Tank Testing of Wave Energy Conversion Systems

Foreword

This document has been prepared in consultation with The European Marine Energy Centre Ltd (EMEC) and with other interested parties in the UK marine energy community. It is one of twelve publications in the *Marine Renewable Energy Guides* series, as detailed in the following figure.

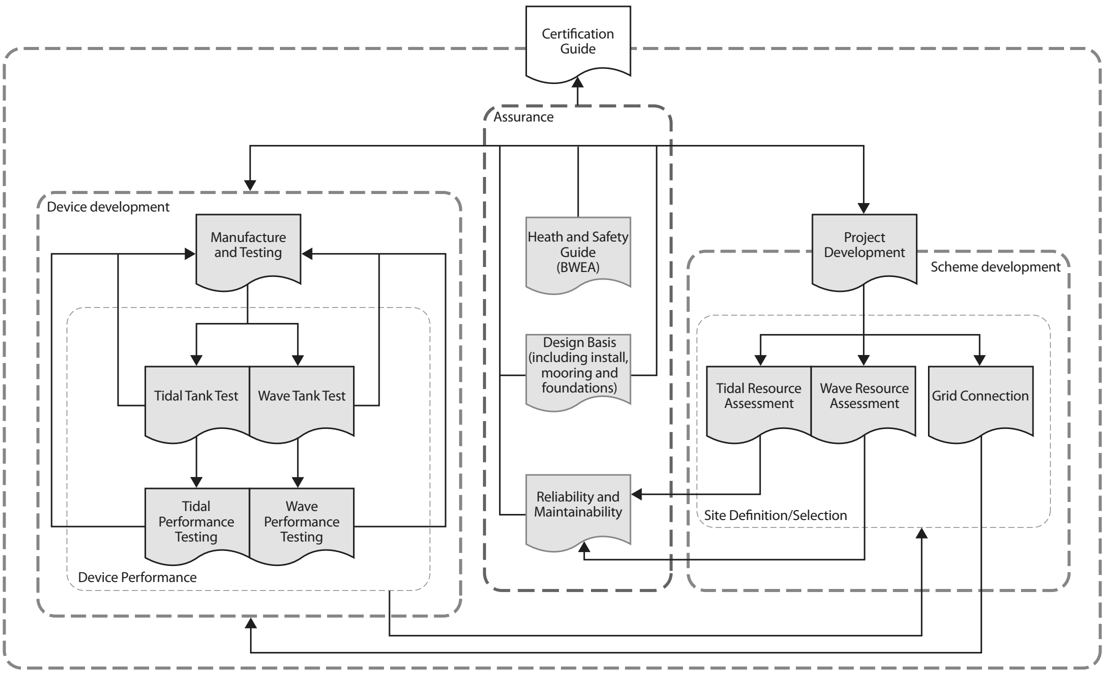

Figure 1 — Marine Renewable Energy Guides

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Tank Testing of Wave Energy Conversion Systems

Marine Renewable Energy Guides

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Introduction

Within the wave energy community there is, at present, no agreed common approach for the development and evaluation of energy extraction devices to assist small and medium-sized enterprises (SMEs), funding bodies, decision makers or other interested stakeholders. This report attempts to satisfy that requirement by providing guidelines for a structured programme that will mitigate both the technical and fiscal risks.

Although adhering to a controlled and progressive schedule is no guarantee of success, it is probable that not following a test programme, like the one established in this document, is a pathway to failure, or at best lost time and wasted resources. Experience has already shown that this type of phased development path mitigates both technical and financial risk.

The overall programme is based on a five phase approach, which increases in complexity and required investment as it progresses. Table 1 gives an overview of the phases. This document deals with the first three only, that is from initial concept review to large scale (circa $\lambda = ¼$) sea trials at benign outdoor test stations.

At the conclusion of each phase, or sub-phase, a set of decision or stage gates are executed to assist in the evaluation of a device and its potential for successful development. These are shown in Table 2. Since no devices have progressed to commercialization the actual numbers to set as limits for each phase are a combination of estimates from the wave energy community and economics from the off shore wind industry. These will be updated in future editions of this document as more confirmed realistic evidence is collected.

Please also note that although a standard format can be used to impartially assess the progress of devices, each test programme will be bespoke in detail. This document, therefore, describes the minimum test requirements. At the end of each phase, it is imperative that the evaluation of the status of the device development is conducted in order to carry out the appropriate planning process for future phases.

This test procedure is to be regarded as codes to follow, based on best practices established over previous years, rather than rules that have to be accepted verbatim.

It is also stressed that the test programme presented is a basic, practical approach for the device development not a rigorous, academic thesis.

Table 1 — Phase overview

	Phase 1 *Validation model (lab.)*			Phase 2 *Design model (lab.)*	Phase 3 *Process model*	Phase 4 *Prototype*	Phase 5 *Demonstration*
	Concept	***Performance***	***Optimization***		***Sea trials***		
Primary scale (λ)	$\lambda = 1 : 25 - 100$ ($\therefore \lambda_t = 1 : 5–10$)			$\lambda = 1 : 10–25$	$\lambda = 1 : 3–10$	$\lambda = 1 : 1–2$	λ = Full size
Tank	2D flume and 3D basin			3D basin	Benign site	Exposed site	Open location
Duration (inc. analysis)	1–3 weeks	1–3 months	1–3 months	6–12 months	6–18 months	12–36 months	1–5 years
Typical no. tests	50–500	250–500	100–250	100–250	50–250	Continuous	Statistical sample
Budget (€,000)	1–5	25–75	25–50	50–250	1,000–2,500	5,000–10,000	2,500–7,500
Excitation/Waves	Monochromatic linear waves (10–25 Δf) Panchromatic 5 reference	Panchromatic waves (20 min full scale) +15 classical spectra long crested head seas		Deployment: pilot site sea spectra Long & short crested classical seas Select mean wave approach angle	Extended test period to ensure all seaways included	Full scatter diagram for initial evaluation, continuous thereafter	

Table 2 — Decision gate criteria

	Phase 1 *Validation model (lab.)*			**Phase 2** *Design model (lab.)*	**Phase 3** *Process model*	**Phase 4** *Prototype*	**Phase 5** *Demonstration*
	Concept	***Performance***	***Optimization***		***Sea trials***		
Evaluation (Decision gates)							
Absorbed power (kW)							
Converted power (kW)							
Mass (t)							
Manufacturing cost (€)							
Capture (kW/t)	< ⅛ –¼			¼–½	½–1	2–5	
Production (€c/kW)	< 25 €c/kW			≤ 15 €c/kW		≤ 10 €c/kW	≤ 5 €c/kW

1 Scope

This document specifies a structured development programme and specific test procedures for the early stages of a wave energy converter development. The format is based on traditional engineering methods similar to the Technology Readiness Level (TRL) introduced by National Aeronautics and Space Administration (NASA).

2 Terms, definitions, abbreviations, symbols and units

2.1 Terms and definitions

2.1.1
beam sea
seaway impacting on the side of the hull of a floating body at 90˚ to the longitudinal axis, and travelling from port to starboard or vice versa

2.1.2
bi-modal spectrum
spectral shape consisting of two distinct concentrations of energy variance due to a locally driven wind sea in the presence of a swell sea where a valley exists between the low frequency swell and the high frequency wind sea

2.1.3
Bretschneider spectrum
expansion of the Pierson–Moskowitz (PM) spectrum, allowing for the description of the spectral shape of seaways other than fully developed by utilizing the variance and peak frequency as input

$$S(f)_B = \frac{5}{16}\frac{H_{m0}^2}{f}\left(\frac{f_p}{f}\right)^4 \exp\left[-\frac{5}{4}\left(\frac{f_p}{f}\right)^4\right]$$

2.1.4
device power
pneumatic or mechanical power produced by a device due to the interaction of the relative inertias of the device system as excited by the seaway

EXAMPLE Device hull and water column, seabed and float, water reservoir and turbine.

NOTE Pneumatic power = air pressure × air flow
Mechanical power = force × velocity

2.1.5
draft
dimension of a floating body below the mean water surface due to a load bearing on the body

2.1.6
finite waves
waves outside the linear regime that have a finite amplitude

NOTE When this is the case the waves are asymmetrical about the mean level, and so it can not be said that the surface elevation will be Gaussian distributed.

2.1.7
following sea
seaway impacting on a floating body at the stern, and travelling in direction from the stern to the bow of the body

2.1.8
freeboard
dimension of a floating body above the mean water surface

2.1.9
Froude scaling
scaling method based on the ratio of inertial forces to gravitational forces, used to model wave and surface behaviour

2.1.10
head sea
seaway impacting on a floating body at the bow, and travelling in direction from the bow to the stern of the body

2.1.11
heave
translational oscillatory motion parallel to the vertical axis of a floating body caused by an excitation or a displacement from rest along the vertical axis

2.1.12
Joint North Sea Wave Project (JONSWAP) spectrum
multiplication of the PM spectrum by an enhancement function to facilitate fetch limited conditions, having three input parameters: peak frequency, peak enhancement factor and the enhancement shape widths:

$$S(f)_J = \left(\frac{\alpha g^2}{(2\pi)^4} \frac{1}{f^5} \exp\left[-\frac{5}{4} \left(\frac{f_p}{f} \right)^4 \right] \right) \left(\gamma^{\exp\left[-\frac{(f-f_p)^2}{2\sigma^2 f_p^2} \right]} \right)$$

2.1.13
linear waves
waves based on the assumptions of Airy wave theory

NOTE This is a theory for the propagation of waves on the surface of a potential flow above a horizontal bottom. The free surface elevation $\eta(x,t)$ of one wave component is sinusoidal, as a function of horizontal position x, and time t.

$$\eta(x,t) = a\cos(kx - \omega t)$$

where a is amplitude, k is wave number, and ω is angular frequency.

The probability distribution of a random sample of the surface elevation of a wavetrain composed of the superposition of linear waves will yield a Gaussian distribution. This means that there will be no second or higher order effects.

2.1.14
monochromatic wave excitation
excitation of a floating body due to a sinusoidal wave composed of a single frequency

2.1.15
panchromatic excitation
excitation by a sea state comprising the superposition of multiple single frequency sinusoidal components, the distribution of which is dictated by the spectral shape

2.1.16
Pierson–Moskowitz (PM) spectrum
empirical equation defining the one dimensional spectral shape of the distribution of variance over a frequency range, based on the assumption that the input wind is in equilibrium with the waves, also known as fully developed

$$S(f)_{PM} = \frac{\alpha g^2}{(2\pi)^4} \frac{1}{f^5} \exp\left[-\frac{5}{4} \left(\frac{f_p}{f} \right)^4 \right]$$

2.1.17
pitch
rotational oscillatory motion about the horizontal transverse axis of a floating body due to an excitation or displacement from its equilibrium position

2.1.18
quarter sea
seaway approaching a floating body at an angle between a beam sea and a following sea

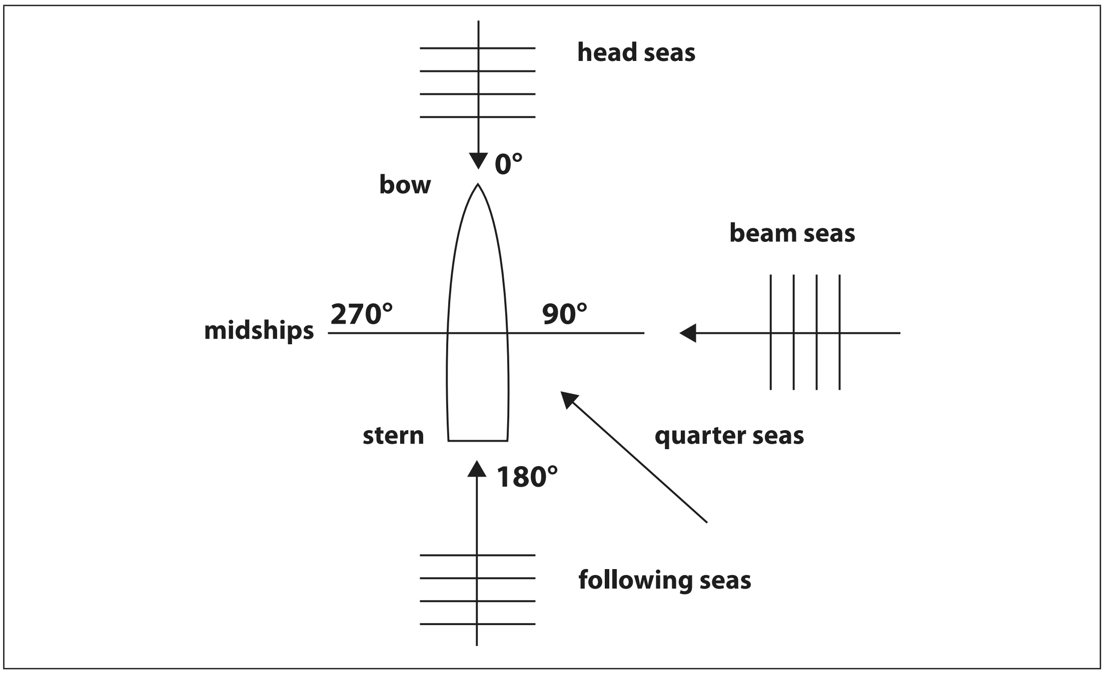

Figure 2 — Seaway definitions

2.1.19
roll
rotational oscillatory motion about the horizontal longitudinal axis of a floating body due to an excitation or displacement from its equilibrium position

2.1.20
significant steepness, S_s
ratio between the significant wave height and the wave length for a panchromatic time series:

$$\frac{2\pi H_s}{gT_z^2}$$

Sea states defined by the Pierson–Moskowitz equation have a constant significant steepness of $S_s = 0.0507$. Seaways in general do not exceed a significant steepness of $S_s = 0.1$.

2.1.21
spreading
directional distribution applied to one dimensional spectra to form three dimensional spectra

NOTE $S(f,\theta) = S(f)D(\theta,f)$, where $D(\theta,f) = F(s)\cos^{2s}\frac{1}{2}\left(\theta-\theta_m\right)$ is the most common assumption with a peak at the mean direction.

2.1.22
steepness, *S*
ratio of the wave height, H, to the wave length, λ, of a single frequency sinusoidal wave

NOTE The steepness at which sinusoidal waves in deep water will break is $S = 0.142$.

2.1.23
surge
translational motion parallel to the horizontal longitudinal axis of a floating body caused by an excitation or a displacement in the direction of the longitudinal axis from its equilibrium position

2.1.24
sway
translational motion parallel to the horizontal transverse axis of a floating body caused by an excitation or a displacement in the direction of the transverse axis from its equilibrium position

2.1.25
water depth, *h*
<airy linear wave theory>
shallow water: $h/\lambda \leq 1/20$, intermediate water: $1/20 < h/\lambda \leq 1/2$, deep water: $h/\lambda > 1/2$

NOTE λ is the wavelength defined as the horizontal distance between the consecutive up or down zero crossing point of a wave measured orthogonally to the wave crest.

2.1.26
wave height, *H*
measure of the vertical distance from a wave trough to a wave crest

NOTE It is equal to twice the wave amplitude in sinusoidal waves, $H = 2a$.

