be set to record all events to the on-board logger and transmit the status marker to shore. The operational parameter recording system can file all data on board but also transmit the full time series

Since sea trials can be conducted several nautical miles off the coast the telemetry system must be selected based on the distance requirements (radio, GSM, wifi, etc.). If power is tapped off the generation system there should not be problems with battery life but emergency back-up should still be incorporated in the circuitry. For data archiving, synchronised date/time stamps must exist for all the recorded channels.

Digital video cameras are useful

MEASUREMENT SENSORS

For both input and output quantities, sensor redundancy is recommended in particular for the hydrodynamic subsystem, due to the lack of precedence for most measurement cases and the consequently limited confidence in accuracy. Multiple sensors, not necessarily of the same kind, should be provided, on the prime mover, or directly connected components (PTO). Sensors can also be provided elsewhere, e.g. on the reaction frame, or shore-based, such that the motions of the prime mover can be recovered. Independent data acquisition and machine control systems are recommended.

The following sensor types can be of particular use for the identification of the hydrodynamic subsystem, however this should not be a complete list, as different requirements may exist and sensing technologic progress is relatively fast:

<u>Direct Prime Mover Measurements</u>

- Strain-gauging of the prime mover elements (e.g. blade roots for bending moments);
- Load cell on breaking mechanism;
- Thrust dynamometer on the thrust block for axial flow systems;
- Position or displacement sensors (arrays/stacks of proximity sensors);
- Velocity sensors: magnetic/resistive systems using the motion of a magnetic field or the motion of a ferrous material. Can be uni- but preferably multi-directional, and capable of detecting the difference between zero velocity and null signal;
- Accelerometers: an accelerometer pack must be positioned and oriented according to the manufacturers guidelines. Preferably 3-axis accelerometers capable of low-g detection.
- Gyroscopes/inclinometers for angular displacements;
- Displacement measuring interferometers;
- Digital video cameras and optical systems using e.g. painted markers can be used, however light attenuation in the water column must be considered, especially at the infra-red wavelengths associated with “in the dry” optical measurement.
- GPS receiver for positioning (to date precision only for verifying station-keeping, not performance). DGPS combined with accelerometer packs are capable of delivering high spatio-temporal resolution in device position.

<u>Prime mover motion through PTO flow/force/position</u>

- Position and velocity should be monitored in convenient locations on the drivetrain, and be capable of being correlated with prime mover positions/velocity.
- Pressures, volumes and flowrates must also be measured as part of the PTO subsystem, and these too should be capable of being correlated with prime mover positions/velocity.

In addition to the main physical quantities indicated above, the following sensor types may be relevant:

additions to the instrument pack but are bandwidth consuming appliances when streamed to shore (picture quality can be reduced or time lapse photography applied). They may also be placed on a separate transmission system for data safety.

Extreme emergency events, such as drifting off station, power take-off malfunction, grid loss, hull breach or survival mode failure, etc should all be on a potentially separate priority warning circuit.

- Fast response thermometers/thermocouples for water temperature;
- Hygrometers for any “dry” circuits.

Instruments should be located where they can be easily calibrated and replaced during routine maintenance. Particular attention to positioning will be required if the exchange operation is to be performed at sea.

Data Analysis

It is vital for the credibility of the sea trials that the methodologies for data analysis follow common standards and are as transparent as possible. As for the other subsystems, the ultimate aim in both stages S3 and S4 is to populate the scatter diagram with relevant performance data, in order to yield a power matrix for the overall system.

On one hand, sufficient number of measured results must exist, in order to reduce the interpolation errors required to fill the blank blocks. A typical requirement of 3-5 measurements for each tidal occurrence element so that a true representation is obtained. This requirement relates to the variability in power production levels due to different spectral profiles of the tides that can occur. Deliverable 4.2 of the EquiMar project offers a methodology to combine several tidal states in bins for the (likely) cases that not all tidal states can be satisfactorily covered by the sea trial data.

For tidal devices, each data point should have as basis the tidal velocity over a recording period of 5-10 minutes.

Further, a sensitivity analysis is to be performed to establish how many readings are required for a statistically stable result to be generated and what the error bands are. Recommend appropriate techniques for data processing including the generation of summary statistics and estimates of uncertainty

Both time domain and frequency domain analysis techniques are required to investigate and summarise the data from the two phases of sea trials.

One particular difficulty for tidal energy that must be accommodated during detailed analysis, particularly in the time domain, is that the incident energy

DATA PRESENTATION

In order to yield a convincing statement towards technical advisors, investors and other target groups, the processed data must be presented in a clearly understandable and sufficiently commented way, with regard to the target group of the information. In general, it should be expected that two distinctive approaches are required:

(i) Commercially sensitive material for internal consultation;

(ii) Publicly available reports required to promote the device.

The decision on what information will be in which section will be conditioned by the company policy, however naturally the more data and results are published, more credibility can be triggered in the target groups.

Whereas there is no reason to publish the performance and functionality specific to the hydrodynamic subsystem (unless considered relevant for scientific articles), the commercially sensitive material to be prepared for review should include:

- Sea trial log of what proving trials were achieved and of all events requiring intervention, and particular focus on survival-relevant scenarios;
- Full “hydrodynamically absorbed” power matrix with data including estimates of uncertainty (see also Deliverable 4.2);
- Summary results comparisons and eventual design modifications for the prime mover identified during the sea trials

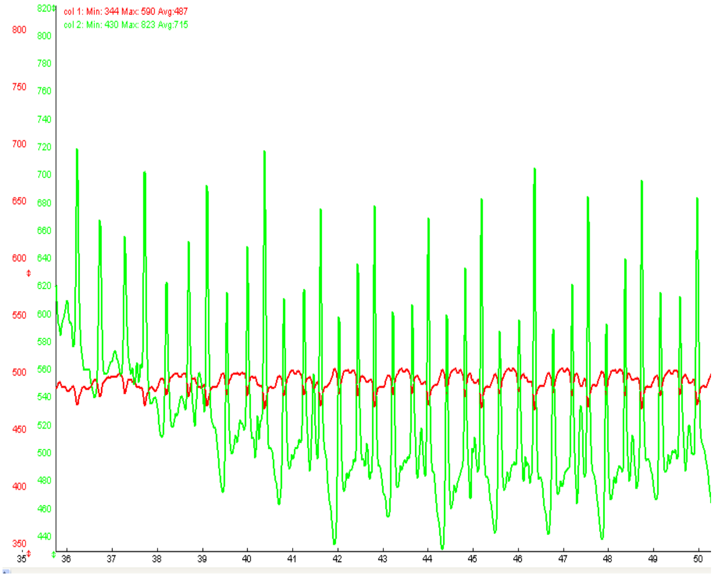
The preferable sea state parameters to be used in the scatter diagrams (hence in the “hydrodynamic power matrix”) are inflow speed at the centroid of the performance area, inflow vector heading, and operating depth according to the overall/general power matrix (input: sea state – output: active electrical power): the size of the cells delimited by the increments on the axes, can be defined as considered relevant for the concept, but as a guide a cell size of 0.1 – 0.2m/s for velocity and 0.5 – 1.0m for water depth and wave height appears reasonable.

In general, tidal device performance will be require averaging, since e.g. turbulence fluctuations in velocity, wave action etc. will produce very variable measured response. Raw data should always be analysed in case averaging removes a signal maximum, due to e.g. slamming. Short duration time series data will allow phenomena to be examined visually, and in particular the device performance response to the mean conditions. An example of this is shown below for the blade loads on a coaxial tidal turbine.

measurements and device responses can not be exactly synchronised because of the spatial separation between the two units. So, even when the two logging clocks are concurrent there will be a delay before the velocities measured by the ADCP appear at the device, at which time there may be a slight change in the velocity due to the multi-frequency mix of a real sea conditions, turbulence and wave interactions. This means full matching from the time history is complex.

To conclude, the two major issues to be addressed in S3 and S4 sea trials are:

- QUALITY assurance;
- UNCERTAINTY assessment.



Example for time domain records of incident blade loads on a rotor operating under different turbulence conditions

Performance from simulated sea trials of a tidal turbine (based on [ref. Bahaj et al 2007] scaled to R = 10m, RPM = 60)												
Environmental parameters					Non-dimensional parameters				Performance parameters			
Zone	U	P_{avail}	Prob	P_{avail}xProb	η	s	n	CI	P	s	CI	P.Prob
	[m/s]	[kW]	[-]	[kW]	[-]	[-]	[-]	[-]	[kW]	[kW]	[kW]	[kW]
1	1	161	0,206	33	0,323	0,223	21641	0,003	52	35,9	0,5	10,7
2	1,5	544	0,157	85	0,435	0,133	16465	0,002	237	72,5	1,1	37,1
3	2	1291	0,107	138	0,419	0,080	11238	0,001	541	103,5	1,9	57,8
4	2,5	2521	0,068	173	0,365	0,045	7204	0,001	919	114,6	2,6	63,0
5	3	4356	0,041	177	0,295	0,022	4284	0,001	1286	95,0	2,8	52,4
6	3,5	6917	0,017	117	0,225	0,009	1776	0,000	1554	63,9	3,0	26,2
Weighted Average		723			0,342	0,106	6	0,106	247	76,7	76,6	
Total			0,595	723								247,1
Yearly Production [MWh/y]									2.166			
Load factor [-] (2,2MW installed capacity)									0,11			

Example for detailed hydrodynamic subsystem (prime mover) performance matrix: available incident wave power and absorbed power by the rotor system of a simulated tidal turbine, for the chosen sea state 'bins' according to Del. 4.2.