2.1.27
wave number, *k*
spatial analogy to frequency

NOTE It is the measurement of the number of repeating units of a propagating wave $k = 2\pi / \lambda$

2.1.28
wave period, *T*
time interval in seconds between the consecutive up or down zero crossing point of a wave

2.1.29
wave power
combined potential and kinematic energy of a sea state being transported with a speed equal to the group velocity normal to a unit width of wave crest in deep water

$$P = \frac{\rho g^2}{64\pi} T_e H_{m_0}^2 \text{ [kW/m]}$$

2.1.30
windage
deflection of a floating body due to the force of the wind acting on the freeboard

2.1.31
yaw
translational motion about the vertical axis of a floating body caused by an excitation or a displacement from its equilibrium position

2.2 Abbreviations

BDM	Bayesian Directional Spectrum Estimation Method
CoB	Centre of Buoyancy
CoG	Centre of Gravity
DAQ	Data Acquisition System
DoF	Degrees of Freedom
EU	European Union
FFT	Fast Fourier Transform
IEA~OES	International Energy Agency ~ Ocean Energy Systems
IWS	Internal Water Surface
JONSWAP	Joint North Sea Wave Project
LWL	Load Water Line
NASA	National Aeronautics and Space Administration
OWC	Oscillating Water Column
PADIWA	Package for Directional Wave Analysis
PTO	Power Take-Off
RAO	Response Amplitude Operator
RMS	Root Mean Squared
SS	Proprietary Mooring System

SWL	Still Water Line
TRL	Technology Readiness Level
WEC	Wave Energy Converter

2.3 Symbols and units

g	acceleration due top gravity, 9.81 (m/s^2)
ρ	density: freshwater = 1000 kg/m^3 seawater = 1027 kg/m^3
α	energy scale parameter for Pierson–Moskowitz spectra, 0.0081
γ	peak enhancement parameter for JONSWAP spectra, mean = 3.3, range [1 : 7]
σ	JONSWAP enhancement shape parameter, $f < f_p$, $\sigma = 0.07$, $f > fp$, $\sigma = 0.09$
λ	Froude scaling parameter, length ratio of model to full size prototype
Fr	Froude number
v	stream velocity
l	length scale
s	spreading parameter to define directional distribution
θ_m	mean direction of wave propagation
θ	direction of wave propagation
$S(f)$	spectral variance density (m^2/Hz)
Δf	frequency division/step
m_n	spectral moment, $m_n = \int S(f) f^n \Delta f$
a	amplitude of a sinusoidal wave
a_i	incident wave amplitude
a_r	reflected wave amplitude
C_R	reflection coefficient
H	double amplitude measure of a sinusoidal wave
T	period of a wave, time taken for a particle to return to its original position
η	surface elevation profile
f	frequency, inverse of period, T (Hz)
f_p	the frequency at which the variance of the spectrum is at its maximum
ω	circular frequency, $2\pi f$ (rad/s)
k	wave number
H_s	significant wave height
$H_{1/3}$	average of the highest third of waves in a time series
H_{m0}	significant wave height derived from spectral moments, $4\sqrt{m_0}$
T_p	peak period, inverse of the frequency of the maximum of $S(f)$, f_p
T_{02}	average period derived from spectral moments, $\sqrt{m_0/m_2}$
T_e	energy period, $\left(m_{-1}/m_0\right)$
T_z	average period from zero-crossing analysis of time series

h	water depth
λ	wavelength, $\frac{gT^2}{2\pi}\tanh\left(\frac{2\pi h}{\lambda}\right)$ or for deep water, h/λ > 0.5, $\frac{gT^2}{2\pi}$
S_s	significant steepness, $\frac{2\pi H_s}{gT_z^2}$
P	energy flux per metre wave crest (kW/m)
M	mass of the body (kg)
M_a	added mass of the body (kg)
A_{wp}	water plane area of the body (m^2)
I_{yy}	mass moment of inertia (kg m^4)
I_{yya}	added mass moment of inertia (kg m^4)
I_c	moment of inertia of a plane area (m^4)
T_H	period at which body resonates in heave, $2\pi\sqrt{\frac{M+M_a}{\rho g A_{wp}}}$
T_θ	period at which body resonates in pitch, $2\pi\sqrt{\frac{I_{yy}+I_{yy}^a}{\rho g I_c}}$
T_D	device natural period, inverse of the frequency of the peak of the power spectrum
kW	1,000 watts, measurement of power
MW	1,000,000 Watts

3 Purpose of testing

3.1 General guidance

3.1.1 General

It is prudent to test wave energy converters (WECs) through increasing model scales since physical trials provide a mechanism for risk reduction, both technical and financial. This considered approach is achieved by progressively improving engineering and scientific knowledge from the initial verification of the concept(s) to the demonstration of the economics with large scale models. The rationale for this measured approach is to ensure due diligence can be successfully performed on the technology and business plan whenever private or public finance is sought to support further development and progression.

Technical output of a well constructed WEC testing programme can provide information for all of the following objectives if applied in accordance with the recommendations shown in Table 3:

- verification of the concept;
- validation and calibration of numerical models;
- quantification of technical performance variables;
- provision of environmental loading data to allow design(s) to be improved, including moorings and foundations;

- identification and development of understanding of relevant hydrodynamics and other physics processes;
- provision of data for optimized performance design;
- generation of detailed information for the power take-off engineers;
- evaluation of the economics;
- qualification of the device's seakeeping ability and general seaworthiness;
- survival (large scale models @ benign sites);
- environmental impact (large scale models @ benign sites).

Different investigations should be applied in specific phases of the development programme. An essential element of the test schedule is to ensure the correct science is investigated at the appropriate time. This approach can be seen in Table 3, which expands on the information contained in the previous overview of the test schedule.

The decision as to which parameters should be addressed at each phase should be based on practical considerations and previous experience, especially towards the reduction of uncertainty in later phases.

EXAMPLE Mooring forces can be measured at small scale to produce guidelines on the system's capability, but not at the expense of omitting its monitoring during later phases when scale issues are less of an issue.

Test programmes should, therefore, have overall specific objectives set for each phase, into which additional investigation can be incorporated as required. Figure 3 shows an example of a phase 1 performance schedule with the addition of some specific examinations. These flow diagrams, or similar, should be produced to plan each test campaign. The mantra for any test engineer should be:

'Always have a plan but be prepared to improvise'.

3.1.2 Scaling consideration

3.1.2.1 General

The following description outlines each of the three phases covered in this document and the rationale and purpose of the trials to perform in each of them.

3.1.2.2 Phase 1 – Small scale (λ = 1 : 25–100)

This initial phase is subdivided into three stages, each offering a different perspective.

a) *Concept*
Most new device proposals incorporate some unproven concept or combination of ideas that should be verified prior to more extensive testing. No performance evaluation is required at this time so an idealized device configuration can be utilized.

Table 3 — Technical output of phases

	Phase 1 *Validation model (lab.)*			**Phase 2** *Design model (lab.)*	**Phase 3** *Process model*	**Phase 4** *Prototype*	**Phase 5** *Demonstration*
	Concept	***Performance***	***Optimization***		***Sea trials***		
Model	Idealized with quick change options Simulated PTO (0 – ∞ damping range) Std mooring and mass distribution		Distributed mass Minimal drag design dynamics	Final design (internal view) Mooring layout	Full fabrication True PTO and elec. generator	Grid control electronics Emergency response	First fully operational device
Objectives	Concept validation Performance variables RAOs PTO and mooring characteristics Diffraction and radiation.		Real sea performance Dir sensitivity Deployment seaways RAOs Seakeeping	Verify phase I Active control Seakeeping Failure modes	Wave-wire performance Mooring forces Survival and seakeeping (where applicable)		
Measerand	Motion, forces, waves, mooring tension				Control strategy Electrical supply		
Specialize	DoF (heave only) 2D Solo and multi hull	Short crest seas Angled waves As required	Storm seas (3 hr) Finite regular (as required)	Power take-off bench test PTO and generator	Survival forces Salt corrosion Marine growth Permissions	Quick release connections Service ops	Solo or small array (upgrade to generating station)?
Maths Methods (Computer)	Hydrodynamic, numerical frequency domain to solve the model Undamped linear equations of motion		Finite waves Applied damping Multi freq inputs	Time domain response model and control strategy Naval architects design codes for hull, mooring and anchorage system Economic and business plan		Array interaction Economic model Electrical stab.	Int. market projection for devise sales

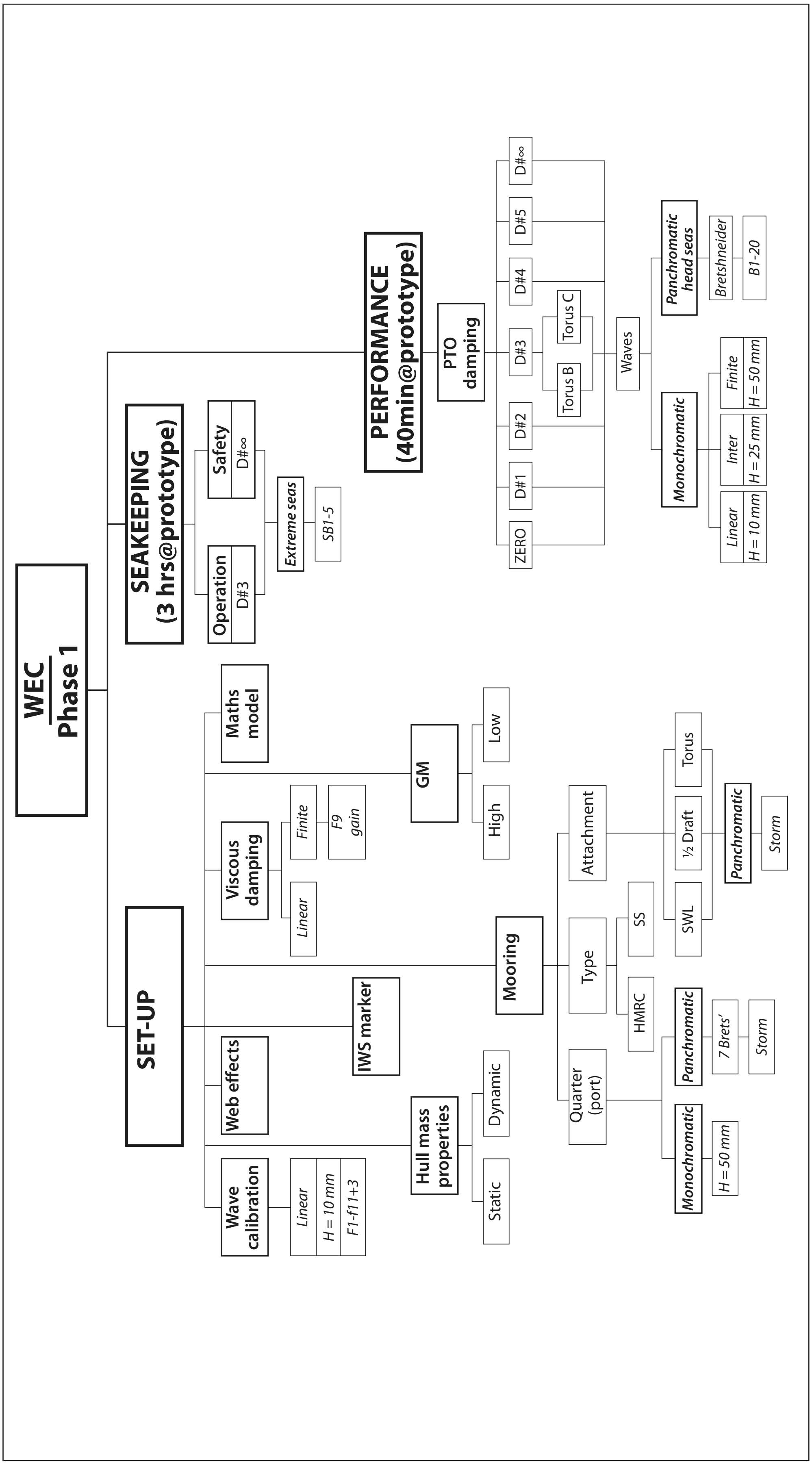

Figure 3 — Phase 1 performance plus schedule

The primary excitation can be small amplitude monochromatic waves. Observation can play a leading role in the evaluation but if successful some measurements of basic parameters can be useful, such as hull motion and power take-off (PTO) force/pressure. Trials will be at zero, full and a medium setting for the applied damping.

On successful confirmation that the physical processes work the model should be subject to a limited number (5) of reference irregular seaways to corroborate operation and gain insight into the important parameter to vary in proceeding stages, rather than the actual settings required.

b) *Performance*
The primary objective of the second section of the test programme is to investigate the device variables and physical properties that affect the performance, or energy absorption. They should be regarded as the opportunity to quickly and cost-effectively establish the working principles of the device and establish the design variables that affect performance.

Initial testing will be conducted in regular, linear waves but include finite waves to evaluate higher order influences on the behaviour. These results will also be used for mathematical model calibration and validation. Depending on the device and the facility it is possible that these tests can be conducted in a flume. However, blockage effects and wall reflections should be factored into this decision including how they influence the post-processing and data analysis.

Fully two dimensional testing should only be run for the mathematical model verification.

Once the underlying important physical variables have been identified a selection of the key design parameters should be tested in irregular seaways. Since these are still for comparison purposes classical spectral profiles can be adopted. It is more important to cover a range of sea states representative of perspective deployment sites scatter diagram (i.e. open ocean, confined sea, shallow water etc.). For most near-shore applications the Bretschneider spectrum is recommended.

Diffraction and radiation trials can be included in this stage (see 3.1.4.2).

It is not essential to know the final mooring arrangement at this time. A system that has minimal influence on the body motion can be considered. Initially this can even be a securing rig that reduces the degrees of freedom of body motion.

The power take-off will be simulated by an energy dissipating damper representative of the proposed PTO.

c) *Optimization*
Based on the previous two stages an optimized version of the device should be evaluated over a range of extended excitation conditions. The basic design, especially the hull components, should have been reviewed by a naval architect group or structural engineers to confirm the design is acceptable, is manufacturable and that it could be certified as fit for purpose by the appropriate authorities. Any adjustments or refit resulting from this technical due diligence should be incorporated in the model, even if this dictates a new model being constructed. The design should first be verified by rerunning to the previous stage monochromatic tests.

Additional trials will include:

- extended seaway selection (15–20);
- short crested seas;
- storm conditions (3 hours duration);
- alternative spectral profiles;
- mean direction of wave approach;
- mooring options.

3.1.2.3 Phase 2 – Medium scale ($\lambda = 1:10–25$)

Once the fundamentals have been established in phase 1 a larger model can be used to investigate other parameters. These trials will be conducted in irregular wave fields, which can be either generic or site specific. Of particular merit will be the generation of storm conditions to establish the seakeeping characteristics of the hull or structure. If an advanced power take-off simulator is fitted, PTO end stop issues and component survival may also be considered. The finalized mooring should be included by this time so main failure modes can be experienced. Though not essential a facility offering current and wind effects could be considered, depending on the expected influence of these environmental conditions on the device. If a model at the larger end of the scale range is selected this phase of testing could provide an acceptable platform for control equipment so different strategies can be investigated.

By phase 2 the model should have advanced from the idealized version of phase 1 into a unit resembling the wet sections of the proposed WEC in most detail. An important output from the trials is the verification of the previous phase results and the associated decisions made from those data.

Ideally phase 2 trials should be conducted in a three dimensional basin but if there is a requirement for in-depth investigations of specific criteria, then a wide flume could be selected. An obvious example of this would be an active control system fitted to the power take-off simulator. Once the fundamental algorithms have been established and short crested seas are required, even these investigations should be concluded in a wide basin. Mooring trials, and especially failure modes, should be run in basins that can accommodate the full mooring line spread footprint.

The advantage of phase 2 is that it is still conducted at a hydraulic facility where excitation conditions can be controlled. Even at laboratories with external tanks the wave field is selectable and repeatable so device set-up options can be objectively studied and configuration variations quantified.

Typically medium scales also enable improved sensor selection since models are large enough to accommodate many proprietary transducers. This is particularly the case with submersible gauges which are often too heavy for phase 1 models.

3.1.2.4 Phase 3 – Large scale (λ = 1 : 3–15)

Although large models can still be tested in (a limited number of) flumes or basins it is anticipated this phase will be conducted at a benign external site. To assist in this process sea trial locations have now been established in some countries. In Europe, both Denmark and Ireland have a pre-designated location where deployment permits and licences have already been obtained. This is a most important phase so should be approached carefully and extensively. A typical scale for this work would be circa λ = 1 : 4, which for megawatt size WECs will be a large physical device of several tonnes. As such the model will include all the equipment necessary to be a fully operational unit, including PTO, generation and power electronics. The developer will therefore have the opportunity not only to test the complete system but encounter the difficulties of bringing together a disparate disciplinary team and multi-technology device for the first time. This factor should not be underestimated.

Sub-megawatt units (< 500 kW) might not benefit fully from this phase, though evidence has shown a ½ or ⅓ scale units of 10 kW can provide realistic and valuable data prior to full size prototype build.

Of particular merit for benign site trials is the opportunity to study devices close to shore and where scaled 50 year storm conditions are $H_S \leq 5$ m. It is probable that once deployed at an open ocean power park site the behaviour of WECs in extreme waves will never be visually observed since it will be unsafe for humans to be in the vicinity at such times.

3.1.3 Selecting scale

3.1.3.1 General

Similitude criteria and similarity conditions enable physical properties to be appropriately scaled and investigated at different model sizes. These rules should enable most aspects of a WEC to be investigated at a small scale (circa λ = 1 : 50–100) but practical considerations and non-scalable parameters result in the suggested progressively increasing size scheme.

3.1.3.2 to 3.1.3.4 describe some of the factors that particularly require consideration when deciding a model scale or interpreting the results from tests.

3.1.3.2 Air compressibility

In pneumatic devices the stiffness of the air spring is not scaled correctly by geometry. For static devices this can be compensated for by the use of an external air reservoir. In mobile buoyant units this is more difficult due to the practicality of not influencing the vessel motion. The degree to which this parameter will affect any test result depends on the level of applied PTO damping.