Finally it should be mentioned that when results are up-scaled from reduced scale tests, the relevant Similitude Laws should be applied.

Stage Gate Criteria

Device survival and system reliability are important factors that must be considered for the start of a programme. Hull seaworthiness and extreme loads can be monitored and measured in the early stages followed by full systems survival and component reliability from Stage 3 and beyond. Devices should not advance out of a stage until these issues have been fully investigated and any problems resolved.

Two key factors to success during the sea trials with particular relevance to the hydrodynamic subsystem at all stages are:

(i) to design the device incorporating reserve buoyancy that would prevent total flooding or sinking in the event of a hull breach.

(ii) to ensure safety and security of the moorings and anchors even if this requires some built in line redundancy.

Further, the following items should be considered with care when planning and during the S3 and S4 trials, in order to characterise the hydrodynamic subsystem:

- install as many useful sensors as can be technically justified (and afforded);
- ensure inflow measurement is conducted simultaneously with device performance measurement;
- extend the sea trials until all identified operational combinations are covered, in particular survival-relevant sea states;
- ensure that sea states and device dimensions are correctly scaled.

MILESTONES TO PASS STAGES SUCCESSFULLY

Stage 3 – Systems validation stage gate requirements

TRL5 Sub-system Bench Tests;

TRL6 Full-system Sea Trials (scale 1:10 to 1:3)

For the transition between the two TRLs of this trial stage, it is not deemed reasonable to indicate specific requirements, as bench tests are unusual for the hydrodynamic subsystem, and there are no clear generic benchmarks for TRL5. To pass TRL6 and as such from S3 to S4, the following main targets should be met with reference to the hydrodynamic subsystem:

- Physical properties that are not well scaled are analysed and performance figures validated;
- Control strategies and impact on primary power conversion is presented;
- Environmental factors (i.e. the device on the environment and vice-versa) identified, e.g. marine growth, corrosion, windage and drift due to currents;
- Survival conditions, mooring behaviour and hull seaworthiness quantified and verified;
- Manufacturing, deployment, recovery and O&M (component reliability) methodologies defined;

Stage 4 –Device Validation stage gate requirements

TRL7 Prototype Sheltered Site;

TRL8 Prototype Exposed Site

Similar to S3, the first TRL (7) of this sea trial stage is not meaningful with respect to the hydrodynamic subsystem without terminating TRL8. It is rather a transitory phase to check the full system functionality and the generic seaworthiness of the device. The final outcome of S4 with respect to the hydrodynamic subsystem should include:

- Hull seaworthiness and survival strategies;
- Mooring and cable connection issues, including failure modes;
- Component and assembly longevity;
- Absorbed pneumatic/mechanical power (power matrix);
- Application in localised incident conditions;
- Service, maintenance and operational experience [O&M].

Stage 4 is a crucial phase of the development process in particular of tidal energy devices, covering a solo machine pilot plant validation at sea in a scale approaching the final full size (circa 1:1). This stage is a proving programme of designs already established rather than actually experimenting with new options. By end of 2010, scarcely any device can be considered to have overcome this phase.

Power Take Off SUBSYSTEM

Technology Development Stages 3 & 4

PTO

Rationale

The PTO subsystem is responsible for extracting the tidal energy captured by the hydrodynamic sub-system and convert it into electricity. It usually consists of an assembly of several components of different nature (e.g. mechanical, hydraulic, pneumatic, electrical) that have to deal with highly concentrated flows of energy for a wide range of operating conditions. In addition, a control system is required to improve the overall sea to grid energy conversion efficiency.

The Sea trials, throughout their different stages, allow a step by step reality check of the PTO's design and assembly, concerning both its performance and reliability, under the harsh and highly dynamic conditions at which it has to operate. Furthermore, the sea trials should also be used for acquiring the first experiences with manufacturing, installation, operation, servicing and decommissioning of the PTO subsystem. Thus, beside an extensive measurement program, systematic inspection, maintenance and repair of the PTO components are an essential part of the sea trials.

All the information and experience acquired during the sea trials will be extremely valuable to feedback into the design process of the PTO sub-system, in order to further improve its construction, performance, maintainability and reliability.

Objective

The main objectives to perform sea trials with the PTO sub-system are:

- ❍ To evaluate the performance of the PTO's power conversion chain and its power output quality.
- ❍ To evaluate different control strategies to enhance the PTO's performance.
- ❍ To provide sufficient information to validate numerical models of the PTO sub-system for the full range of different operating conditions.
- ❍ To assess the endurance of the PTO components and its overall reliability, when operating in real sea conditions.
- ❍ To acquire experience with the construction, installation, operation and maintenance of the PTO subsystem.

Pre-Sea Trials Requirements

The first step, prior to carrying out the sea trials, is to perform a careful design of the PTO, its control and the data acquisition system. Although performance is an important design aspect, special care should be also given to reliability and maintainability. Neglecting these aspects may lead to long downtimes, data loss and therefore unsuccessful sea trails. The design process should be supported by: a) numerical models of the PTO dynamics, in closed loop with the hydrodynamic and control systems, for the full range of possible operating conditions expected at the test site and b) reliability analysis based on tools like FMECA (Failure Mode, Effects and Criticality Analysis) and FTA (Fault Tree Analysis).

Secondly, with the information and insight provided by the models and reliability analysis, detailed testing and maintenance plans for the sea trials should be developed, as well possible bench tests of the PTO components identified as critical.

KEY ELEMENTS

- ➢ Establish a testing plan with all physical quantities to be measured as well the testing scenarios.
- ➢ Consider reliability and maintainability in the design of both PTO and data acquisition system.
- ➢ Synchronise the time of all data logging systems.
- ➢ Extend sea trials to cover as much as possible the full range of operating conditions.
- ➢ Be prepared to accommodate major re-fit of key components.

IMPORTANT REFERENCES

IEC TC-114	EQUIMAR WP8, Del 4.2
IEA-OES-IA Annex II	Carbon Trust 2005: "Guidelines on design of WEC"

Development Stages

As stated in the introduction and other sections of this document the solo device sea trial stages (S3 & S4) of a wave energy converter development covers a wide scope. Devices must progress from the pre-prototype scale (circa 1:4) ***systems*** proving units, through ***pre-production*** full scale design and on to a ***pre-commercial*** machines ready to be certified as fit-for-purpose and small array deployment.

This progressive increase of the testing scales reduces both the technical and financial risk that would be required if the device development went straight from laboratory scale model to a full size prototype deployed at an exposed ocean location.

Development Stages S3 and S4

Stage S3 - ≈ 1:4 scale model of MCT (top photo: Marine Current Turbine Ltd) and Stage S4 – full scale Atlantis prototype (Bottom photo:Atlantis Resource Corp.)

The primary factor common throughout sea trials is that the tests have moved from the controllable and comfortable surroundings of an indoor facility where currents can be generated on demand, to the natural outdoors

TEST PROGRAMMES

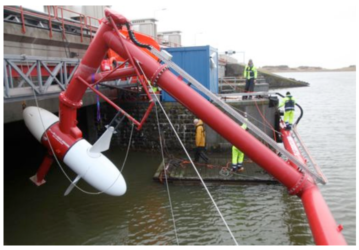
There are two stages covered in the Sea Trial section of a device development schedule, each of which is further subdivided into two phases. These are:

Stage	Section	TRL	Timetable
S3	Sub-system Bench Tests	5	6-12 months
	Full-system Sea Trials	6	6-18 months
S4	Prototype Sheltered Site	7	1-2 years
	Prototype Exposed Site	8	1-5 years

For each phase of the sea trials, the priorities can be different:

- **Sub-System Bench Tests:** Prior moving to the sea trials, various components (or all) of the PTO subsystem could be subject to bench tests. This could e.g. be a PTO component subjected to an accelerated fatigue test, test of auxiliary systems (pumps, valves, etc.) or tests of the full power chain conversion in closed control loop.