Little empirical evidence yet exists to quantify the difference in results due to this phenomenon since few full scale devices have been deployed to provide data for scale comparisons. Theoretical studies suggest that if compressibility is to be an issue it will only be encountered at prototype (full) scale.

3.1.3.3 Viscosity

Model testing, particularly at a small scale, tends to produce conservative results. Viscosity, and in particular vortex shedding from edges, does not scale appropriately and can be overestimated during physical testing. Attention to detail during model construction can minimize this effect but the best solution is to increase scale when investigating critical parameters.

This factor often leads to difficulty matching physical and theoretical mathematical model results (see 3.2.2). Empirical results can be used to calibrate numerical models but, since this is still an art rather than a science, care and attention to detail should be applied.

Experience in the offshore engineering industry suggests that floating structures exhibit little viscous effects so coefficients are set to unity in mathematical models. However, these are usually very large bodies designed to move as little as possible. Conversely wave energy devices are relatively small (<1,000 t) and experience large excursions in at least one degree of freedom. They also have the added complexity of a power take-off system that feeds back into the modes of motion so the unity approximation might not be valid.

3.1.3.4 Friction

Mechanical friction should also be carefully dealt with during model construction since it too does not scale when Froude similitude is imposed. This is particularly important during phase 1 and phase 2 of the programme. Power take-off simulators can be a source of problems if friction is not minimized. Forces experienced at small scale will only be a few Newtons and even well engineered PTOs can have resistance such that losses are proportionally high percentages of absorbed power.

A very careful selection of simulator is required. Low friction dampers can alleviate some of these uncertainties.

3.1.4 Specific tests

3.1.4.1 General

When developing the device test programme there will be a requirement for specific tests designed to address other important issues affecting the performance of the WECs. Two examples of these are given below.

3.1.4.2 Radiation and diffraction

If sophisticated mathematical time or frequency domain models are being developed in parallel with the physical programme it can be advantageous to conduct explicit trials to obtain the diffraction and radiation forces. These are measured by two different techniques, one in monochromatic waves and the other in initially still water.

- *Diffraction*: the device is held fixed by a frame incorporating a force transducer. Excitation waves covering a range of periods impact on the device and the hydrodynamic forces applied on the body are measured.
- *Radiation*: the device is held by a motor containing a force transducer. In still water the device is oscillated by the motor at different periods and the corresponding force measured. The radiated wave might also be monitored for use in the theoretical study.

3.1.4.3 Arrays and clusters

The programme presented so far is based on the development of a solo unit. It is constructed to enable the optimal performance of any WEC to be established under real sea conditions by an increasing scale approach to address the relevant issues at each phase. A parallel consideration is that of the influence of devices on each other when in near field proximity. Little archived research material exists on this topic, of which most is theoretical in origin.

At what stage this matter should be addressed has not been clearly defined by either academics or from developers' previous practical experiences. For multiple small individual WECs clustered in close proximity to each other ($d \approx D$) on a single platform the situation is clearer. These should be considered as a solo unit with the model scale adjusted to suit the practicalities of such a single conversion unit.

For device wave parks some fundamental studies are now underway which should identify the importance of unit interactions in a qualitative way. Based on these studies a recommendation will be included in future editions of this document.

3.2 Use of regular seas

3.2.1 General

Monochromatic or regular single frequency waves play an important part during the early stage of a WECs development programme. They are used to provide an indication of how a device works. The three fundamental applications of results from this sort of testing are:

1. to validate and/or calibrate mathematical models;
2. to observe and monitor device response to regular excitation forces that define the basic operation of a device;
3. to evaluate higher order effects by the comparison of behaviour in linear and finite waves.

Regular waves are defined by their wave period (wavelength), amplitude (height) and surface profile. Figure 4 shows these relationships.

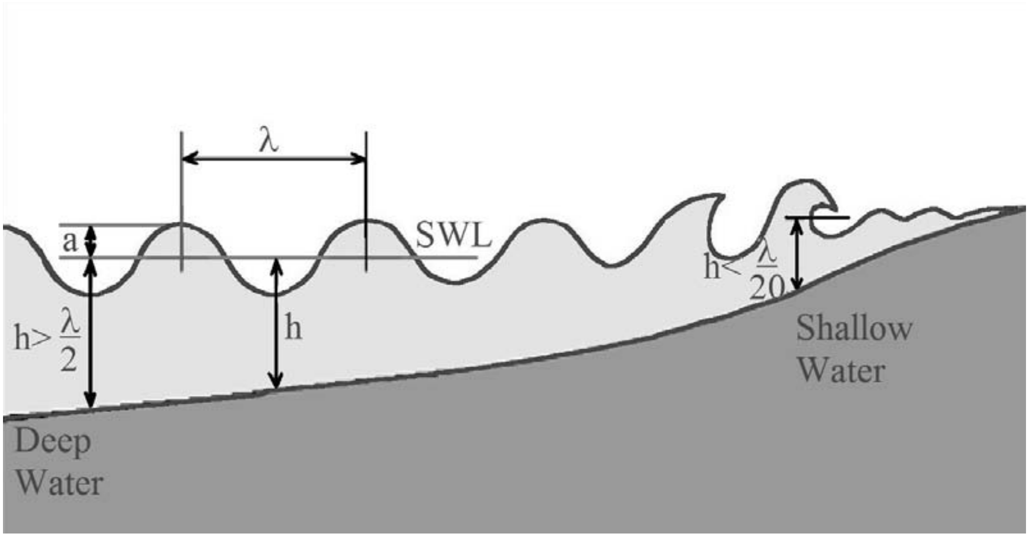

Figure 4 — Linear wave theory definitions

Table 4 provides some basic physical definitions for gravity sinusoidal waves based on linear theory.

Table 4 — Linear theory definitions

	Water depth		
Parameter	**Deep –** $h > \lambda/2$	**Intermediate –** $\lambda/2 > h < \lambda/20$	**Shallow –** $h < \lambda/20$
Wavelength, λ	$\frac{gT^2}{2\pi}$	$\frac{gT^2}{2\pi}\tanh(kh)$	$T\sqrt{gh}$
Wave celerity, c	$\frac{gT}{2\pi}$	$\frac{gT}{2\pi}\tanh(kh)$	$\sqrt{gh}$
Group velocity, c_g	$\frac{c}{2}$	$\frac{c}{2}\left(1+\frac{2kh}{\sinh 2kh}\right)$	c
Wave energy/unit area $E = \frac{1}{2}\rho g a^2$ (J/m^2)		Wave power/unit length $P = Ec_g$ (kW/m)	

3.2.2 Theoretical model verification

Both frequency domain and time domain numerical models require either validation or calibration by empirical data before they can be confidently applied as a WEC design tool. This verification procedure can best be achieved by comparison with practical results produced from scaled physical models and in particular those obtained during regular, single frequency plane wave trials.

Advanced frequency domain models such as WAMIT, AQWA, Aquadyne etc., take as their input monochromatic oscillation so for direct response comparisons regular wave excitations are preferable. Time domain models can operate with regular or irregular input signals but are best proven in the simpler case of monochromatic waves. Figure 5 shows a comparison of theoretical and practical data. As expected the mathematical model predicts higher response around resonance and better agreement away from the natural period. These results can be used to adjust the hydrodynamic damping coefficients in the mathematical model. When external damping, such as a PTO, is imposed the peaks are reduced in both cases such that the results are usually closer without modification.

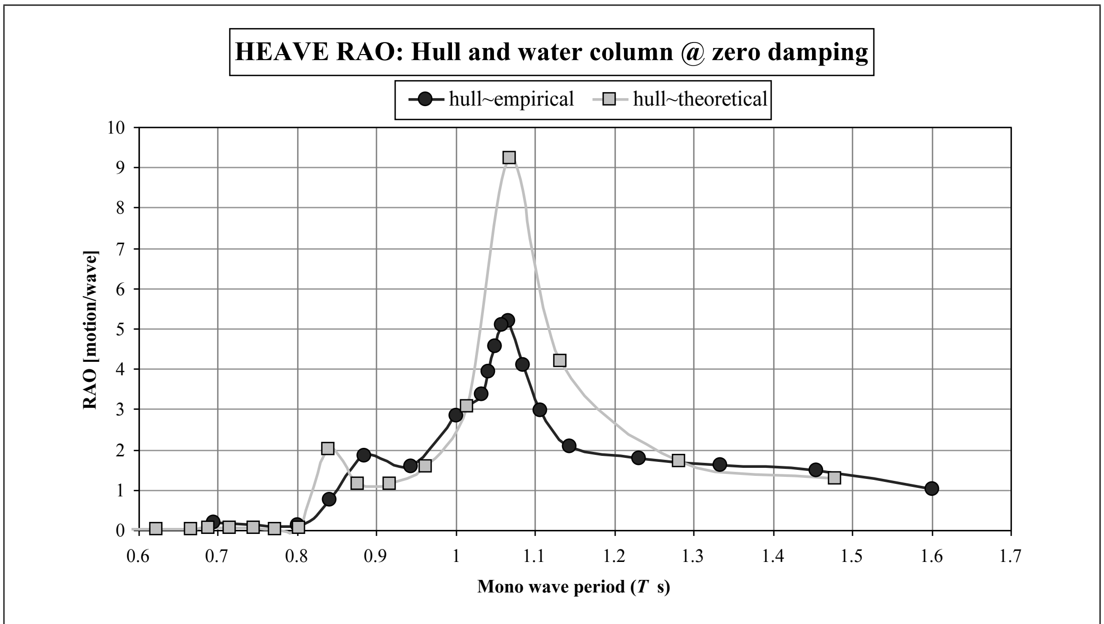

Figure 5 — Mathematical model verification

3.2.3 Device response

The physics processes controlling the behaviour and performance of WECs are not always fully appreciated or initially known. Tests to monitor the device response in regular waves can reveal many elements of the behaviour and, in particular, a change in performance due to design variable refits. Regular excitation is also the traditional method that naval architects employ to produce the response amplitude operators (RAOs) for floating, buoyant bodies. Figure 6 shows the particularly interesting case when two hulls with different natural periods are in close proximity. Tests were conducted on solo and combined, but uncoupled hulls (zero). The results indicate the independence of the system. When connected with infinite damping the system is forced to respond differently as shown by the black graph line (infinite). At some point between these two extremes the optimal power extraction will be achieved.

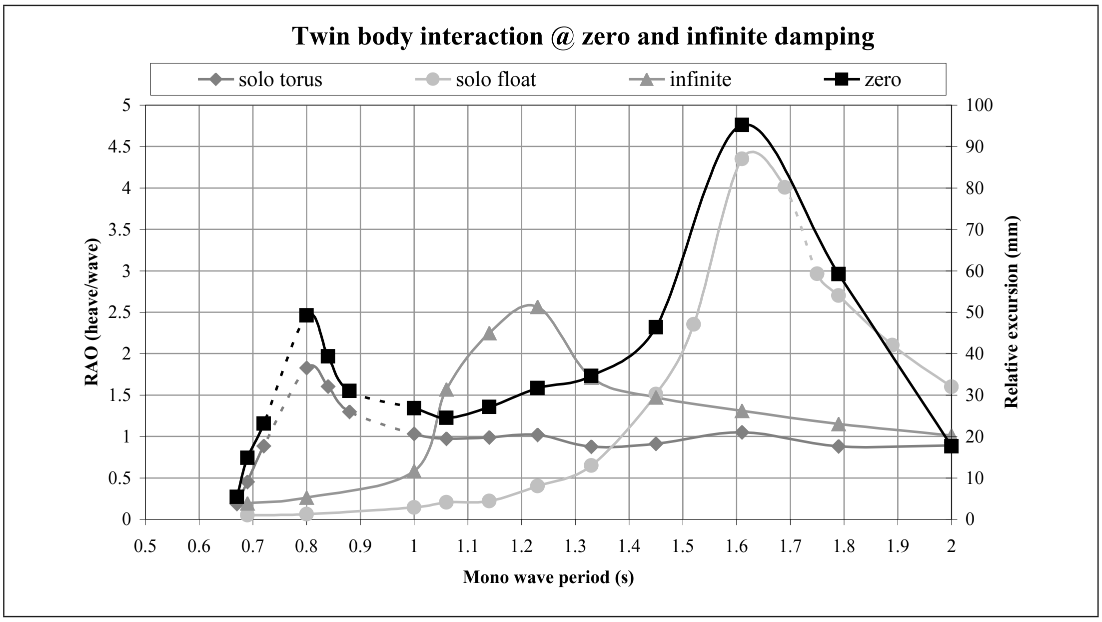

Figure 6 — Energy extraction principle

Figure 7 displays the power performance of a WEC with respect to the PTO damping for several different device configurations. The optimal level can quickly be located for use in later, more complex trials.

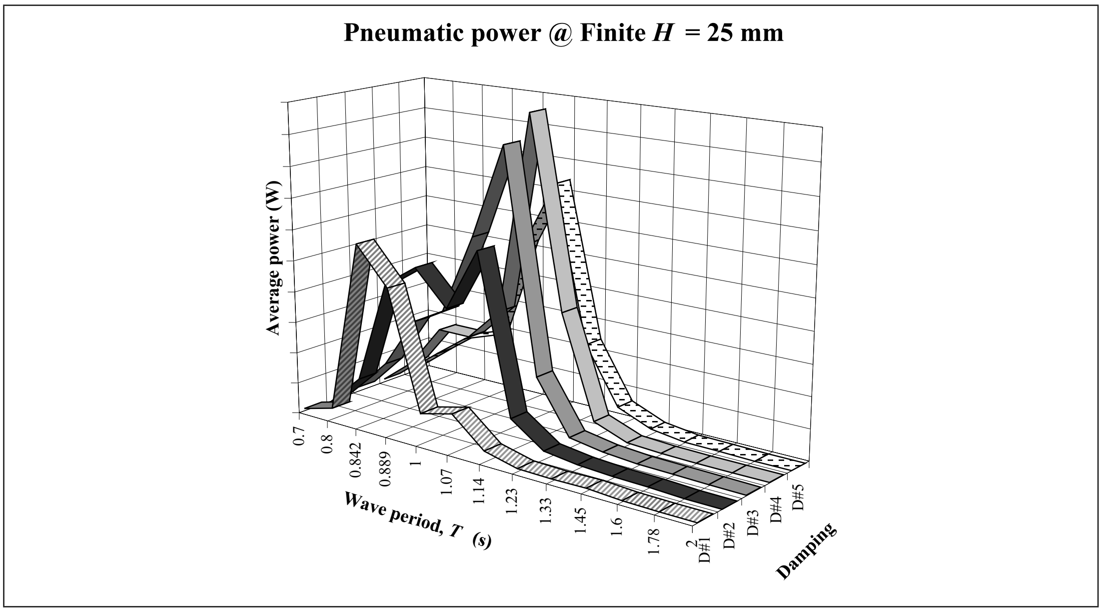

Figure 7 — Device configuration power comparison

3.2.4 Non-linear effects

As previously stated most numerical models, certainly those in the frequency domain, are based on linear wave theory. Small amplitude waves are therefore used when providing data for the mathematical model validation. Higher order effects can also be studied in regular waves by increasing the wave height and monitoring the physical parameters' corresponding response. Figure 8 shows a typical buoyant body's heave RAO at different wave heights.

It should be noted that the graph is the magnification ratio not the absolute motion of the body which will produce a different relationship.