- **Full-System Sea Trials:** Although at a large size (typically 1:4), rather than full size, these trials represent the first time the device will be in a real sea environment and equipped with a fully operational electricity generating PTO. At this phase, the PTO subsystem will have to handle relatively small power levels (typically less than a few hundreds kW). Grid connection may therefore not be a technical necessity and will depend mainly on its accessibility and cost. Focus is given to the PTO's performance evaluation with different control laws. First insights on the PTO's construction, installation, operation and maintenance will be also experienced.



≈ 1:2 Scale (250kW) OpenHydro Prototype offshore Orkney, Scotland (Left photo: OpenHydro Ltd) and 1:4 Scale (30kW) Tocardo prototype at the Afsluitdijk sea barrier, The Netherlands (Right photo: Tocardo Inter. BV*)*

- **Prototype Sheltered Site:** following Stage 3 it is expected that a full, or approximately full, size prototype device will be constructed for sea trials. The power levels of the PTO sub-system will now range from several hundreds of kW to a few MW. It could be anticipated that a shake-down period to prove the component, assemblies, manufacturing quality and instrumentation would be conducted at a station with a less aggressive climate that the final destination. This option is made more possible if a fully certified grid emulator is utilized instead an actual grid connection. This would negate the requirement of a subsea cable for grid connection and open up more nursery sites. Prior to the offshore launch accepted as they occur and test programmes adjusted to suit.

OpenHydro Prototype at Orkney, Scotland (Photo: OpenHydro Ltd)

Another important feature of the sea trials is that the larger scale at which the tests are now conducted, compared to the ones of the previous stages (S1-S2), enables the installation of realistic and fully operational PTO sub-systems in the devices.

Thus, sea trials will not only allow to test the performance and reliability of the PTO sub-systems in realistic conditions but also to acquire experience with all the aspects related to its manufacture, installation, operation and maintenance.

The level of detail of the data regarding the PTO subsystem required at the different stages will vary although the underlying mantra should always be to gather as much data as practically possible.

of the device, tests on the PTO and auxiliary systems (e.g. brakes, instrumentation and controls) should be conducted to assure their operability. If feasible, the PTO system should be driven by the best power input available. This may be limited for large machines (>500kW) but fundamentals can still be verified at low speeds.

- **Prototype Exposed Site:** once the operator is confident the pilot plant is functioning acceptably it should be transferred to a location with similar conditions to those expected at a typical power park and grid connected. The sea trials are now specifically for proving rather than modification, so deployment should be for an extended duration to facilitate component lifecycle verification, full range performance verification and survival diagnosis. More focus is now given to condition monitoring of the PTO sub-system in contrast than at stage S3. Data for both operational and extreme conditions are here anticipated. However, extreme design conditions are not likely to be experienced during the early tests and an important element will be the extrapolation of measured peak loadings and corresponding responses to design levels. This should include calibration/validation of numerical models.

Full Scale (1.2MW) SeaGen prototype at Strangford Lough,Ireland (Photo: Marine Current Turbine Ltd*)*

Data Acquisition

One of the main objectives of the sea trials is to acquire information on the PTO performance and reliability, in realistic sea conditions. Data acquisition is the first step required to obtain this information, which can be done both automatically and manually.

Although the cost of obtaining data during sea trials is high, the price for not monitoring well all variables will be higher. Therefore data quality, reliability and maintainability of the data acquisition system are vital aspects that should be taken seriously into account in its design.

Automatic Data Acquisition

Automatic data acquisition can be performed by a variety of systems that range from specific sensors with dedicated data loggers to full SCADA systems. During the sea trials, different systems may be installed at quite separate locations like the sea (e.g. wave buoy), on-board of the device (e.g. PTO sub-system) and at land (e.g. grid connection). Experience has shown that the more separate systems are used, the higher the problems in data integration and synchronization.

The following aspects should be given a special attention:

❍ **Sensors** correspond to the first step of the data acquisition process and should be therefore carefully selected, in particular their accuracy, range and bandwidth. Improper choice of one of these aspects may lead to poor data quality (e.g. low resolution, saturated signals, filtered transients). The index of protection (IP) of the sensors should be chosen in accordance to the environmental conditions at which they have to operate. Improper protection may result in early failure of the sensor.

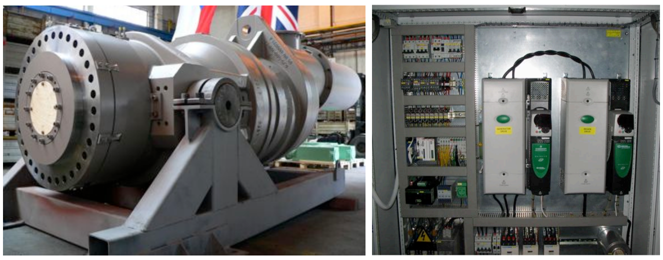
The sensors should be installed

MONITORING PARAMETERS

The PTO sub-system consists generally of an assembly of different components, like **hydraulic** (e.g. rams, hydraulic units), **pneumatic** (e.g. compressors, valves), **mechanical** (e.g. bearings, gearboxes, brakes) and **electrical** (e.g. generators, power electronics, control systems, etc). While many components are off the shelf, others are specially designed and custom made. A few examples of typical PTO components used in marine energy devices are shown below.

Seagen 600kW Induction Generator (left photo: Marine Current Turbine Ltd) and Tocardo 30kW PM Generator (right photo: Tocardo Inter. B.V.)

PTO Brake and corresponding Pneumatic Auxiliary Unit (Photo: Tocardo International B.V.)



Seagen 1.2MW Gearbox (left photo: NKE Austria GmbH) and Tocardo – 45kVA AC/AC Converter (right photo: Tocardo Inter. B.V.)

Each PTO component will have its specific monitoring parameters that depend on its nature and stage of development. Hence, the set of parameters to monitor the complete PTO sub-system, during the sea trials, will be highly device dependent. However, the monitoring parameters should in general cover the following aspects:

- **Model Validation**: To calibrate the numerical model of the PTO sub-system, it's necessary to obtain times series from its inputs, outputs and state variables. Depending on in accessible locations to facilitate maintenance or repair actions, while locations with high noise level should be avoided (e.g. installing pressure or flow sensors at locations where high turbulence is expected).

Cabling and grounding are also key aspects for noise reduction. Instrumentation cables should be properly shielded, grounded and installed far from strong electro-magnetic field sources (e.g. power cables and power electronics).

❍ **Data Logging** should in general happen close-by the sensors to assure that data will not be lost due to communication failure. When a reliable communication system is available, remote data logging at shore could be considered as an option.

Time stamping of recorded data should be based on a real time clock. Since different logging systems may coexist during the sea trials, it's crucial to assure time synchronization among them in order to correlate the different data sets or at least to keep track of the time shifts between the clocks of the different data logging systems.

❍ **Data Redundancy** should be implemented both at the data collection and data storage level. The first can be achieved by direct sensor duplication or by the use of other sensors from which the desired measurements can be derived (e.g. position can be obtained by integration of velocity with reset by a position switch). The second may be achieved by periodic automatic data backups done locally at each data logging system (e.g in separate hard disks) or centrally, at shore, in a redundant data storage unit (if a reliable data transmission is available).

❍ **Power Supply** of the automatic data acquisition systems should be reliable and guarantee the continuity of its operation, even if the PTO is not producing power. In absence of a cable

the PTO components, the variables can be for example:

- *Hydraulic/Pneumatic Components*: pressure, temperature, flow rate (mass and/or volumetric) and fluid level;
- *Linear Mechanical components*: force, displacement, velocity and acceleration;
- *Rotational Mechanical Components*: torque, angular displacement, angular velocity and angular acceleration;
- *Electrical Components*: voltage and current;

These monitoring parameters allow not only to identify the parameters of the PTO's numerical model (e.g. inertia, damping, stiffness) but also to directly evaluate the loadings, motions and the power conversion performance of the PTO sub-system. The power level at each energy conversion step can be obtained from the product of the stresses (e.g. pressure, torque, voltage) with the corresponding motions (e.g. flow, angular velocity, current).

- **Condition Monitoring**: A multitude of different phenomena like corrosion, wearing, misalignments, fatigue and fouling can degrade and eventually cause failure of the PTO subsystem. To evaluate the reliability of the PTO sub-system it's therefore of vital importance to monitor the condition of its components and assembly. This can be done automatically on-line or manually during maintenance visits. Typical examples of condition monitoring parameters acquired automatically are:
  - *temperature* (e.g. generator coils, bearings),
  - *vibration* (e.g. bearings, gearboxes),
  - *oil particle distribution and moisture* (e.g. hydraulic units, lubrication units),
  - *strains* (e.g. shaft, blades),
  - *motor current analysis* (e.g. generator, motors).

  Corrosion and fouling are on the other hand typical examples of condition monitoring parameters obtained manually by visual inspection.