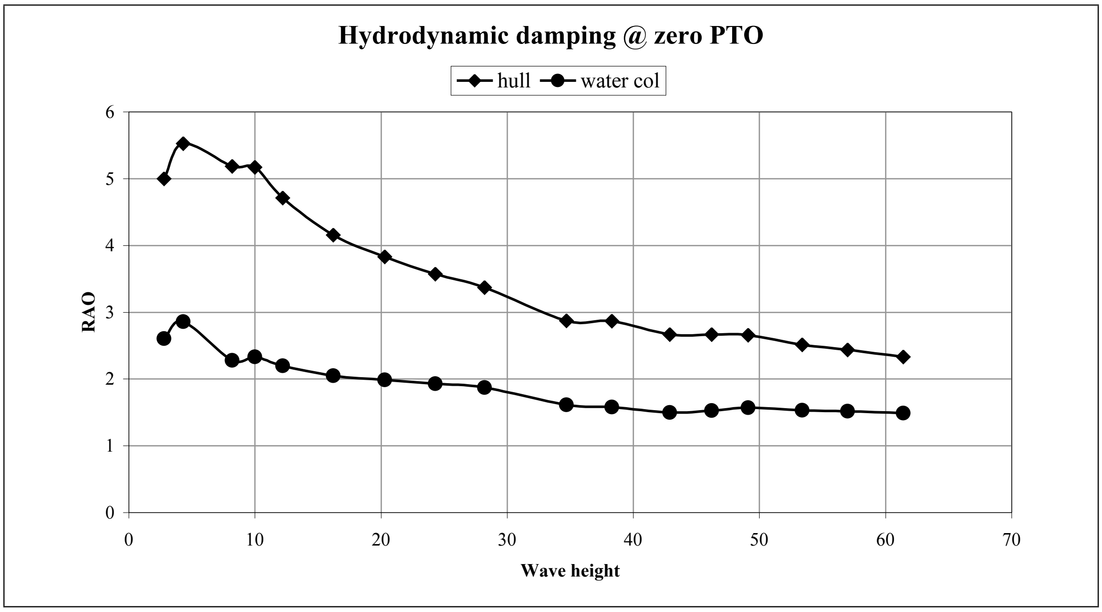

Figure 8 — Heave RAO transition from linear to finite waves

3.3 Use of irregular seas

3.3.1 General

Following the fundamental studies of a WEC in regular waves it is usual to advance testing into more realistic seaways. These are then applied throughout the advancing scale changes until the sea trial phase when they occur naturally and are no longer controllable and available on demand.

Whilst regular, monochromatic trials can be regarded as a method to learn how a device works, irregular, panchromatic trials begin to reveal how the device will perform.

There are certain important considerations when specifying a test programme in irregular waves:

- type of spectrum;
- length of wave time series;
- sea state summary statistics;
- directionality;
- spreading.

The discussions on these seaway options depends on several factors and in particular the phase of the device development. The following description includes some recommendations of best practices that have evolved over recent years.

3.3.2 Spectral selection

3.3.2.1 General

The main consideration at an early stage of testing is between the use of generic, classical spectra or site specific data. Primarily phase 1 trials are designed to compare the key design variables identified in the monochromatic stage. It is viable and valid therefore to adopt classical spectra, which most wave generation systems are capable of producing quickly, accurately and consistently.

It is also probable that the wave energy extraction device's final deployment site has not been established at this time. Indeed the unit could be under consideration for several locations. This more generic approach is required to account for all possibilities. Finally, site specific records may not be available at all, or limited in duration and mix.

3.3.2.2 Generic spectra

There are several classical spectral equations used to describe the frequency composition of an irregular water surface elevation time history. Some have their origin based in wind wave energy transfer processes whilst others depict the relationship with respect to the summary statistics of a particular seaway (i.e. H_s, T_p, T_e, T_z etc.). It is the latter designations that are of most interest to wave energy device developers since the sea state generation mechanism is of secondary importance.

Three principal spectral forms are:

1. Pierson–Moskowitz (one variable: T_p);
2. Bretschneider (two variables: H_{m0} and T_p);
3. JONSWAP (five variables: T_p, α_{PM}, γ, σ_a and σ_b).

Each of these seaway types are related and all produce the same wave conditions under specific circumstances. They are back-traceable such that a Bretschneider can describe a Pierson–Moskowitz and a JONSWAP can represent both a Pierson–Moskowitz and a Bretschneider.

This would infer that JONSWAP could be used as the base formula to accommodate all cases of classical testing. Two caveats can prevent this being the case. Firstly, the wave tank generation system may not be capable of producing sufficient variants of the spectrum, i.e. it is applied to a Pierson–Moskowitz equation rather than a Bretschneider. Secondly, insufficient information is available on which to design the spectral shape so default settings are used which then become Bretschneider spectra anyway. Figure 9 shows the relationship between the three options with the same T_p, but not for the same energy content so the shapes can be identified.

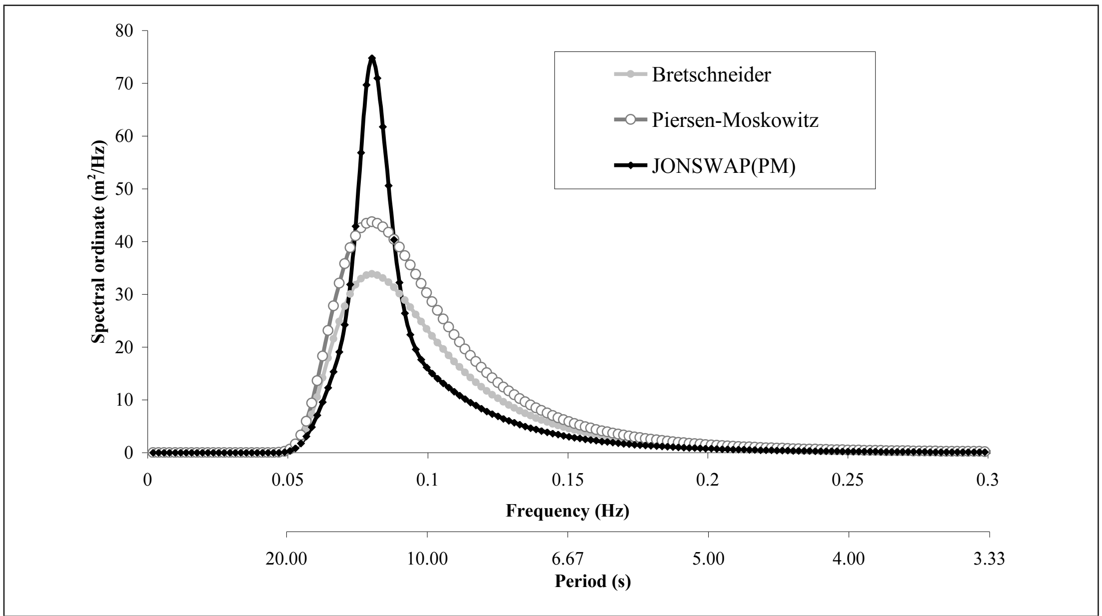

Figure 9 — Comparison of empirical spectral shapes

3.3.2.3 Site specific spectra

As testing moves into the latter part of phase 1 and certainly by phase 2 it is preferable and advantageous if actual site data, from at least one, primary deployment location, is used to evaluate the device performance and seaworthiness in these conditions.

By this time most principle device design options should have been finalized but their influence under different excitation scenarios need to be established. The importance of these trials obviously varies, depending on how much any particular station conditions vary from the classical shapes. In near-shore North Atlantic resource monitoring projects evidence suggests that by weekly average, and longer time periods, spectra begin to conform to standard conditions as shown on Figure 10. Individual seaways can be significantly different but the occurrence should be limited if they do affect the average.

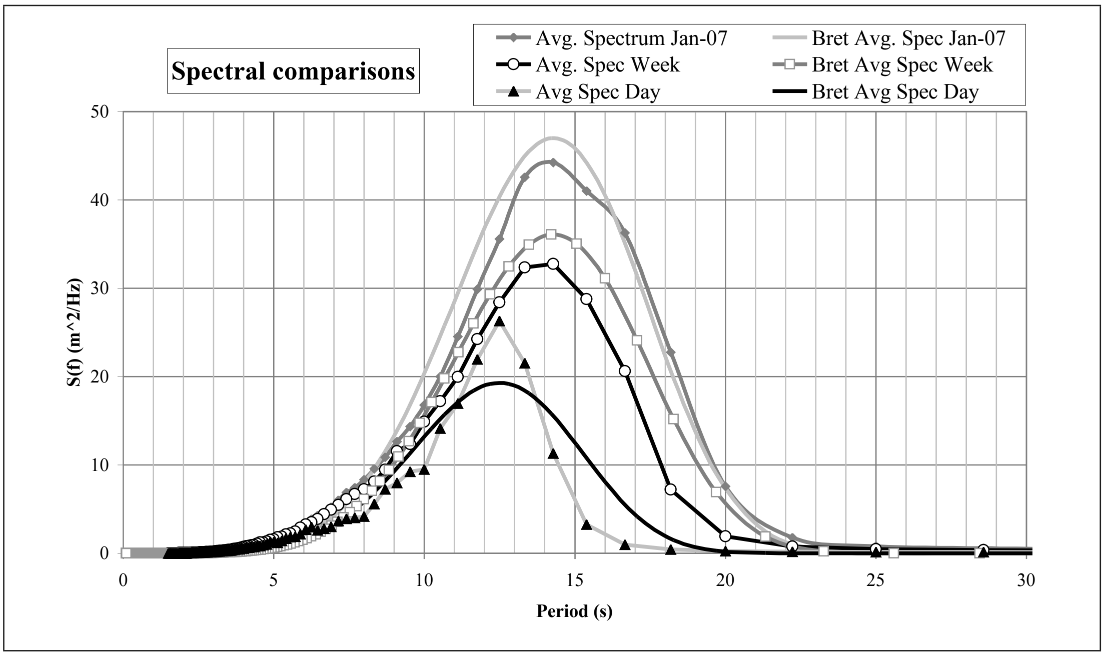

Figure 10 — Conformity of averaged spectra to classical shapes

3.3.3 Time series duration

The industrial standard length of time a seaway should be monitored to obtain accurate harmonic components of the time series is 20–30 minutes at full scale (i.e. approximately 150–200 waves). This can be adopted as the reference duration to apply for generating the spectra in tanks. The figure is based on two factors:

- temporal homogeneity of a seaway;
- appropriate maximum to average wave height ratio.

These criteria can be applied to most fundamental tank testing investigations considering a device's average performance and behaviour. Analysis of wave time histories derived from this approach should reveal that the correct Rayleigh type distribution of wave height is present, as shown in Figure 11. Test facilities (including benign sites) should also verify conformity to the conditions prior to testing.

Deterministic derived criteria can be defined satisfactorily in this duration. Probabilistic phenomena require longer wave time series to improve the confidence limit on the results. Also, storm durations are defined as 3 hours at prototype scale so for extreme testing it is conventional to take this extended period (see 4.2).

Recent resource studies have shown that storms can track much faster than this development criteria so site specific tests might require temporal modification.

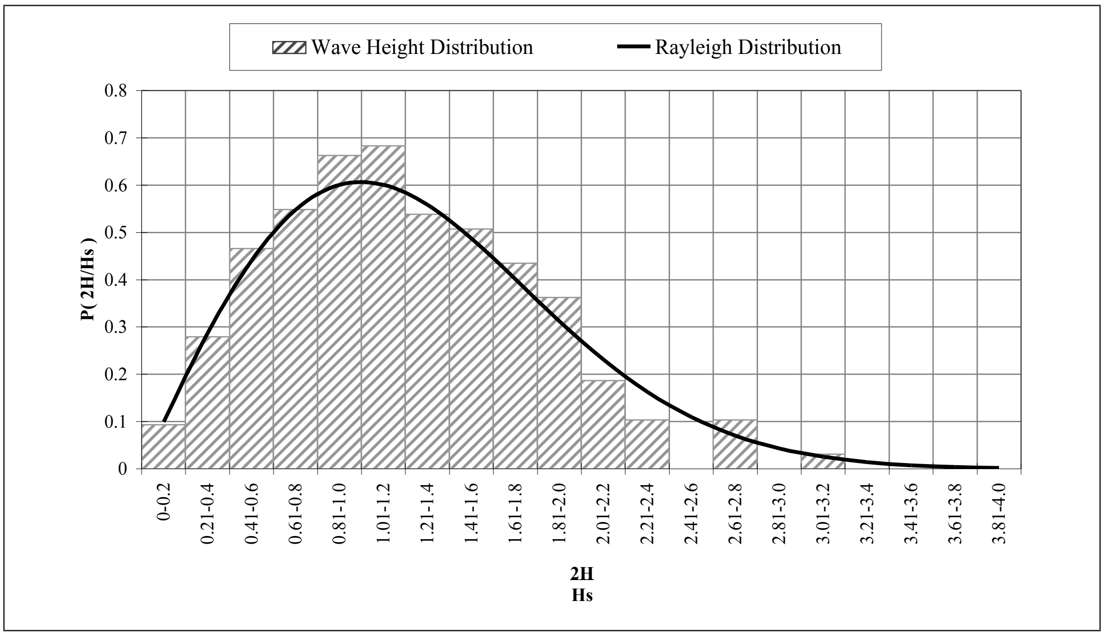

Figure 11 — Compliance of wave heights to Rayleigh distribution

3.3.4 Scatter diagram

Having defined the spectral shape(s) and duration appropriate for a series of tests the number of seaway to apply should be decided. This will be determined by the stretch of water in which the device will eventually be deployed (i.e. Atlantic, North Sea, Baltic, Southern Ocean etc.). The location defines the number of different height and period combinations that can occur. It is also a function of the scatter table step size used to produce the bivariate array. Experience has shown that a 1 m by 1 s element is sufficient to accurately determine the performance characteristic of a wave energy converter up to phase 3.

3.3.5 Directionality

3.3.5.1 General

There are two considerations regarding the question of wave approach angles and their importance depends on the sensitivity of individual devices to each. It would be expected that point absorbing WECs behave independently of both factors but this might not be the case when clusters or arrays of these devices are considered. Similarly, mooring effects will be influenced by wave directionality.

The two elements requiring investigation are:

1. mean approach direction (other than head seas);
2. energy spreading (i.e. wave crest length).

3.3.5.2 Approach direction

This is applicable for monochromatic waves and long crested irregular seas. It describes the mean angle at which the wave front impinges on the WEC. Axi-symmetric point absorbers (i.e. < ⅓ wavelength) would usually remain robust against this parameter but mooring arrangements will have an influence on the tests. This in turn will affect motions. Some trials at different mean approach directions should therefore be accommodated in the programme, especially bow, beam, quarter, following and a special case directly along a mooring line.

Approach angle changes can be produced by programming the wave generator or rotating the model and mooring configuration.

3.3.5.3 Energy spreading

This two dimensional aspect of seaways is less well described than the traditional one dimensional spectral shape. No agreed standard has yet been specified to cover general cases, mainly because there have been limited measurements of crest length criteria to date.

As with directionality the effect of this seaway parameter will vary, depending on the WEC under investigation. The best practice evolved to date is to generate an extreme spreading, for example a cosine squared ($\cos^2$) relationship which produces very short crest lengths, and monitor the difference in performance indicator between this and the long crested case.

4 Recommended wave tests

4.1 Energy capture performance

4.1.1 General

In all the phases of a test programme the device's ability to capture and convert the wave energy can be regarded as an important criteria. Programmes should be constructed around investigating the device design variables to optimize power production. Some practical aspects of this approach have been described in Clause 3. Manufacturing, materials, deployment and connectivity matters etc., should also be considered in economic reviews but these are somewhat more ephemeral criteria that can change over time whist the fundamental energy conversion will not.

4.1.2 Energy input

4.1.2.1 General

To successfully conduct an energy capture evaluation it is essential to define the wave energy available to the device, relative to a time scale.

4.1.2.2 Monochromatic waves

In phase 1 and the early part of phase 2, the investigations can be based on monochromatic wave excitation such that the effect of one individual design parameter can be assessed relative to itself. For the same input power two variants of the same device might display very different output power. Figure 12 shows this effect whereby the unit with the increased heave motion produces much less power, probably due to phase considerations.

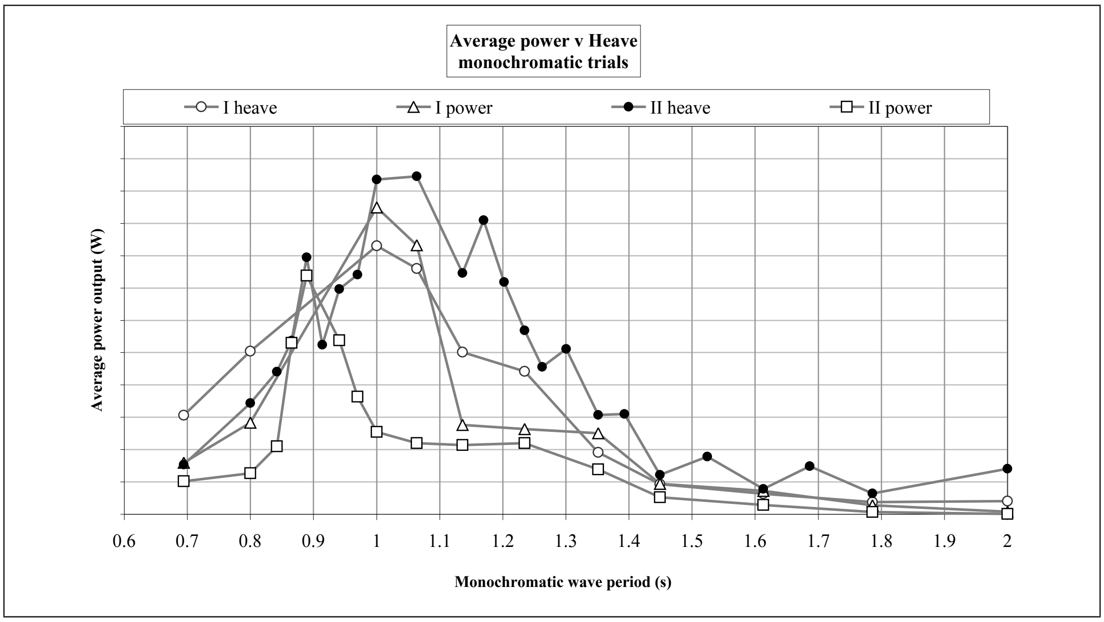

Figure 12 — Production and motion relationship

In higher waves it is usual that more power will be produced but as shown earlier in 3.2.4 the efficiency of a device will most probably decrease with increasing wave height. This is shown in Figure 13.