- **Internal PTO Environment**: Certain parts (or all) of the PTO-subsystem are installed inside a protective case due to limitations of their operating environmental conditions. During the sea trials, these environmental conditions like e.g. temperature, humidity or pressure should be monitored to check if the protective case is performing its function well. Abnormal values of these variables are good indicators of problems like leakages, bad heat dissipation or water condensation that could potentially lead to PTO failure.

- **Power Output Quality**: The ideal voltage output of an electricity generating PTO would be a three phase balanced sinusoidal signal, with constant frequency and amplitude. Deviations from this reference should be connection to the shore, a battery pack with sufficient capacity and possibly alternative charging options should be considered.

Manual Data Acquisition

Although automatic data acquisition systems allow collection and storage of large quantities of data at rates that would be virtually impossible to acquire manually, they're not able to collect all the relevant information to fully describe the sea trials. This additional information must be collected manually by human operators, that follow all the activities related to the sea trials, and consists generally of:

- ***Ongoing activities*** (e.g. type of test, maintenance or repair actions);
- ***Singular events*** (e.g. storm, component failures, accidents);
- ***Changes of configuration*** (e.g. PTO layout, settings, sensors, control law and gains).
- ***Condition monitoring*** (e.g. oil samples for lab analysis, visual inspection of PTO components, corrosion, leakages, fouling).

In the process of data collection, it's very useful if human operators are also able to make a correct interpretation of their observations, by using their critical sense and expert knowledge, in order to detect false alarms and correctly identify failures.

During the trial programme, all the information manually acquired should be diligently recorded on a daily basis in a logbook, together with other relevant SCADA or met-ocean data that could be useful, to give a complete account of the sea trials.

This information will be very valuable to understand the context in which the measurements were conducted and therefore vital to interpret them correctly at a later stage.

monitored by tracking for e.g. the variations in the RMS value and frequency of the voltage, voltage harmonic content and phase unbalance.

- **Operational Status and Settings**: The PTO sub-system is usually supported by a set of auxiliary systems like e.g. Brakes, Cooling, Hydraulic Units, Control System. The operational status and settings of these systems (e.g. Pump on/off/tripped, Valve position/tripped, Circuit breaker on/off, Controller setpoints and gains) should be monitored for the following reasons:
  - allows the human operator to access the operational status of the PTO sub-system during the sea trials. In case of failure detection, the corresponding corrective maintenance actions can be triggered;
  - it helps to contextualize the measured data at the later stage of data analysis (model calibration, performance analysis, etc.),
  - allows to perform reliability analysis based on the failure records.

Data Analysis

Data Analysis is the process of extracting useful information from the large quantities of raw data acquired during the sea trials. The correctness of the extracted information directly depends on the quality of the data and the data processing methods to compute the information. Therefore, the first step of data analysis consists of the selection of raw data sets with good enough quality for further processing. On the other hand, the data processing methodologies used for information extraction should be based on solid scientific principles and follow common standards. These methods can be based both on time and frequency domain analysis techniques applied to signals and/or systems.

It may happen that during the sea trials not enough quality data is acquired to fully cover all possible testing conditions. Information that cannot be obtained directly from the missing data, can still be estimated from the remaining data by extrapolation and interpolation methods (both function or model based) but of course with smaller accuracies.

Data Selection

The Data selection should in general take into account the following aspects:

❍ **Noise Level** should be low compared to the signal level (i.e. high SNR-signal to noise ratio). Noise with spectral content located outside the signal frequency range of interest can be filtered out with linear band-stop filters. On the other hand, gross outliers are more effectively removed, without significant signal distortion, by the use of non-linear filters (e.g. median filter).

❍ **Sampling rates** should be high enough to capture the fastest transients of interest. For high

DATA PRESENTATION

All the information and experience gathered during the sea trials is hard won and represents a substantial part of the developer's knowledge capital. It's therefore very important that all this knowledge is well documented, so maximum benefit can be derived from it for different uses like:

- **Internal consultation**, for information sharing within the developer's organization;
- **Investors due diligences**, by presenting clear and sound information that allows potential investors to perform correctly the risk assessment of their investment.
- **Device promotion**, through brochures, publicly available reports or scientific publications.

In general, at each phase of the sea trials, documentation should be produced covering the following different aspects:

Commissioning

- **Data acquisition systems reports**, which should include P&I diagrams, instrumentation and data acquisition electronics data sheets and calibration information of all instrumentation.
- **Control system reports,** with detail description of the different control loops (e.g. block diagrams, control laws, settings) and preliminary performance measurements.
- **PTO report**, with detail description of PTO components and auxiliary systems, measurements of design variables (e.g. electric isolation levels generator windings, oil pressure, vibration levels) and test results on its operability in the different modes (e.g. normal, standby, emergency stop).

Operation

- **Periodic reports**, with summary statistics of data quality, power production level, alarms, PTO downtime, etc.. These reports can be automatically generated by the SCADA system and provide to the developer a quick overview and a periodic update of how the sea trials are progressing.
- **Data quality check reports**, with detailed analysis of the acquired raw data quality covering aspects like sensor availability, signal coherence, noise characterization and filtering. Along the sea trials, changes in these characteristics may occur and should be promptly detected and corrected. Data selection for further processing should be well justified, with bad

sampling rates, irregularities in the sampling periods can be still corrected by interpolating the signals at the desired time instants. However long sampling periods will lead to irreversible data loss.

- **Data coherence** of directly physically related measurements should be high. This can be tested by comparing measurements of duplicate sensors or of different sensors related to each other through a more complex form (e.g. velocity is the time derivative of position). A measurement with a low signal coherence with other related measurements is a strong indication of low data quality (e.g. sensor offset or damage).

Nevertheless, even incomplete data is a valuable commodity and should be archived as future analysis may possibly yield some benefit.

Data Processing

Not all information of interest can be directly measured and therefore some level of data processing is required to extract the desired information from the measured data. The complexity of the data processing can range from a simple arithmetic operation to high order non-linear regression. The information of interest to extract during the sea trials consists generally of:

- **PTO Performance** of its power conversion chain. At each energy conversion step, the power signals can be obtained from the product of the stresses and flows signals (if no direct measurement is available). This will allow the calculation of the energy conversion efficiency along the complete power train. Due to their high variability, summary statistics (e.g. average, std, max, min) should be computed for fixed periods of time, under which the sea resource can be considered stationary. This process should be

data sets properly identified.

- **Data analysis reports**, covering separately topics like Power Production Performance, Control performance, Power Output Quality, Model Calibration/Validation, Condition Monitoring and Reliability. For all presented results, a clear description of their accuracy as well the raw data sets and processing methodologies used to obtain them should be made. Missing data and non-proven results should be also identified.
- **Servicing reports**, with detailed account of the maintenance and repair actions, failure identification and changes in the PTO configuration.

Demobilisation

- **Inspection report**, with detailed description of the observations made of all dismantled PTO components, with identification of developing faults (e.g. corrosion, wearing) and other reliability aspects.

After the sea trials, it's also useful if a ***final report*** is made with the overall conclusions of the trials and recommendations for further improvements of PTO sub-system, regarding its performance, maintainability and reliability. **Proven and non-proven results should be clearly identified.**

The quality of the produced documentation can be improved if the following general aspects are taken into account:

- **Document Referencing System**, should be defined prior to the sea trials. It will highly valuable for cross referencing the large number of documents expected to be produced during the complete sea trials.
- **Test phase, objectives, authors and version** of each document should be clearly identified.
- **Context information**, under which the tests occur should be provided in the documentation, since it contributes for a better interpretation and understanding of the presented results. For this purpose it's important that document production **runs parallel** with the sea trials, since risk of loosing some valuable context information is highly reduced.

Some practical examples of data presentation from sea trials are shown below.

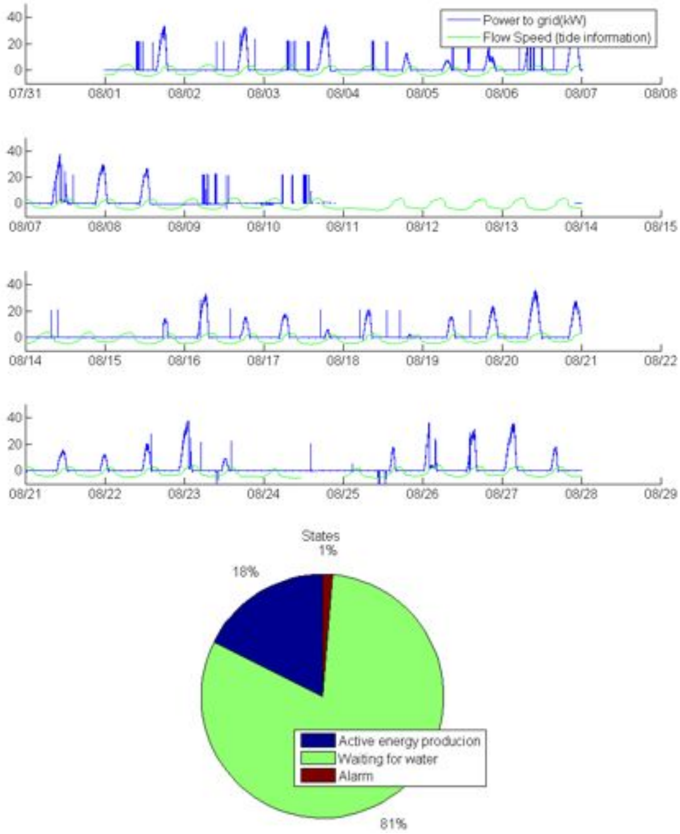
repeated for all available different measured sea conditions, see EQUIMAR Deliverable 4.2 for more details. For each PTO performance evaluation, the control law and settings should be kept fixed.

❍ **Control Performance** of the existing control loops in the PTO sub-system. For regulators, typically the control performance is characterized by the band-width (time-response), overshot and static error of the closed loop system response. This information can be obtained both in time and frequency domain by looking into the time series of the setpoints and controlled variables or at the closed loop transfer function (from setpoint to controlled variable). This analysis should be done for different operating conditions to check the control performance robustness.

❍ **Power Quality Output**. Similarly as done for the PTO performance characterization, sum mary statistics of the different measured power quality indicators (e.g. variations in the RMS value and frequency of the voltage, voltage harmonic content) should be computed for the different sea conditions and control settings.

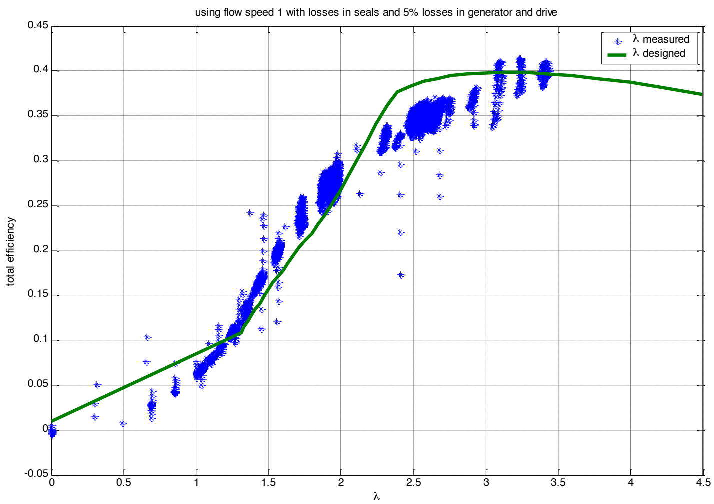
❍ **PTO model parameters** for calibration purposes. The estimation of the models parameters should be based on standard system identification techniques with input-output data sets (calibration data set) that cover as much as possible the full range of operating conditions. To simplify this process, it's recommend to perform separately system identification of the sub-models individually rather than of the complete PTO model. This will however require more input-output data available. The calibrated models should be checked by comparing measurements and model outputs, both in time and frequency domain, using a different data set (validation data

Periodic Operation Report - Example



One month time series of power output and water speed with summary statistics of the device operating status - Tocardo tests at the Afsluitdijk sea barrier, The Netherlands, 2010 (Courtesy: Tocardo International B.V.)

Power Conversion Performance - Examples

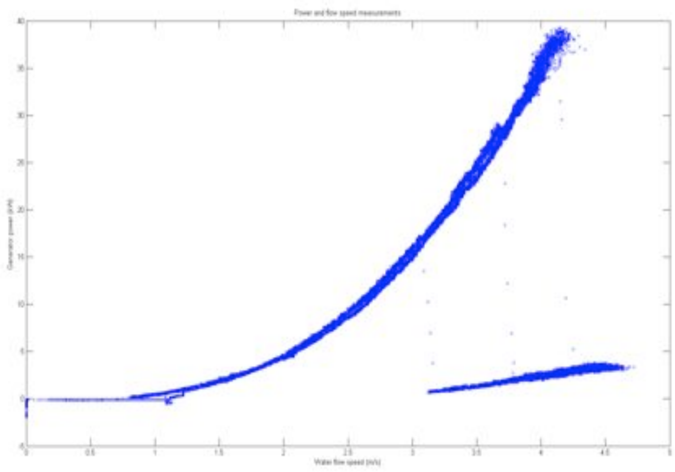


Adimensional performance curve:Power coefficient (Cp) versus tip speed ratio (λ) - Tocardo tests at the Afsluitdijk sea barrier, The Netherlands, 2005 (Courtesy: Tocardo International B.V.)

set). A well calibrated PTO model is a valuable tool for supporting the design process and performance estimation.

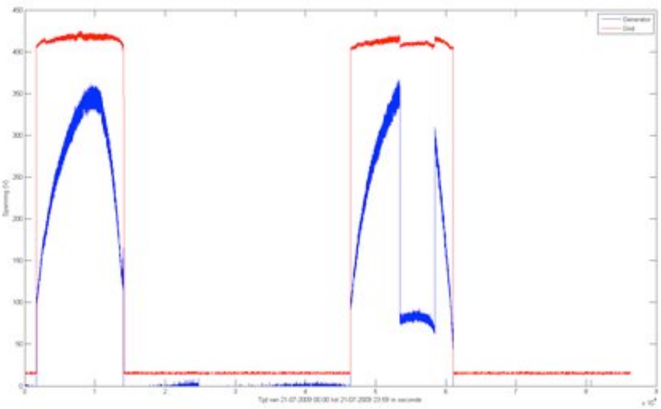
❍ **Detection of Developing Faults** for condition monitoring purposes. Feature extraction for fault diagnosis should be investigated, based on system analysis approach due to its robustness to changes in the operating conditions. For this purpose, models of the PTO sub-systems should be developed and trend analysis of the models residuals or parameters should be performed to check its applicability for early fault detection. An early detection of developing faults allows the implementation of condition based maintenance, which may significantly reduce the downtime of the device and therefore improve its economics.

❍ **Failure Rates and Modes** are essential for reliability evaluation. From the SCADA database and logbook important data related to system and component reliability (e.g. failures, downtime, repair actions, corrosion) can be used to perform statistics on the failure modes that occurred during the sea trials and also the corresponding probabilities. Due to the limited time period of the sea trials, not all possible failures will occur and therefore it be will in general difficult to acquire enough data to fully characterize the reliability of the device. During the demobilisation phase of the sea trials, careful visual inspection of the internal parts of the dismantled PTO components, may provide additional valuable information on not detected failure modes in development (e.g. sealing wearing, corrosion of electrical connections).



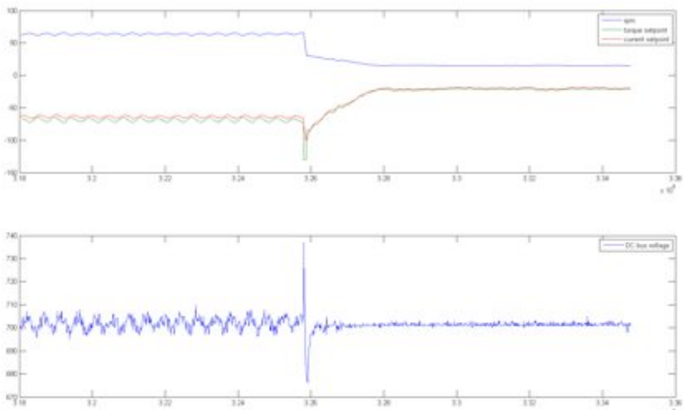
Performance Curve: Output power versus water speed for both normal and stall operation mode - Tocardo tests at the Afsluitdijk sea barrier, The Netherlands 2009 *(Courtesy: Tocardo International B.V.)*

Power Output Quality - Example



A full day time series of the RMS voltage on the generator side (blue line) and grid side (red line) of the AC/AC converter - Tocardo tests at Afsluitdijk sea barrier, The Netherlands, 2009 (Courtesy: Tocardo Inter. B.V.)

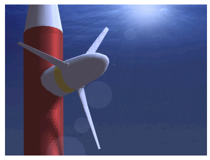
Control System Performance - Example



Time series with response of the torque control system to a change from normal to stall operation mode (Top graphic: rpm, measured torque and torque setpoint; Bottom graphic: converter DC bus voltage) - Tocardo tests at Afsluitdijk sea barrier, The Netherlands, 2009 (Courtesy: Tocardo Inter. BV)

Reaction SUBSYSTEM

Technology Development Stages 3 & 4



Moorings

Rationale

Information on the response of the reaction subsystem during sea trials should be regarded as an essential requirement. This subsystem considers all support structure, including rigid foundations, anchoring and mooring arrangements when suitable, and the structural elements of the device itself.