The input power of these monochromatic waves is derived from the equations defined in Table 4, i.e.

$$\text{Power} = \frac{\rho g^2 H^2 T}{32\pi} \text{ (W/m)} \approx H^2 T \text{ (kW/m)}$$

The amount of energy flux actually available to a wave energy converter can be expressed in several ways. Two common and recommended approaches are defined by:

- the hull width;
- the capture width.

a) Hull width
In this instance the power per unit length of wave front (W/m) is multiplied by an appropriate length scale taken from the device to define the total power (W) input to the WEC.

b) Capture width

An alternative definition of the power available to drive the wave energy converter derived as the quotient of the machine power and the wave energy flux.

$$C_W = \frac{\text{Device power (W)}}{\text{Wave power/unit length (W/m)}} \text{(m)}$$

A further calculation can be used to define the capture width as a ratio with the device width perpendicular to the wave front.

$$\text{ratio} = \frac{C_W}{D_L}$$

C_W: capture width
D_L: longitudinal dimension

NOTE Since the wave power equation produces the average power/wave cycle it is recommended that the average converted power is also used.

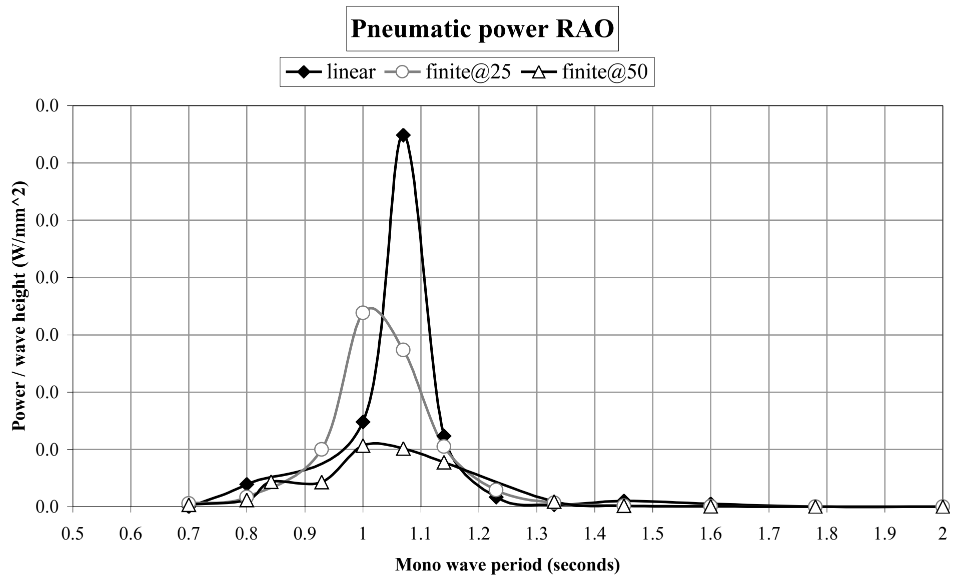

Figure 13 — Comparison of linear and finite wave excitation

4.1.2.3 Irregular waves

Having defined the device variables of interest the performance trials can progress to real seaways. The types of spectral shapes to be included have been described in 3.3 and can be selected from classical or measured data. Whichever the source, the important factor is to cover a spread of conditions such that the annual power production figure can be extrapolated.

For energy capture trials it is conventional that the test duration is a scaled equivalent of 20–30 minutes at prototype scale.

A similar formula and approach to that used for the regular wave definition can be implemented to obtain the wave power in real seas. These equations, however, are based on the measurement of the specific time period above which the stationary summary of that seaway are obtained, rather than a single cycle.

The wave power/unit length (in deep water) is defined as:

$$\text{Power} = \frac{\rho g^2 H_s^2 T_z}{64\pi} \text{(W/m)}: \quad \text{Time series analysis}$$

$$\text{Power} = \frac{\rho g^2 H_{m0}^2 T_{02}}{64\pi} \text{(W/m)}: \quad \text{Spectral analysis}$$

NOTE The power input or capture width are defined as for regular waves but now as a time averaged value.

4.1.3 Power absorption

It is not necessary to test all of the scatter diagram elements and the offshore industry recommended practice is to select 15–20 of these H_s-T_z combinations such that the overall behaviour of a structure can be determined. This policy is adopted for evaluating the performance potential of a WEC across the various seas it will encounter. Device engineers can then use this information to finalize design parameters to optimize annual output of a unit. Figure 14 shows an example of tailored seaways for any selected test site with the appropriate wave combinations marked. It will be noted that lines of constant significant wave height and average/peak period are included. This allows extrapolation graphs to be drawn up such that, if required, all elements of a bivariate table can be computed. An example of how the limited test data can be extended to seaways not included in the test programme is shown in Figure 15. As can be seen from this graph the changes between sea states becomes a deterministic relationship with no discontinuities existing in the curves. This enhances confidence in the extrapolation procedure.

During phase 3, input conditions are no longer controllable and should be accepted as they occur naturally. This imposes a greater requirement for organization and rigour when specifying test programmes. It is not sufficient just to obtain the seaway summary statistics since most WECs are resonant oscillators which respond in the frequency domain. The full spectrum should be obtained from surface elevation time series such that performance values can be related to known similar input conditions. Figure 16 shows an example of measured power performance for seas exhibiting the same statistics but with significantly different spectral shapes. In this case a wave energy device would not generate similar power levels for this sea state due to resonance characteristics.

This matter is explained in more detail in the analysis in Clause 6.

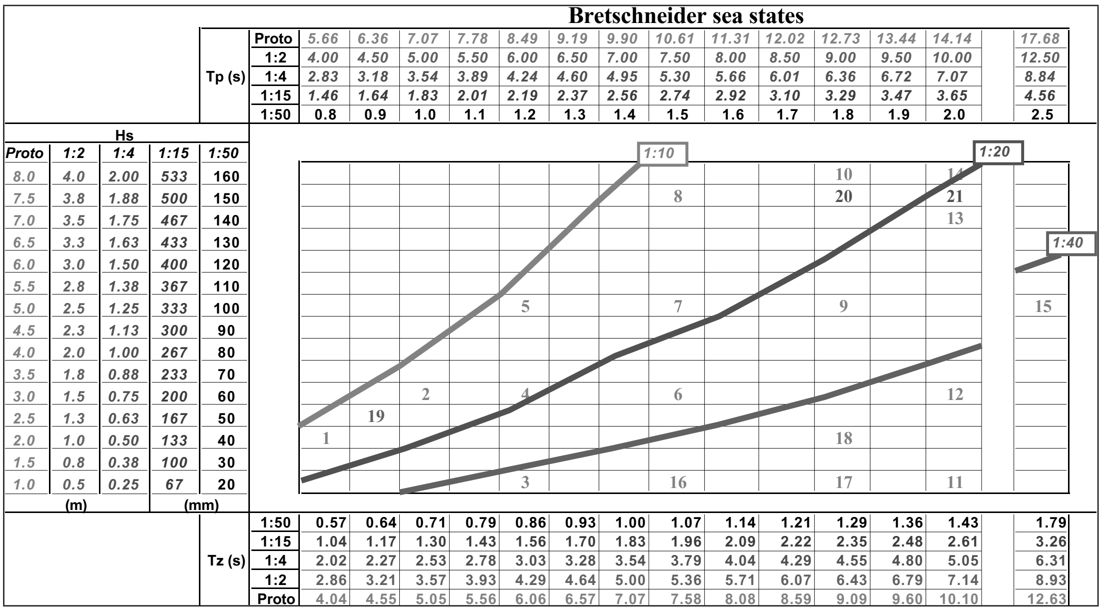

Figure 14 — Scatter diagram of test seaways

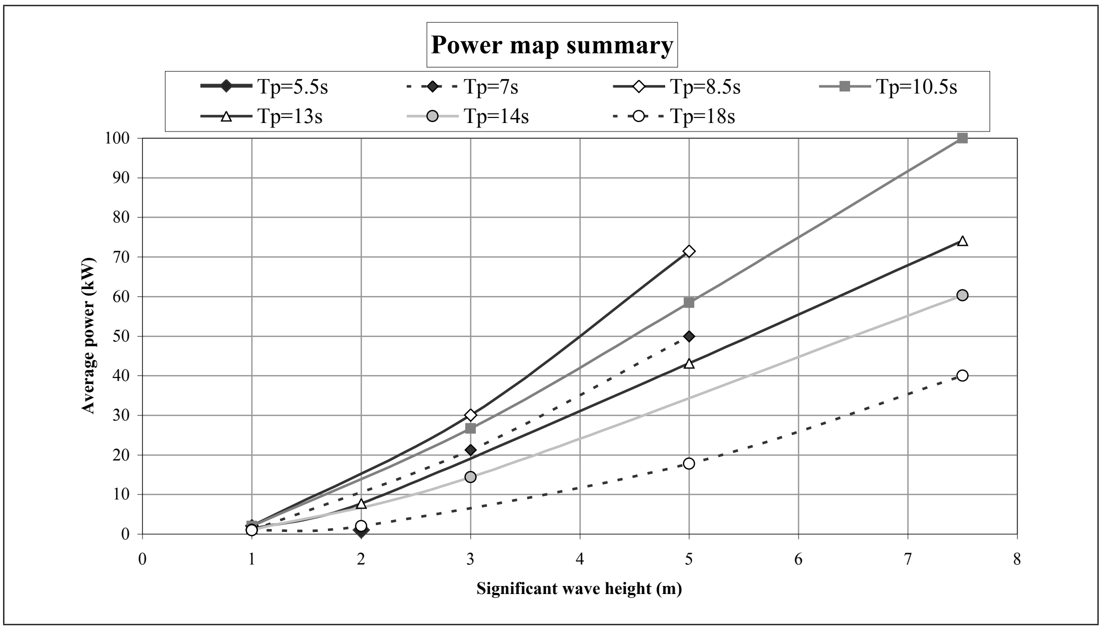

Figure 15 — Isolines of peak period

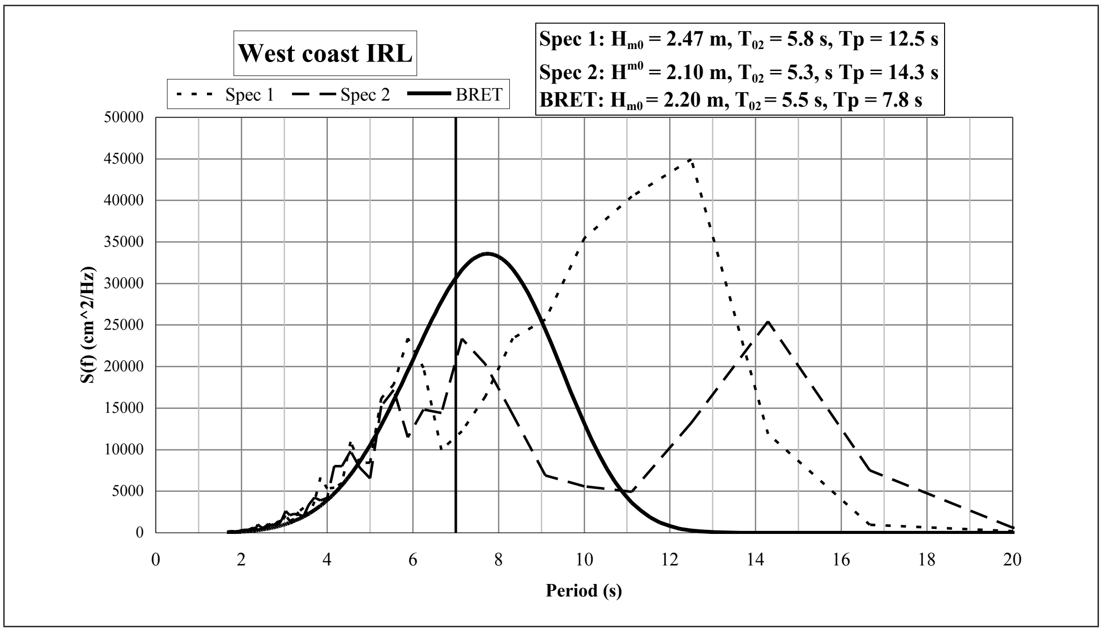

Figure 16 — Spectral shape variation of scatter diagram element

4.1.4 Power conversion

During phase 1 tank testing PTO simulators are employed. It is sufficient for the mechanism to be adjustable at stepped values which apply external damping to the relative motion between the WEC's inertial masses. When equipped with a force (or pressure) transducer and the corresponding body motions are measured, the instantaneous absorbed power can be calculated for each specified damping setting, since for example:

Power = Force × Velocity

As shown in Figure 17 the two parameters can be graphed to establish that a representative simulator has been selected. These trials produce the maximum power performance since the PTO has no constraints, such as end stop, or decoupling, that will be presented in a real PTO. They are to provide the environmental load data, including extremes, from which the PTO rating can be derived.

Phase 2 trials are fundamentally to expose the device to sea conditions likely to be encountered by the prototype machines. However, because the model is physically larger a more sophisticated PTO simulator can be incorporated. This is not essential at this time but can be regarded as advantageous to progress. The primary requirement for all configurations is that the characteristics of the final PTO are reproduced. This statement assumes the PTO is known, which might not be the case. Experience has shown that unless a very complex type system is to be used a high quality energy dissipater provides a generic representation suitable for most options. The exception to this general rule is if the PTO will include a control feedback option that attempts to tune a device to the incoming waves as a time domain system. For such experiments a more complex PTO model is required.

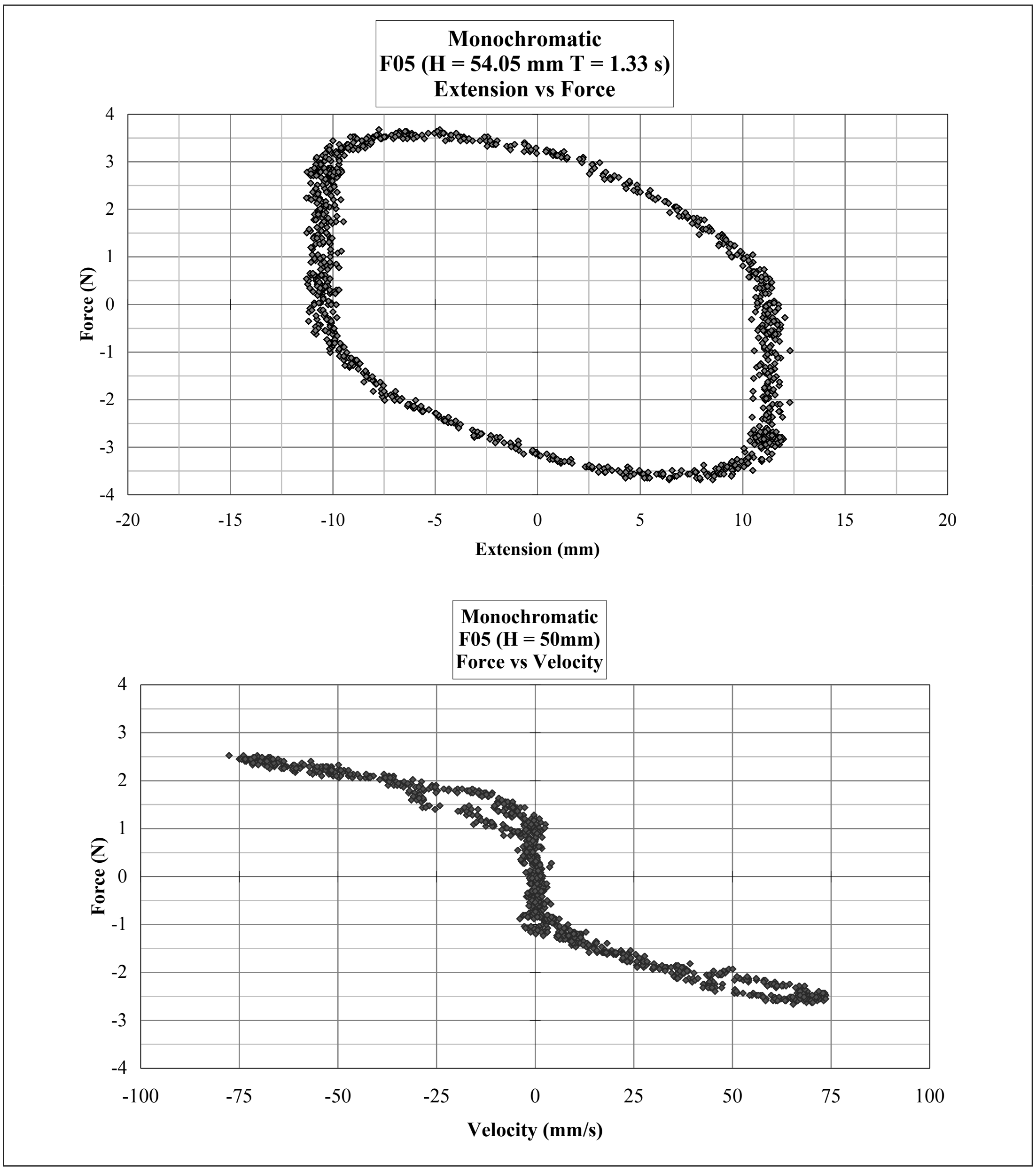

Figure —17 Force, extension and velocity relationship of modelled PTO

Work over many years at Edinburgh University has concentrated on developing electro-magnetic motors that can be adjusted in real time by a predetermined source feedback signal to facilitate active control. Although they can operate at the small phase 1 scale the advantages off conducting this work on a medium scale phase 2 model are recommended.