The level of detail necessary, however, can be adjusted to suit the stage of the tests. Of specific interest is the response of the device in terms of forces and motions of the device in the sea, focusing in the extreme conditions (Ultimate Limit State), as the main concern here is the seaworthiness and station keeping capability of the device. Prolonged exposure to strong currents and in particular cyclic loading due to turbulence may impact upon the lifespan of structural members of the system through fatigue. Any part positioned close to, or above, the surface will also be required to withstand additional wind and wave loading.

Additionality, e.g. in terms of observations and experiences related to marine growth / anti-fouling and corrosion protection can prove to be valuable for future development.

Finally the structural responses measured during sea trials are of significant value for the validation/calibration of numerical models describing the structure's response to the incident resource.

Objective

There are several reasons for obtaining accurate measurements in the Reaction Subsystem at each particular test site. The main reasons are:

- To evaluate the station keeping ability of the device.
- To provide information on loadings on three different levels.
    - Global loads.
    - Cross sectional forces / internal stresses.
    - Local loads.
- To provide data for device evaluation in the various limit states – Ultimate, Accidental, Fatigue and Serviceability.
- To asses the influence of the reaction subsystem on the energy yields.
- To assess the endurance of mooring components
- To assess performance of foundations / fixing to seabed.
- To provide sufficient information to validate numerical model of structure's reaction to incident resource

Pre-Sea Trials Requirements

Prior to carrying out any sea trials a design of the reaction subsystem components needs to be carried out for the intended deployment site. For this, met-ocean data needs to be obtained prior to deployment of the device. This includes both operational and extreme conditions. If the device is bottom mounted, geotechnical data is required to inform e.g. pile drilling. Once the structure and the mooring arrangements have been designed the expected characteristics should be known. This includes the mooring characteristics in terms of force-displacement relations, dynamic response functions in all relevant DOFs for the body etc. The device should be instrumented to enable acquisition of the relevant data to verify the design.

Furthermore, the sea trials should be used for acquiring the first experiences with O&M of the reaction subsystem. Thus, systematic in-service inspection, maintenance and repair of reaction components are essential.

KEY ELEMENTS

- Establish the correct monitoring duration and acquisition rate for each specific test programme
- Ensure the measuring instrument has sufficient resolution and range to handle the conditions that will be encountered.
- Ensure the instruments are not structurally the 'weakest link'.
- Consider how to extrapolate measured data to events with longer return periods than events encountered during the sea trials.
- Synchronise the time of all acquisition systems

IMPORTANT REFERENCES

EquiMar WP2 & WP8	IEC TC-114: Assessment of Mooring systems for MECs
IEA-OES-IA Annex II	API-RP-2FP1

Development Stages

As stated in the introduction and other sections of this document the solo device sea trial stages (S3 & S4) of a tidal energy converter development covers a wide scope. Devices must progress from the pre-prototype scale (circa 1:4) ***systems*** proving units, through ***pre-production*** full scale design and on to a ***pre-commercial*** machines ready to be certified as fit-for-purpose and small array deployment.

The primary factor common throughout sea trials is that the tests have moved from the controllable and comfortable surroundings of an indoor facility where conditions can be generated on demand, to the natural outdoors were test conditions have to be accepted as they occur and test programmes adjusted to suit.

Prototype at sea in energetic conditions

The level of detail of the data regarding the reaction subsystem required at the different stages will vary although the underlying mantra should always be to gather as much data as is practically possible.

One factor will be of major importance, and that is the fact that the device most probably will not be exposed to the extreme events for which it has to be designed within the first years of testing. This means that with regard to comparison to design data, extrapolation will be needed. For this, calibration/validation against numerical models and previous (or parallel) laboratory testing will be of significant importance.

TEST PROGRAMMES

There are two Stages covered in the Sea Trial section of a device development schedule, each of which is further subdivided into two phases. These are:

Stage	Section	TRL	Timetable
S3	Sub-system Bench Tests	5	6-12 months
	Full-system Sea Trials	6	6-18 months
S4	Prototype Sheltered Site	7	1-2 years
	Prototype Exposed Site	8	1-5 years

The minimum details of data required at each of the stages can be different without diluting the stages trials too much, although it should again be emphasised that the more data gathered at all times the better.

- **Sub-System Bench Tests:** Various components of the reaction subsystem_could be subject bench tests. This could e.g. be a mooring component subjected to an accelerated fatigue test.

- **Full-System Sea Trials:** Although at a large, rather than full size, these trials represent the first time the device has been in a real sea environment. At this stage often the structural dimensions and e.g. the mooring design will not be directly scalable compared to the intended full scale device. Main focus is therefore on ensuring similitude with full scale, e.g. the mooring system might not resemble the final layout, but its response in terms of force-displacement characteristics should. Depending on choice of device size and test location, loading tests could be accelerated, e.g. if the device is sized smaller than that which a direct scaling based on prevailing environmental conditions would dictate.

- **Prototype Sheltered Site:** Following Stage 3 it is expected that a full, or approximately full, size prototype device will be constructed for sea trials. It could be anticipated that a shake-down period to prove the component, assemblies, manufacturing quality and instrumentation would be conducted at a station with a less aggressive climate that the final destination. At this step extreme conditions are not likely to occur and the main focus regarding the reaction subsystem will be on fatigue conditions.

- **Prototype Exposed Site:** Once the operator is confident the pilot plant is functioning acceptably it should be transferred to a location with similar conditions to those expected at a typical power park. The sea trials are now specifically for proving rather than modification, so deployment should be for an extended duration to facilitate component lifecycle verification, full range performance verification and survival diagnosis. Here, data for both operational and extreme conditions are anticipated. However, design conditions are not likely to be experienced during the early tests, and an important element will be the extrapolation of measured loadings and responses to design levels. This should include calibration/validation of numerical models.

Data Acquisition

Acquisition of data for the reaction subsystem is normally integrated in the overall data acquisition system on board the device. Normally, the system will be setup to handle various types of input, but often voltage or current signals are primary types. Thus, for signals coming from strain gauges, or strain gauge based instruments such as force transducers and pressure cells, a pre-amplification prior to the data acquisition is necessary. Other instruments will by default deliver the signals as voltages in relevant measuring ranges (e.g. +/- 10 V). However, yet other measuring devices, e.g. "all-in-one" 6 DOF and GPS tracking systems, will deliver the measurements in digital form using some standard (or even non-standard) communication protocol (e.g. RS-485). In this case the data might not even be available with equal time intervals, which makes further pre-conditioning of the measure time series necessary prior to performance of the data analysis.

Another element of 'data acquisition' is registrations from inspections, and any observations must be recorded in a log.

MONITORING PARAMETERS

For evaluation of loadings of the reaction subsystem a variety of sensors have to be deployed to enable measurements on three different levels:

- **Global forces.** Typically, if the device uses mooring lines as a station keeping system, these forces can be measured using load cells / shackles at the attachment points of the moorings on the device. Hereby the resulting total forces on the structure that the mooring system has to withstand can be established. If a rigid structure is employed, thrust measurements of the device can be used to calculate these forces.
- **Cross sectional forces / stress/strain levels.** For the overall structural design it is valuable to record measurements of strains/stresses in selected cross sections of the structure. This will typically be obtained through deployment of strain gauges. These should be deployed at carefully selected locations, which typically can represent the most loaded points of the structure. The strain gauge measurements can either be used for direct calculation of cross sectional forces and moment (in case of a well defined stress distribution) or used for validation of FEM based calculations. In any case it is important to consider what type of strain gauges to deploy. In case of a well defined stress distribution unidirectional strain gauges might be sufficient, but in more complex situations rosette type strain gauges should be deployed, as such gauges can supply all the stress components in the plane.
- **Local pressures.** For design of local structural details, check of numerical simulations etc. it can be valuable to investigate, for example localized pressures at the base of the structure. This can be done by deployment of pressure transducers in the areas of interest.

Evaluation of the response of the reaction subsystem normally includes measurement of absolute and/or relative displacements in the relevant degrees of freedom. This aims to evaluate the station keeping ability of the device. The types of sensors relevant for these measurements include motion sensors, such as accelerometers, compass, and position sensors, often based on GPS. Recently, tailor made "all-in-on" systems, able to track 6 DOF motions assisted by GPS tracking, have become available.

The environmental loads acting on the structure supported by the reaction subsystem are generally made up of contributions from wind, current and waves. If the structure is pile mounted the dominant force will be that of the current. Monitoring at the foundations and throughout the pile will be necessary to assess the vibration and displacements on the column. Gravity based foundations should be monitored in a similar way to ensure reasonable distribution of loads throughout members. If the structure is floating, the wave forces acting on the structure can generally be divided into constant and varying wave drift loads (second order loads) and first order wave loads. Normally, the wind, current and constant wave drift loads will determine the mean position of the floating structure. The varying wave drift force and the first order wave loads results in oscillations around the mean position. The relative magnitude of the oscillations due to varying drift forces and first order wave loads depends on the characteristics of the mooring system. If the system is stiff, the first order response will dominate, while if the is system is compliant (i.e. the natural period of the system is long compared to the wave periods) the varying wave drift response will dominate. It is normal practice to aim for a compliant system when designing floating structures, to limit the design forces to be handled by the mooring system.

When monitoring the reaction subsystem it is important to identify the situation for the device under investigation, and decide on instruments, ratings, acquisition rates etc. accordingly, so that all of the relevant features of the different components can be captured. For example, if measuring the vibrations present in a pile foundation, sensitive vibrational wire gauges can be used.

Finally, systematic visual inspection, supplemented with other inspection methods when necessary, of the structural components should be a part of the monitoring program. Subjects for inspection should include marine growth, degradation due to corrosion, fatigue accelerated corrosion, wear and tear, state of anti-fouling and corrosion protection measures, etc.

Long term considerations should focus on the interaction between the supporting structure and the seabed - scour, sand-waves etc. and the effects of biofouling on the submerged structure, especially with respect to alteration of existing or introduction of new resonant or natural frequencies.

Data Acquisition

When setting up the data acquisition an important part is the decision on the sampling rate. A number of considerations should be made regarding this. The sampling rate should be selected so the time resolution is sufficient for capturing the physical phenomena being measured. Many of the signals can be sampled using a sampling as for measuring the wave elevations. Typically, the sample rate should be twice that of the relevant frequencies expected, in accordance with basic signal processing theory (the Nyquist frequency). For devices with flexible moorings, snapping, slamming or similar can occur, and significantly higher samples rate will be needed (>100 Hz). As it will generate enormous amounts of useless data to sample continuously at these high rates, triggered sampling can be adopted, leading to the high rate data sampling only being stored if high frequency peaks occurs in the signals.

SENSORS AND DATA ANALYSIS

Load cells / shackles in mooring lines.

From load cells / shackles in mooring lines time series of the in-line force will be recorded. In the analysis of such data statistical parameters should be derived. Here, for each recorded time series F(t), local maxima (and possibly minima) should be identified, and the statistical distribution plotted. Characteristic statistical time domain parameters, such as the average of F, standard deviation of F, $F_{1/250}$, should be derived. In addition to analysis of the individual force time series, resulting forces and moments might be established by combining the individual time series, and these can then be analysed correspondingly. Transfer functions in the frequency domain (ratio between force and environmental (wave) spectra) can be established by combining results from multiple records.

Strain gauges / rosettes.

From measured time series of stresses, measured in the structure for sectional forces and moments and FEM calibration, various analyses can be carried out. In the case of well defined stress distribution and properly distributed strain gauges, time series' of selected cross sectional forces can be calculated. In case of more complex stress conditions at the measuring point, measurements from a rosette type gauge can be used to calculate time series of principal stresses or von Mises stresses. Then, based on the calculated time series of key forces F (or stresses), for each time series the local maxima and minima should be identified and plotted. Characteristic statistical time domain parameters, such as average of F, st. dev. of F, $F_{1/250}$, should be derived. Transfer functions in the frequency domain (ratio between stresses / forces and environmental (wave) spectra) can be established by combining results from multiple records.

Pressure cells.

From measured time series' of pressures various analyses can be carried out. In case well defined pressure distribution and properly distributed pressure cells, time series of selected forces acting on the structure can be calculated. Then, based on the calculated time series of key forces F (or pressures), for each time series the local maxima and minima should be identified and plotted. Characteristic statistical time domain parameters, such as average of F, st. dev. of F, $F_{1/250}$, should be derived. Transfer functions in the frequency domain (ratio between pressures / forces and environmental (wave)_spectra) can be established by combining results from multiple records.

Motion / position sensors.

Depending on the method of measuring motions and positions, the measured time series might have to be (double) integrated (e.g. going from an acceleration time series to a displacement) or otherwise pre-conditioned. The analysis of motions /

positions of the various DOF will generally include both time and frequency domain analysis. For time series demonstrating the influence of wave interactions, a zero up or down crossing analysis should be performed and their distributions (e.g. 'wave heights') should be plotted. Characteristic statistical parameters, such as average, st. dev., selected fractions (such 1/3 and 1/250) should be derived. Transfer functions in the frequency domain (ratio motions in the individual DOFs and environmental (e.g. wave or turbulance) spectra) can be established by combining results from multiple records.

Data Analysis

Whilst significant analysis must be devoted to tidal current responses, the primary fatigue load for any surface piercing structure or tethered device is likely to be wave induced. This is in part due to the irregular nature of waves relative to tidal currents, which are highly predictable with appropriate location data.

The duration of the individual recorded time series is an issue which should be considered. There are a number of items which pull in opposite directions when the duration of the individual recorded time series is decided. In principle, it is desirable to have long time series consisting of a large amount of waves (thousands) in order to have a stable description of the tail of the probability density functions (e.g. F1/250 based on 5-10 points), as this otherwise will give large uncertainties on the value. On the other hand, it is then implicitly assumed that the wave state is stationary over the duration of the recorded time series, which will very rarely be the case in the natural environment. In order to get reasonable compromise it is recommended to record 500-1000 waves in each time series.

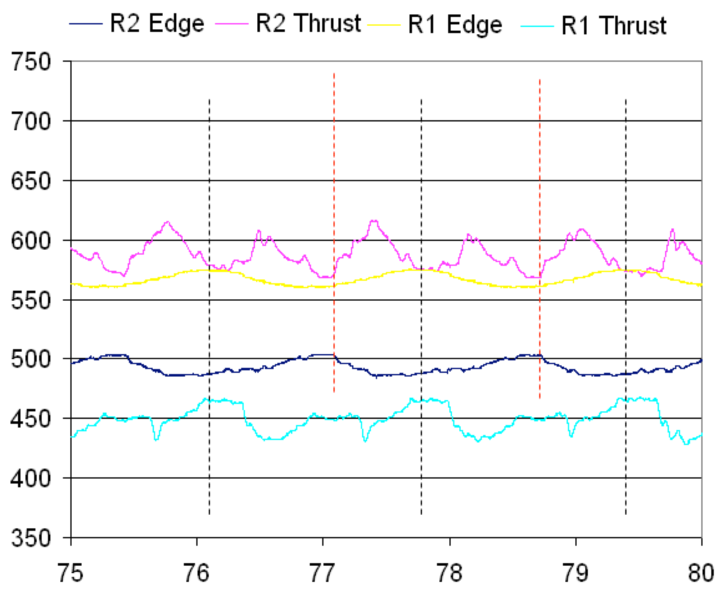
DATA ANALYSIS AND PRESENTATION

The data collection can be analysed on both time and frequency domain to fully identify the key parameters that will best show the viability of the reaction subsystem.

TIME DOMAIN

The primary design driver of the support system will be due to the thrust loading of the device. It is imperative this data is collected and has already been considered within the instrumentation of the device itself for characterising performance. However the drag force of the full structure including mooring lines, pile and gravity base foundations must also be determined.

Time series data taken from load cells will provide the temporal thrust measurements as displayed below:



The use of time domain data from inclinometers, displacement meters and accelerometers will provide the motions of the device. While it is anticipated that these will not vary greatly for installed rigid foundation devices, they will be of significant importance for installation and recovery and also in measuring vibration modes, and as such should be monitoring in kHz. Six DOF nacelle motions plus the various other degrees of freedom (e.g. rotorspeed plus 3DOF blade motion per rotor, articulated component dynamics, etc.) of flexibly moored devices must be monitored during the entire time in location with particular emphasis on attaining the magnitude and directionality of the mooring system attachment loadings especially slamming or cable snaggin.

FREQUENCY DOMAIN

An entire vibrational analysis will need to be undertaken to identify the main frequencies that could lead to the failure of the reaction subsystem through resonance or fatigue. The main contributing factors are turbulence, vortex shedding, wave oscillations and device induced.

The identification of peak frequencies caused by these factors is fundamental to the integrity of the system. The frequency analysis will confirm the design frequencies of various components within the device e.g. blade loads, bearings, angular velocity of the device and any other moving parts. The vortex shedding may occur at a specific frequency for any surface expose to the flow, for example mooring lines. This must be considered at an early stage and designed out so as to minimise impact. Wave motion will occur over a range of frequencies. It must be identified whether these frequencies pose a problem to the system. Finally, turbulent energy is likely to be spread over a large range of frequencies, as described by the Batchelor Spectrum. As such, turbulence interactions are unavoidable and must be tackled through damping mechanisms and design factors.