4.1.5 Output power

By phase 3 sea trials, it would be expected that an operational PTO and generator combination is under investigation rather than the secondary conversion system. A scaled design of either a pneumatic air turbine, hydraulic or direct drive generator should be incorporated. This might have to be specifically designed for the large scale application, rather than direct copies of the final full size prototype PTO, but the characteristics will be similar. This ensures results from the trials can be confidently extrapolated. Even at this large scale electricity output levels are small due to the Froude scale factor for power. This limited level makes connection to the grid a moot point which can be decided by convenience, cost or public relations issues.

The calculation below is an example of this power scale issue for a 1 : 4 design.

Power (kW) $\rightarrow \lambda^{3.5} \rightarrow 4^{3.5} = 128$
$\therefore$ 1MW Prototype ≈ 8kW @ ¼ scale

It should not be regarded as a requirement for phase 3 sea trials that a link to the local distribution network is required. The restricted power rating enables resistive load banks to be used to dissipate the energy, even the high peaks experienced in irregular seas.

Technically, even if the connection was made, it can not be regarded as addressing multi-megawatt prototype grid issues. Other power electronic options, however, do scale sufficiently for the developer to investigate supply matters with the aim to improve the quality of the electricity output. It would be recommended that this work should be studied on dry test rigs prior to sea trial deployment if possible. However, such test programmes are beyond the scope of wave tank trials.

NOTE Established large scale test site owners may be encouraged to provide a power cable since multiple use could validate the expense of connection.

4.2 Survival tests

4.2.1 General

Before undertaking phase 3 sea trials it is important to conduct specific trials to establish the seaworthiness of the WEC, both for the hull(s) and the mooring. These tests are to provide the extreme motions and loads exerted on the hull, power take-off, mooring lines, anchors and foundations for fixed or gravity structures.

Initial investigations can be undertaken at the small scale but it is highly recommended that the scenarios studied are conducted using a medium scale model in an appropriate sized basin.

Sections of breakwaters, or other fixed type devices, can still be studied in 2D flumes but the medium scale would still be recommended.

The selection of wave conditions becomes an important issue, as described in this subclause, but in general the duration of trials would be extended from the half hour general trial specification to a typical storm length of 3 hours at full scale. This becomes approximately 30 minutes at small scale and 45 minutes at medium scale. Since these are quite long trials the number of sea states investigated may be restricted.

An important consideration when developing the survival test programme is that most simulation test facilities have a limitation on the size of waves (sea states) that can be produced. Although the conditions that will combine to produce the extreme loads are not well defined some trials will be conducted in high energy seas approaching 50–100 year storms. This means the scale of the model used for these tests might require adjustment from the energy capture model. An alternative can be to a use small scale model in the medium size facility as a compromise.

Short crested seas and directional wave approach should be included in the overall programme for each of the test types described below.

The selection of sea states will usually lie between the fully exposed limit (S_s = 1 : 10) and the fully developed sea line (S_s = 1 : 20).

4.2.2 Seakeeping characteristics

As stated in 3.1 these trials can be conducted at small scale providing the test facility can generate high seaways. These need not necessarily be only the highest energy seas but also steep waves in shorter period seas where the breaking limit is being approached. Devices should be observed under operation conditions with the PTO working and also failed scenarios modelled with both zero damping and infinite damping. Individual trials should be conducted over an extended test period. As suggested above the recommendation is a scaled equivalent of a 3 hour storm such that the wave train series will contain sufficient individual waves to produce an acceptable H_{m0}/H_{max} ratio (i.e. 1 : 1.8–2).

4.2.3 Extreme environmental loading

It still remains a debated topic as to which wave group combination produce the worst loading condition on a structure, mooring or foundation. This aspect might also be a device specific issue so observation made during the seakeeping section, phase 2, should provide pointers to specific test cases requiring review. For floating devices it is possible that periods close to one of the resonance responses will create maximum loads in the hull structure and moorings.

NOTE The recommendation would be that investigations into this area are conducted at the intermediate scale (circa λ = 1 : 15) though indication can be inferred during small scale trials.

4.2.4 Extreme motions

Knowledge of the device fundamentals will assist in the design of tests aimed at monitoring and measuring response to irregular wave excitation. This series of trials will be an extension of the seakeeping programme and can be combined with it. Tests can be constructed along the wave breaking limit (S_s = 1 : 10) and include seaways based on each of the six degrees of motion (6 degrees of freedom (DoF)) natural periods. Angled seas should be included or the model (and mooring) rotated to ensure all motions are observed. Short crested seaways should also be used since, although these conditions tend not to create maxima, they do excite all the motions simultaneously.

4.2.5 Most demanding sea state

Identifying the worst seaway in terms of motion and/or loads of the device can only be achieved by testing across a range of conditions and/or spectral shapes. The combinations for these are extensive therefore a systematic sweep approach should be adopted. The details for selecting bins from a wave scatter diagram was covered in the previous section so in this instance selected H_{m0}–T_{02} combinations based on a classical Bretschneider spectrum should be used to attack the model. From the worst cases a set of adjusted JONSWAP offering increasing peak factors will reveal the sensitivity of the device to wave steepness. Twin peaked and bimodal seas can contribute to these and the previous survival tests.

5 Test equipment

5.1 Model design

5.1.1 General

As well as being correct in geometric scale, physical models should be exact dynamic replicas of the prototype device they represent. This is achieved by following fixed scaling laws based on Froude similitude criteria and similarity conditions.

A full description of the relationships can be found in Clause 6 of this document but basically all physical properties can be related via inertia scaling such that:

$$\text{Froude number, } Fr = \sqrt{\frac{\text{inertia force}}{\text{gravity force}}} = \frac{v}{\sqrt{gL}}$$

v: stream velocity
L: dimension

Applying this relationship means models can be constructed and tests run which are in geometric, kinematic and dynamic similarity.

For static, or fixed station WECs, only the device geometry need be scaled. For buoyant, floating WECs the key parameters are the mass distribution and associated moments. These dictate the response periods to wave excitation for each of the 6 DoF.

Small and medium sized models (phases 1 and 2) are rarely manufactured from prototype materials. The customary design principle is therefore to construct a model that is lighter than the prototype such that lead ballast can be added at strategic locations to produce the required dynamic characteristics.

5.1.2 Principle physical properties

5.1.2.1 Centre of buoyancy

A location within the frame of a floating body which represents the centre of mass of the water displaced by the submerged portion of that body. When mass and hull dimensions are correct the centre of buoyancy (CoB) will automatically adjust. The exception to this, which is relevant to WECs, is when the body walls are proportionately thick and water is present on both sides. This produces an increased displaced volume and thus a reduced draught. Models should be heavier in air to compensate, which is obviously a compromise.

5.1.2.2 Centre of gravity

This is a point within the frame of a floating body where the total mass of the body can be represented by a point mass. The placement of mass about the body structure influences the position of the centre of gravity (CoG).

5.1.2.3 Mass moment of inertia (I_{xx}, I_{yy}, I_{zz})

This is the distribution of the mass of an object relative to a given axis. It is a measure of an object's resistance to changes in its rotational rate, and is calculated as the product of the distance from the rotational axis squared and its mass. The units are mass × area.

$$I_{jj} = \sum_{1}^{i} m_j \delta_j^2 \quad (\text{kg m}^2)$$

5.1.2.4 Second moment of area (I_x, I_y, I_z)

The second moment of area of the water plane is particularly important for floating bodies. Also known as the moment of inertia of a plane area, this is a measure of the restoring moment and is given by the area multiplied by the distance to the rotational axis squared. It has units of metres raised to the fourth power. It is a similar property to the mass moments but based on distributed area.

$$I_j = \sum_{1}^{i} a_j \delta_j^2 \quad (\text{m}^4)$$

5.1.2.5 Water plane area

This is the area on the water surface broken by a protruding body (m^2). If it is assumed that there is no significant change in the water plane area during heave motion, the ship is said to be side walled at the load water line (LWL) and this parameter can then be expressed as a block coefficient, which is the ratio of the actual area and the bounding rectangle.

5.1.2.6 Metacentre

This is the point at which a vertical line through a tilted centre of buoyancy and centre of gravity crosses the line through the non-tilted conditions.

This point can also be estimated from the quotient of the second moment of area about the water plane and the displaced volume through the equation:

$$\overline{BM} = \frac{I_j}{\nabla} \quad \text{(m)}$$

5.1.2.7 Metacentric height

This is the distance from the centre of gravity to the metacentre. $\overline{GM}$ represents the static stability of a floating body and it is depicted schematically in Figure 18.

$$\overline{GM} = \overline{BM} - \overline{BG}$$

GM: distance from the CoG to the metacentre along the vertical axis
BM: distance from the CoB to the metacentre along the vertical axis
BG: distance from the CoB to the CoG along the vertical axis

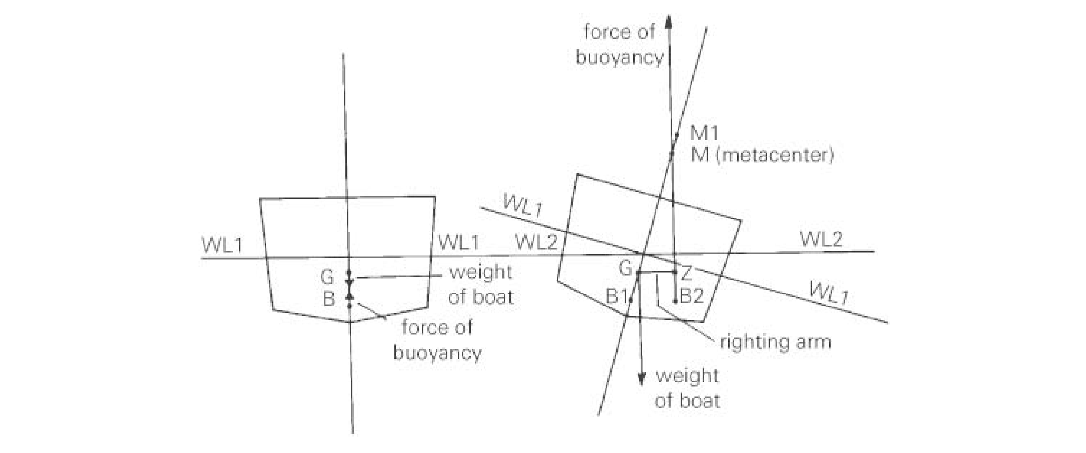

Figure 18 — Hull geometry

5.1.2.8 Added mass and added inertia

This is the change of hull mass and inertia caused by a volume of water that is required to move with the hull. These values are frequency dependent and can either be obtained from mathematical models or empirically by the following series of model validation procedures.

5.1.2.9 Dry rig tests

Following construction the mass properties of the model should be confirmed by various standard balance and suspension practices.

The centres of gravity can be determined in three ways.

i) Firstly by placing the model on a sharp edge until it is balanced. This is repeated for each of the axes the model shape accommodates.

ii) For models that will not facilitate this approach a suspension method can be adopted. For an irregular hull shape if the longitudinal CoG has already been located by the balance method a plum line dropped from the hull suspension point crosses this plane at the vertical centre of gravity.

iii) The hull is suspended horizontally from points on a particular plane and a small weight can be added off centre of that axis to induce a trim or heel. Accompanying equations then produce the location of the centre of gravity whose axis is perpendicular at the suspended axis.

The three dependent mass moments of the inertia are verified separately by the bifilar suspension method. Two long suspension lines are attached to the model about the axis of interest. The model is then caused to rotate about that axis and the oscillatory frequency recorded. Associated formulas permit the mass moment of inertia in that plane to be calculated.

5.1.2.10 Wet rig tests – static stability

Following on from the dry rig, water trials can be used to further validate the model configuration. For these an appropriate moving mass is located on, or vertically above, the horizontal centre of gravity. By displacing this mass along a principle longitudinal or transverse axis the device is inclined at angles, which are measured. A plot of these settings, relative to the applied moment, as shown in Figure 19, reveals the metacentric height ($\overline{GM}$).

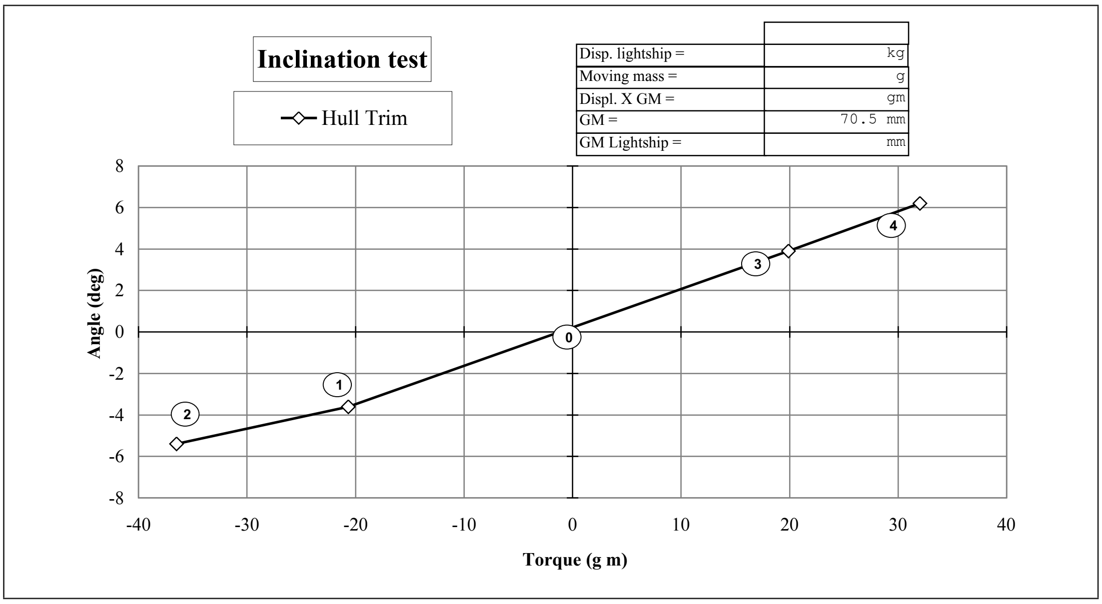

Figure 19 — Inclination test results

Following these tests, sufficient information is available to calculate the important dynamic characteristics of the hull, i.e.