EXAMPLES

Prior to any pile mounted device design, detailed information about the geotechnical makeup must be obtained (see ISO 19901-4, Part 4). The bathymetry or geology local to the intended device location has a major impact on the installation procedure, as well as the natural frequency of the total structure and the structural security of the device. Different methods include direct monopiling, using multiple piles, and using a combination of piles and gravity based foundations. A vibrational analysis of the pile should be anticipated at the design stage and carried out after installation. More information can be found in ISOs (e.g. EN 1993-5:2007).

For example, it might be found that the planned piling method for the device is unsuitable to the location due to a softer than expected clay below the seabed. Thus the structure is redesigned from a monopile to a series of piles.

Cases of successful monopile usage for tidal energy convertors would include MCT's SeaGen and the EMEC trial OpenHydro device.

Steel or cement support structures can be employed as Gravity Based Foundations (GBF). As with piles, a survey on the seabed bathymetry is required to select the different anchoring systems available (e.g. simple gravity base, suction anchors, etc.). A detailed 3D analysis on the internal stresses of the

Check List

Many developers have adopted different techniques to attach the TECs to the seabed. Initially the most common configuration was the pile foundation due to the considerable knowledge acquired from the oil and gas industry and wind industry.

Of the current designs moving to market, gravity based foundations are now also being developed. They have become a popular alternative for anchoring due to transportation and installation.

Deep water locations will be a complicated task for installation and maintenance processes. Therefore, tethered devices may be a solution to deep water challenges, whilst lowering the overall cost of the systems.

members including the mass and added mass and current effects of each member is necessary. Currently, many developers prefer the use of GBF due to its small footprint, visual impact and medium complication of installation and retrieval and GBF is one of the principle mooring strategies employed by the offshore wind sector. Refer to the ISO norms for installation, monitoring and design procedures (e.g. ISO 19902).

Tethered Mooring

The flexible moorings implemented on TEC can be composed of a single point taut configuration, a spread catenary mooring configuration or a combination of both, sometimes accompanied by a turret. The bathymetry on the site will dictate what kind of anchor must be implemented. For example, a drag embedment anchor can be used on a soft soil seabed. A gravity anchor can be employed on a rocky seabed but it is complicated to install on deep water locations. In accordance with the design and the oscillations of the device, the mooring lines may be composed of different materials to add or decrease damping on the system and to control external corrosion or tear and wear of the material. Much of the knowledge can be taken from floating platforms of oil and gas industry, and compliance with guidance from the relevant ISO documentation is recommended (e.g. ISO 19904).

Evopod, SRTT turbine, TIdel and CoRMaT are some examples of tidal energy converters attempting to use a flexible mooring as a support mechanism.

References:

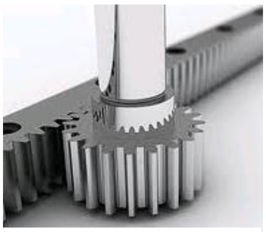
EN 1993-5:2007: Eurocode 3. Design of steel structures. Piling

EN ISO 19904-1:2006; ISO 19904-1:2006: Petroleum and natural gas industries. Fixed steel offshore structures

EN ISO 19904-1:2006; ISO 19904-1:2006: Petroleum and natural gas industries. Floating offshore structures. Monohulls, semi-submersibles and spars

Operations & Maintenance

Technology Development Stages 3 & 4



O&M

Rationale

Design and lab test will have produced a strategy for the operation of the device and the sea trial is the mechanism for how that can be developed and improved and this will include operation & maintenance including the phases of deployment, recovery and decommissioning. Sea trials offer the design team the first opportunity to test these categories in realistic sea states.

Objective

The main objectives to perform O&M sea trials are:

- To learn by doing.
- To prove and validate deployment procedures.
- To establish serviceability and maintenance schedules.
- To provide sufficient information to validate numerical models of the device and subsystems including components for the full range of different operating conditions.
- To give exposure to real-world costs
- To check and develop management procedures including health and safety.
- To prove and validate recovery procedures.
- To assess the endurance of the device and its overall reliability when operating in real sea conditions and identify unexpected failure modes.
- To acquire experience with the construction, installation, operation and maintenance of the device.
- Provides an opportunity to engage stakeholders at an early stage.
- Follow up environmental issues.
- Opportunity to gain experience with the supply chain.
- Finish up with a O&M procedure for a pre-commercial machine.

Pre-Sea Trials Requirements

Perform a careful reliability analysis based on tools like FMECA (Failure Mode, Effects and Criticality Analysis) and FTA (Fault Tree Analysis) and with the information and insight thereby provided, develop detailed testing and maintenance plans for the sea trials, and, if necessary, undertake bench tests of the components identified as critical.

Set H&S objectives to cover the immediate sea trials.

Establish the O&M procedures that will be followed during sea trials.

Investigate and identify the optimum site for trials, in terms of cost, logistics, supply chain, test centre facilities. Check that facilities are available nearby for required operations.

While in sheltered water, check that the maintenance operations required can be performed.

KEY ELEMENTS

- Appoint a Project Manager with overall responsibility for the sea trials, and set a budget to cover the trials and contingencies.
- Incorporate multiple redundant communication channels to the machine
- Perform a detailed reliability analysis
- Establish a logbook and logging procedure that meets the specific requirements of the machine under test.

IMPORTANT REFERENCES

DNV ???	EQUIMAR WP5, Del 5.1
IEA-OES-IA Annex II	Carbon Trust 2005: “Guidelines on design of WEC”

Sea Trial Type

There are 3 stages to implementing an appropriate O&M strategy for sea trials:

Before trials

- Experience has shown that everything that *can* be done before going to sea *must* be done

During trials

- Stick to the plan, be prepared to modify the plan appropriately to meet circumstances – and to record all changes to plan. Trials are expensive, comprehensible data is the mission goal.

After trials

- Extract as much information as possible from the trial experience and the data. Integrate the knowledge gained and update the O&M procedures and design.

A guideline checklist of the recommended activities, gained from experience, is given on the right.

Modifications to the check list will be required to suit which of 4 possible test options has been chosen; each requires different considerations:

- Established test-centre
  - grid connected
  - non grid connected
- Ad-hoc location
  - grid connected
  - non grid connected

There now exists the potential to perform "off-grid" field trials using a grid emulator. This device allows a fully operational PTO and includes all the electrical response characteristics that would occur under a full connection to the grid. Therefore the installed generator and power electronics can be as for a grid-connected machine such that the same units can be used when the unit is connected to the grid at a later stage in the trials

OPERATIONS & MAINTENANCE CHECK LIST

Before Trials

- *Draw up a trials plan*
  - *Identify and perform all tasks that can be done before deployment*
  - *Identify which maintenance can be performed wet*
  - *Develop specialist equipment if required*
  - *Define maintenance schedules*
- *Establish a condition-monitoring system*
- *Establish an automated document control and versioning*
- *Identify fatigue criticalities*
- *Prepare permissions, licenses, insurance, certification, EIA*
  - *Types of navigational aids, safety features required*
- *Identify the key problems related to deployment and recovery*
- *Determine appropriate health and safety requirements for sovereign waters*
- *Devise emergency procedures, including notification of relevant safety authorities*
- *Identify accessibility constraints*
  - *Effects of vessel availability/competition, size and type of vessel*
  - *Collision risk analysis with service vessels*
  - *Identify weather window sensitivity*
  - *Scheduling/timing*
  - *Quality of weather and sea-state forecasting & introduced uncertainty*

During Trials

- *Determine applicability of test programme to weather windows; result of severe failure modes*
- *Confirm on site access time/availability at a given Hs*
  - *Uncertainty of metocean forecast*
- *Implement trials plan, modify appropriately if required and log all changes*
- *Perform regular assessment of data and data quality and SCADA alerts*
- *Perform inspection as part of the maintenance plan*
- *On-site training of future personnel and engineers*

After Trials

- *Perform inspection at component level*
  - *Subsystems as flagged by prior failure mode analysis*
  - *Components as flagged by SCADA alerts during trials*
- *Perform detailed data analysis*
- *Feedback operation and maintenance data into the initial reliability assessment*
- *Update O&M strategy*
- *Update machine design where required to reduce or avoid O&M costs*

Test site options

Variations on the above checklist must be considered relative to the type of test site at which the sea trials will be conducted. It would be anticipated that if an established test centre is selected then it is likely that the device will be grid connected, but not necessarily in the initial stages. It is evident from past experiences that a recognised test centre will provide the best overall support mechanisms for stage 3 and stage 4 sea trials. However circumstance may dictate that an appropriate ad hoc site will be chosen, but the developer should recognise the possible limitations and difficulties that might arise.

A grid connected site will require that the O&M strategy consider the implications of unexpected loss of connection to the operation of the machine. At an ad hoc site, should a cable be installed there will be considerable overhead and risk and the O&M should take the possibility of cable failure and damage into account.