- Heave resonance:

$$T_H = 2\pi\sqrt{\frac{M+M_a}{\rho g A_{wp}}}$$

M: mass of the floating body
M_a: the added mass of the floating body
A_{wp}: water plane area

- Pitch (roll) resonance:

$$T_\theta = 2\pi\sqrt{\frac{I_{yy}+I'_{yy}}{\Delta \overline{GM} g}} \; ; \; \left(T_\theta = 2\pi\sqrt{\frac{I_{xx}+I'_{xx}}{\Delta \overline{GM} g}} \right)$$

5.1.2.11 Dynamic stability

These calculated natural periods should then be checked dynamically in water. The hydrodynamically restored degrees of freedom (heave, pitch and roll) are evaluated directly by both free oscillation and forced oscillation trials.

a) Free oscillation
This reveals the eigen period of the parameter under investigation. The hull is given an initial displacement and allowed to return naturally to its still water equilibrium position. A typical trace of the resulting free oscillations is shown in Figure 20. The period of oscillation for each mode is the resonant frequency for that degree of freedom.

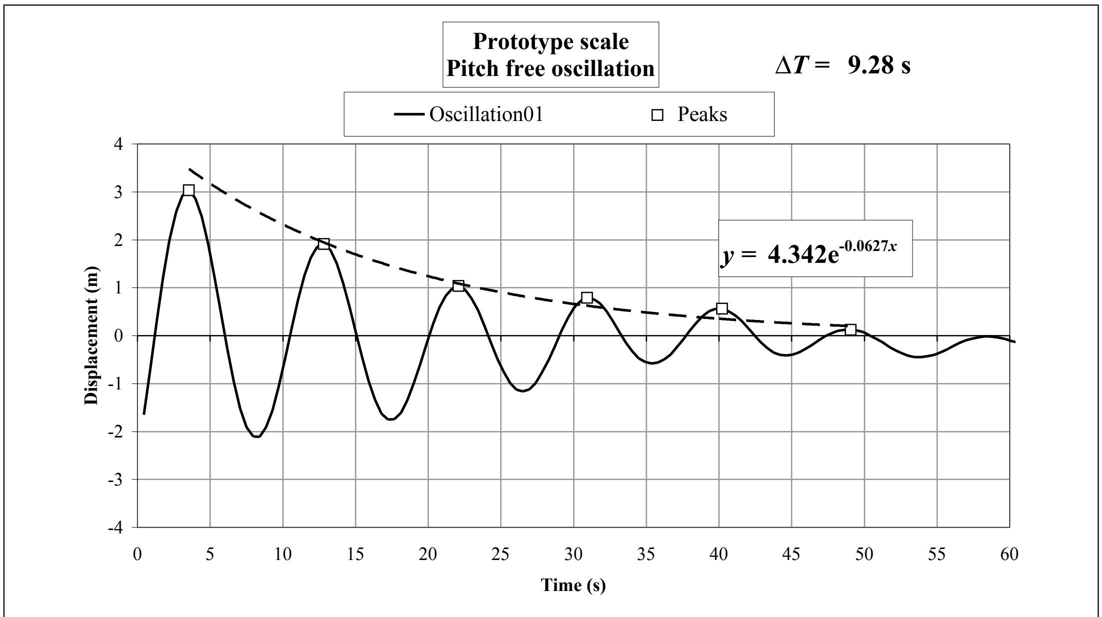

Figure 20 — Free oscillation test

These tests also reveal the amount of hydrodynamic damping present. This is shown by the reduction of the motion with time. The exponential decay is the curve the oscillation peaks trace, the dotted line in Figure 20. This damping is a combination of the primary component, wave-making, and any viscous forces present. The latter is usually in the form of vortex shedding and can be proportionally high in poorly constructed models.

The exponential declination curve is used to calibrate mathematical models if theoretical and practical result comparisons are planned.

b) Forced oscillation

These trials are the results of waves being used to excite the device. Initially monochromatic waves are used but panchromatic seas can also be engaged. Usually irregular waves are for specific purposes or during phase 3 sea trials when there is no alternative. Primary characteristics investigated by this method produce the RAOs of the device.

Response amplitude operators: RAOs are the response of the body relative to the wave excitation. A range of single frequency sinusoidal waves are independently impacted on the device and the responses (motion, force, power, etc.) to each are measured and plotted as the ratio with the wave, as shown Figure 21. This represents the fundamental characteristic of the resonator to harmonic excitation, as will be present in ocean surface waves. From the RAO, the behaviour of the device in any irregular sea can be predicted. The peak period on the graphs should coincide with the natural period measured by the previously described methods.

A similar plot can be generated from real seas by spectrally analysing the irregular time history. A typical example is also shown in Figure 21 where the heave response of a device to the frequency components is plotted and compared to the regular wave RAO.

One advantage of the irregular wave technique can be that frequencies outside those tested in the monochromatic trials exist as harmonic components in the spectral analysis and so the frequency range is extended. However, care should be taken that large peaks in the RAO in this extended range are not a function of noise contamination and very small number division.

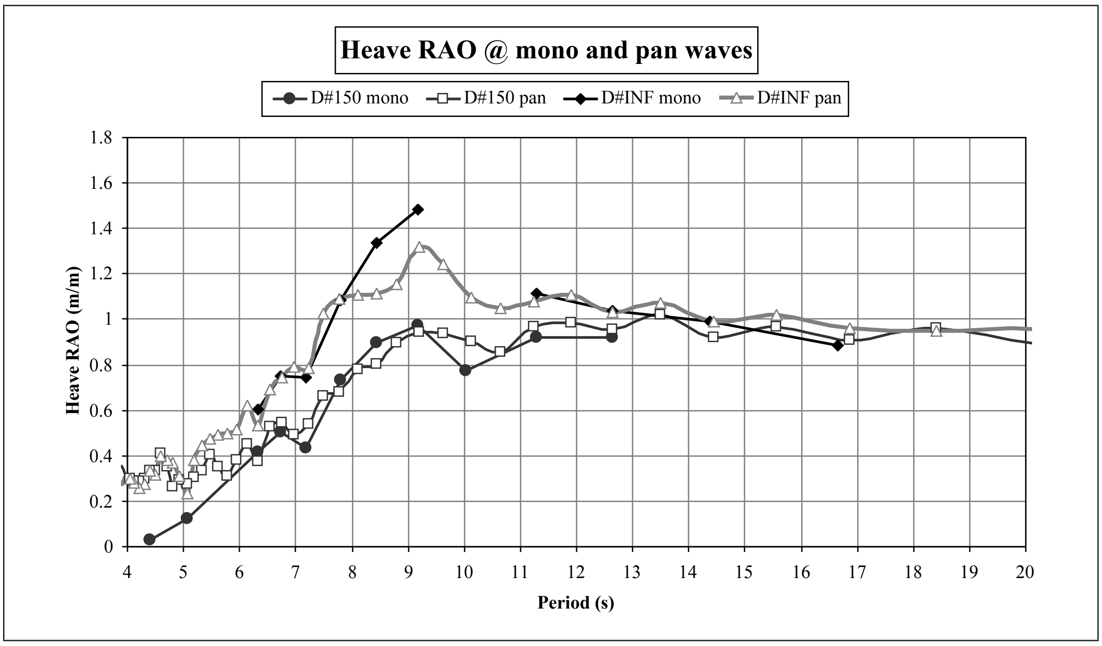

Figure 21 — RAOs derived from regular and irregular trials

The regular wave trials can also be used to produce the phase relation graph, as shown in Figure 22. This procedure is described in more detail in Clause 6. Resonance occurs when the phase shift between excitation and response is at 90°.

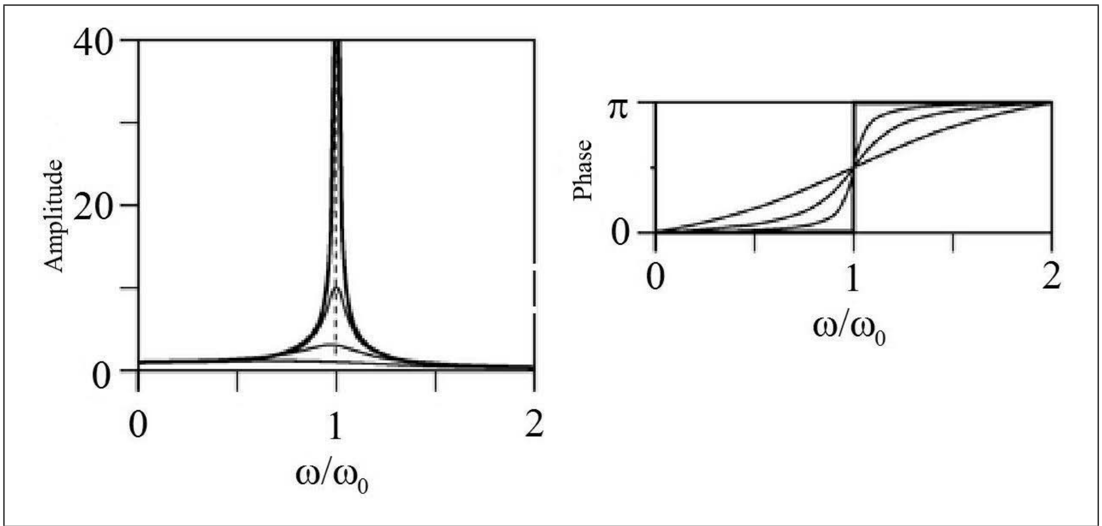

Figure 22 — Relationship between phase and RAO

When the device is moored the missing 3 DoF can be included in the investigation to reveal the second order motion caused by the restoring of the mooring. This information is essential for the mooring design consultants.

The following Table 5 summarizes the degree of freedom situation.

Table 5 — Degrees of freedom

Heave	Hydrodynamic restoring
Surge	Mooring restoring
Sway	Mooring restoring
Pitch	Hydrodynamic restoring
Roll	Hydrodynamic restoring
Yaw	Mooring restoring

There are many variables that can be consulted through the RAOs although more generally these would be the motions.

However, other properties of the device can be characterized by this methodology, such as pneumatic power, force, pressure, etc. By following this approach the characteristics affecting the device performance can be isolated and optimized design parameters located.

5.1.3 Mooring

It is important that the station keeping system is also scaled correctly. The practicality of this depends on the complexity of the proposed mooring system. For simple catenary arrangements it is usually possible to directly scale the mass/unit length of the prototype, which automatically produces the correct load extension curves for a given design. A typical catenary characteristic is shown in Figure 23.

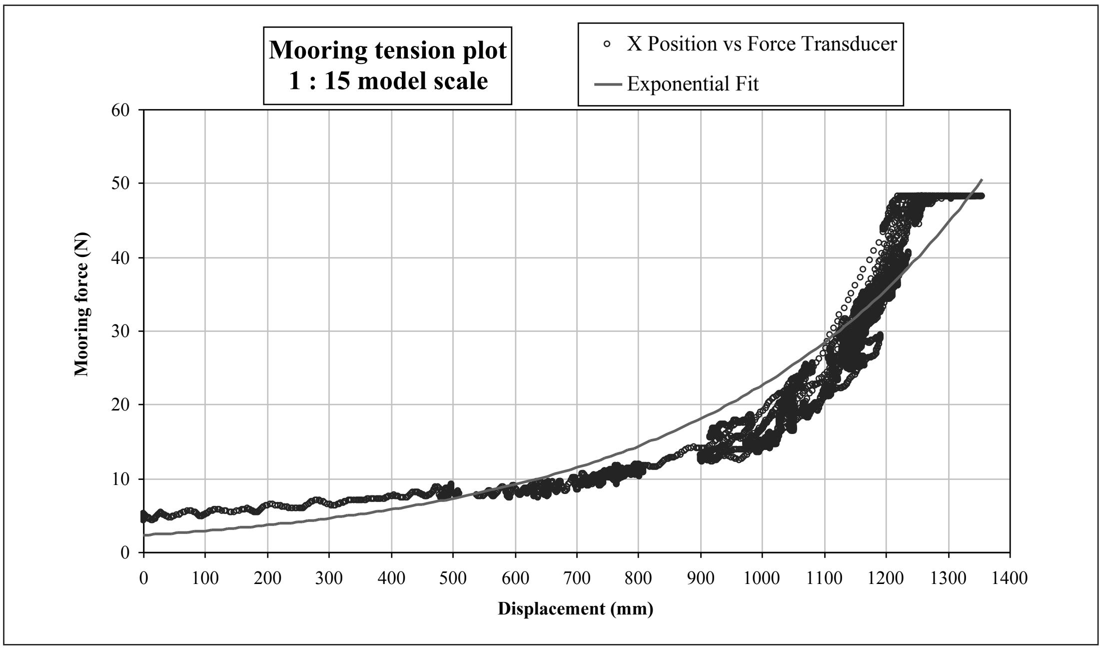

Figure 23 — Mooring tension graph

The fidelity of the modelling should be verified by either hanging weights on the mooring or, if a force transducer is fitted in the line, displacing the model and recording the excursion and corresponding line tension.

When the elastic properties of the mooring lines play a roll in the system a trial and error process of selecting appropriate material should follow. As above, the acceptability of the solution is verified by an empirical load extension similarity.

If buoys are included in the proposed mooring these too should be scaled accordingly. For these units it is the hydrodynamic stiffness, rather than the mechanical stiffness that is important. This can be achieved by geometry and mass similarity.

Until phase 3, anchors can be functional clump weights. Even at the large scale the methodology of scaling the overall system remains the same, as described above.

5.1.4 Model construction

5.1.4.1 General

The materials used for the fabrication of the device will be a function of which phase of testing that is under consideration.

5.1.4.2 Phases 1 and 2 – laboratory tanks

As mentioned earlier small and medium scale models are rarely constructed of prototype materials. Because of this components are not failure tested but rather forces that will be encountered and can be measured for use in full size design integration.

Light alloys, fibreglass and various plastics form the main elements of models and should be selected for suitability of purpose. Acrylics (perspex) can be of particular interest since they are close to the density of water and therefore almost neutrally buoyant. They are also available in transparent forms so useful viewing ports can be incorporated in models to facilitate observation of inertial behaviour, such as inside an oscillating water column plenum chamber.

The value of observation, in addition to measurements, is often underestimated during scale physical model testing programmes. Test runs in storm conditions often offer the only opportunity the engineers will have of witnessing the WECs in seas bigger than could be safely encountered in nature, even at benign test sites.

5.1.4.3 Phase 3 – benign site

Phase 3 models will probably be in prototype materials scaled accordingly. This is not a trivial task, however, since geometrical scaling can lead to the material, such as steel, being too thin for the required strength. Non-scaled materials, however, can produce heavy models since mass is the cube of the linear scale (λ^3).

Large individual components, such as the PTO and power electronics equipment, can be an even greater problem for design engineers at quarter scale. However, experience at the Nissum Bredning and Galway Bay benign test sites suggest that elegant solutions can be achieved with engineering ingenuity. It should not be necessary to resort to exotic lighter materials although these can always be considered.

5.2 Test facilities

5.2.1 General

There are several types of hydraulic test tanks but the three primary ones for wave energy use are:

- towing tanks (2D);
- flumes (2D);
- basins (3D).

In addition to these is the:

- benign site.

The size of the tank should be selected by the test phase under investigation, paying particular attention to the water depth and wave generation capability.

5.2.2 Towing tanks

These were initially constructed for ship model testing. They are long and narrow with a movable carriage that can be driven along the tank to propel the model through the water. Large towing tanks can be a few hundred metres long and although this means they are several metres wide only two dimensional waves can be generated.

Two specific advantages that towing tanks have are:

- long devices can be accommodated;
- short tests can be conducted before the wave field reflects back from the downstream beach.

The main disadvantages that towing tanks have are:

- only long crested seas can be produced;
- side walls are proportionally near so radiated wave reflections result in simulated array effects;
- the mooring footprint might be too wide for accurate deployment.

5.2.3 Flumes

These are similar to towing tanks in that the longitudinal dimension is much greater than the transverse width. However, they do not have driven carriages so are usually much shorter than towing tanks. Flumes vary in size from a few metres to several dozen metres depending on their primary purpose. In general most would conform to being 1–2 short wavelengths wide (i.e. $T = 1.2$ s, $\lambda = 2.25$ m $\rightarrow$ width ≈ 2.4 m)

As with towing tanks flumes have not been constructed for wave energy device testing so should be selected to fit a specific purpose. A selection of flumes include current flows which might be important to check mooring forces and hull behaviour under a limited number of conditions.

Small flumes can be ideal tools for producing two dimensional results for mathematical models or studying new or unproven concepts.

Irregular seaways will be long crested in nature and side wall effects should be considered.

Reflected waves will be present during even short trials.

5.2.4 Basins

These are proportionally wide to their lengths. In general those available internationally are useful for model scales of $\lambda = 1 : 10–100$, and so cover the phases 1 and 2.

Monochromatic and panchromatic long crested seaways can be generated and in advanced facilities short crested directional and bimodal seas can be produced.

Since the side walls are now in the far field, radiated waves present less of a problem. However, the additional width means more transverse modes of oscillation can occur so care is required that cross waves do not develop to contaminate results. Most tanks have specific frequencies to avoid, especially since standing waves are very slow to dissipate as there is no absorption mechanism on the side walls.

In some facilities paddle banks are fitted along one side and sophisticated programming moves paddles independently such that spreading seas occur. An alternative to this approach is to have paddles down two adjacent walls so waves can be propagated from both directions. The choice of facility can become a question of final deployment site conditions.

Both solo and arrays of devices can be studied in 3D basins. Mooring arrangements can usually be accommodated.

The common requirement in each of the tank types is the wave generation system and the downstream energy absorption beach.

Wave generation systems are usually either mechanically or hydraulically driven and computer controlled. They should be capable of producing the variety of waves described in other sections of this report, that is monochromatic and short and long crested irregular seas. There can be other less important features not covered in this document that produce rare events or complex frequency mixes.

The range of wave periods is often the same in different sized tanks but the height that can be generated increases proportionally in the larger, deeper tanks. The functional components of all generation systems are the paddles.

5.2.5 Benign site

There are several important issues concerning the selection of an outdoor test site. These are:

- accessibility, a local convenient and available harbour for light service tasks;
- a nearby port for launch and delivery to site of the model;
- prearranged licences and consents for deployment;
- pre-deployed wave measurement instruments;
- distance to landfall;
- correct water depth;
- appropriate seabed and bathymetry;
- acceptable wave climate.

Of these the most difficult to achieve is the last, the local wave climate. These should be as close as possible to the scale conditions found at the site the test station is representing. There can be more than one representation at different scales.

5.2.6 Wave paddles

Wave paddles come in many forms but the principle of operation is similar for each type. Each paddle has a Biésel transfer function which relates the wave amplitude to the paddle displacement. The most common paddle types are piston and flap.

Piston paddles stay vertical and oscillate in a horizontal translatory mode. Flap types are hinged at the bottom so oscillate in a rotational motion. The latter are regarded as more appropriate to deep water wave production since they cause the water particles to develop orbital velocities quicker than piston paddles.

In well equipped facilities flap paddles have a mid-depth additional hinge and are designated second order types. These can be controlled such that they produce waves with a pure sinusoidal profile whilst single hinge types exhibit higher harmonics and bound waves.

Through the use of sophisticated software combined with electromechanical or hydraulic systems the desired water surface displacement can be achieved. Furthermore by incorporating active absorption into the paddle generation system, secondary reflections can be minimized and the quality of the generated sea state greatly improved because it is stable over time.

5.2.7 Sloped beaches and downstream absorbers

It is important to reduce the effect of reflection of the generated waves from the end wall of flumes and basins, so sloped beaches and/or absorption systems are put in place. For shallow basins, these beaches generally have a slope of 1 : 20 to half depth and are combined with porous absorbing material placed on the berm.

For deep water tanks this system is impractical and several alternatives are available. A ubiquitous system is the surface piercing parabolic beach. These are used to dissipate the energy in the active wave as it passes over the beach, breaks and permeates the absorption mesh. In this way, the amount of energy returned by the end wall to contaminate the measuring site is minimized.

The amount of reflection from the beach is a function of the wave period and, to a lesser extent, the amplitude. An efficient absorber should have reflection coefficients of less than 20% by amplitude at the worst wave period.

5.2.8 Active wave absorption

It is inevitable that some energy will return to the paddles due to the primary reflections from either the test device or the end wall boundary. This will reduce the accuracy of the trials as the reflected components will interact with the incident wave field and modify it. If secondary reflections from the paddles occur the situation becomes unstable as the incident wave will increase over time. This can be overcome by using a wave generator with an active wave absorption system that can generate the desired incident wave field while simultaneously absorbing any waves that are reflected back towards the paddle. The active wave absorption system maintains the programmed incident wave field at the test structure while preventing spurious wave energy build-up in the section of the tank between the wave generator and the test structure.

Two types of absorption systems are available. One uses wave probes measuring the surface elevation close to the paddle, while the other method uses dynamic force on the paddle. Either set of readings can be used for the feedback signal into the main servo control loop for the paddle motion. Any incoming wave train to the paddle is absorbed while generation of the programmed outgoing wave train continues.

5.2.9 Wave probes

Wave probes are used to give a measure of the elevation of the water surface at any point in the wave base or flume as a function of time. The following are some of the different types of wave elevation recorders available:

- resistance;
- capacitance;
- acoustic.

Resistive and capacitive probes are twin wire electrical probes that pierce the surface. Elevation is measured by the change in conductance between two parallel wires. The conductance and hence immersion can be measured by applying a potential difference between the wires and measuring the current that flows. This change in voltage is linearly proportional to the water surface displacement. As the conductance in water can change, the probe should be calibrated regularly.

Acoustic elevation recorders are less common, however, they are highly accurate and non-intrusive. Their weakness is in their sensitivity to the media properties, wave steepness and cost.

5.2.10 Reflection analysis

5.2.10.1 General

The sources of reflected waves in test tanks have been highlighted and the hardware that can reduce this unwanted contamination has been described. The options for how the water surface elevation at the model station is monitored have also been covered. The final recommendation is that the reflection coefficient of the tank should be measured and quantified.

There are several methods available to conduct this calibration depending on whether the waves are regular or irregular. All methods work on a similar principle, which requires a number of wave probes simultaneously measuring the water surface elevation. These can be in line or in a 2D array. The standard approaches are:

- Goda and Suzuki’s twin probe moveable carriage (2D, frequency domain);
- Funke and Mansard three probe method (2D, frequency domain);
- Zelt and Skjelbreia N probe method (2D, frequency domain);
- Frigaard and Brorsen two probe method (2D, time domain);
- Package for Directional Wave Analysis (PADIWA) Bayesian Directional Spectrum Estimation Method (BDM), seven probe method (3D, frequency domain).

5.2.10.2 Funke and Mansard

To present an example of the methodology the Funke and Mansard approach may be considered for long crested waves.

To achieve the required measurement three longitudinal in-line wave probes should be positioned at any location in the tank. The distances between the probes, however, should be exact spacings referenced to the wavelength under review. Each records a set time history of the water surface which is transposed into associated trigonometrical equations of the Fourier coefficients.

From these calculations the incident and reflected component waves can be obtained and the reflection coefficient, which is the ratio of the amplitudes of the two wave sets:

$$C_R = \frac{a_i}{a_r}$$

a_i: incident wave amplitude
a_r: reflected wave amplitude

5.3 Data acquisition system (DAQ)

5.3.1 General

The data acquisition equipment required for any device or series of tests will vary depending on several factors, such as:

- the phase of testing underway;
- the type of device being investigated;
- the complexity of the trials (active control).

The basic configuration, however, will always be similar as shown diagrammatically in Figure 24. An analogue signal of a physical property is converted into digital form and recorded on an appropriate logger.

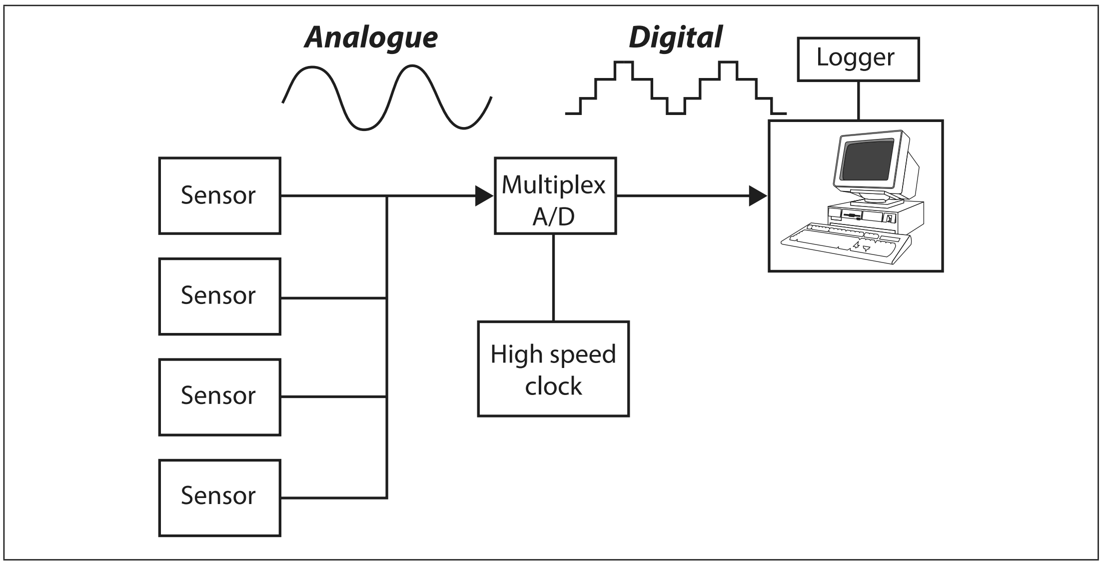

Figure 24 — Analogue to digital schematic

The important criteria are:

- synchronization of the sensors;
- digital conversion rate;
- data file format.

5.3.2 Analogue signal

A specialized sensor is selected for each particular physical parameter being monitored. Sensor requirements are:

- type;
- range;
- calibration;
- accuracy/resolution/repeatability;
- weight/dimensions;
- water resistance.

5.3.3 Signal conversion

The three main requirements during conversion of the analogue signal to digital form are:

- A multiplexer to enable as many input signals as required.
- A high speed clock that will scan channels quickly enough that reading can be regarded as simultaneous. This is not always possible due to the number of input signals and/or variation of sensors. If a time penalty is found the shift should be compensated for in the analysis stage. This can be time-consuming and not always accurate. Recently introduced acquisition systems offer parallel reading so all channels are instantaneously recorded.
- An analogue to digital converter (A–D) which produces the stepped signal shown in Figure 24. The specification for this is that the number of bits available should be sufficiently large for fidelity of the conversion. With modern components 16–32 bits can be quite common, which is more that adequate for most operations.

5.3.4 Digital signal

5.3.4.1 General

As stated above the quality of a digital signal depends on the hardware producing it and the sensors generating the original record. Other than these factors the main requirements are the length of the record and/or number of samples taken, these obviously being related through the acquisition rate. There are two important considerations when establishing conversion settings:

- the physical property being measured;
- the final application of the data.

5.3.4.2 Acquisition rate

The type of physical property being measured dictates the data acquisition rate required to produce acceptable fidelity of the time series. If a slowly varying signal is monitored, which is less than the wave frequency, then the rate can be set coincidental with the water surface elevation acquisition rate. Examples of such variables are non-extreme motions, second order mooring loads, PTO forces etc.

If the physical property has a rapidly varying signal then an increased acquisition rate should be selected and the different time step compensated for during analysis. Examples of these are snatch loads in the mooring, wave slamming, air turbine pressure differences for control purposes etc.

This second group of measurements can lead to very large data files so it is usually kept to a minimum. Early phase 1 and phase 2 tests should have indicated which parameters might require faster than normal acquisition rates, and under which conditions.

Model testing experience has shown that between 16–32 samples per average cycle produces an acceptable accuracy for most signals. The actual rate depends on the scale underway. The equivalent at a benign site for example would be between 2 and 4 Hz. It can also be beneficial to acquire data at the same frequency the forcing function is generated, for the reasons described below.

When the fully functional PTO, generator and power electronics are operational on a phase 3 model task specific rates should be set. This report is concentrating only on the data gathered for performance evaluation, not control.

5.3.4.3 Signal length

The length of the record taken and number of data points in a file is a consequence of the purpose of the time series. Regular single frequency wave trials in hydraulic facilities theoretically need only be one cycle but in practice 50–100 oscillations (depending on period) are usually taken so instabilities or higher order effects become visible.

For irregular, multi-frequency seaways in laboratories or at a benign site, the record length should be longer such that the statistics representing the wave field excitation are obtained. Traditionally this is taken as 20–30 minutes at prototype scale for standard tests and 3 hours for storm seakeeping observations.

The acquisition rate can be selected to generate a 2^n number of data points, usually 4096 (n = 12), for the 20–30 minute record. The approach is appropriate if monitoring is conducted in the truly random wind generated sea, where excitation is not controlled and is not expected to contain periodicity, or in a test facility that uses quasi-random waves generated by harmonic methods that do produce time histories with periodicy. In the latter case it is convenient to select a sampling acquisition rate equivalent to the frequency used in wave spectra generation. This couples the spectral ordinates and reduces numerical errors, such as leakage between the spectral ordinates.

The actual number of data points is set for convenience of Fast Fourier Transform methods but equally applies for frequency or time domain analysis, see Clause 6. The amount of data points required is also a factor of the number of degrees of freedom that will be applied during the analysis and might remove the requirement of a 2^n set. For example if six 512 blocks are used the total will be 3072. However, a single set is still 2^9.

5.3.5 Data logging and measurement sensors

Although the principles of data acquisition should be regarded as the same for both laboratory tests and actual sea trials, the logging hardware differs considerably. For indoor laboratory studies the digital signal usually feeds directly into the computer by an appropriate connection board. This can result in online analysis, or more often, post-processing. At outdoor stations, which obviously are at sea, data can be stored on-board or transmitted to shore for logging in real time. One of the main concerns in all cases is security of data since loss is irretrievable. The advantage of on-board logging is simplicity of the equipment, the disadvantage is possible bulk loss of the data even when checked regularly. The advantages of telemetry are real time monitoring but the disadvantage is equipment complexity leading to higher probable short term loss.

For these reasons it is recommended to adopt both logging methods.

5.3.6 Measured parameters

The type of monitoring required for WEC testing increases in complexity as the scale increases in accordance with the objective of each phase. The core of each schedule is shown in Table 3 and a method of detailing each phase to ensure no item is overlooked by the flow diagram in Figure 3.

Prior to an operational electrical generator being fitted, even if connected to resistive load banks, most areas of interest can be obtained by monitoring only a few parameters. These are:

- water surface elevation;
- body motions;
- PTO forces;
- mooring forces.

These recommendations should be taken as the absolute minimum and it is anticipated several more parameters will be measured during sea trials. If mathematical models are being compared this requirement can increase to include wave forces:

- static body to obtain the diffraction forces;
- mobile body to measure the radiation forces.

5.3.7 Wave monitoring

5.3.7.1 General

A detailed record of the water surface elevation providing the wave energy extraction excitation forces is essential during all three phases of the development path. The equipment used differs, but the principle behind the acquisition should be the same.

5.3.7.2 Phases 1 and 2 (laboratory tanks)

In addition to the pre-calibration wave measurements made in the model deployment zone prior to its installation run time records during trials should also be conducted.

As described in 5.2.9, wave measurements in tanks are usually achieved by surface piercing twin wire probes. These are often, though not exclusively, fixed in space during a single test run so the important consideration is location. For reasons of contained water mass energy reflections (as described in 5.2) and calibration (as described in 5.4) the gauges should be placed such that they record the actual water surface elevation influencing the model.

For fixed devices in long crested waves this position can be athwart of the model and in the far field to minimize the influences of radiated waves. For moored, mobile devices only an approximation can be made within the mooring surge range.

These real time measurements of the impinging waves should be included during all the tests in the programme. This is principally to provide time history information for each test but also verifies that programmed conditions are supplied. For moored vessels the wave probes can be attached to a movable carriage so the sensors can be adjusted to the required surge offset for each different monochromatic wave period under investigation. In irregular seas, where mooring induced surge is constantly varying, only the average setting is possible as stated above.

Wave recorders can also be attached to models so they move around with the device. Since this means they are quite close the influence of radiated waves, especially when out of phase with the incident waves, they should be considered. This approach should be regarded as an approximation method but can still provide useful data during the signal analysis stage.

In short crested seas the situation is more akin to outdoor sea trials in that only a near field approximation can be measured by a 2D system. The pre-calibration station measured records can be referenced in parallel with the real time surface record to ensure there are no major deviations in the summary statistics.

5.3.7.3 Phase 3 (benign site)

Wave measurements during sea trials are also essential if full value is to be taken of the deployment. There are various acceptable types of instruments available, such as surface buoys. An alternative to this is the bottom mounted acoustic Doppler type. Originally introduced to measure current profiles a variant of the ADCP can now furnish the water surface time history similar to the more conventional buoys. The location of the wave recorder is somewhat arbitrary but a station upstream of the device(s) is often favoured. The dispersive nature of water waves dictates that only spectral data can be used reliably, and not the time histories which will differ between the buoy and the device.

5.3.8 Body motion

Until recently for early small scale laboratory trials device hulls had to be connected to rotary or linear potentiometers by physical means, such as wires or drive cords. The body motion was then measured by the position sensor. To facilitate small amplitude assumptions the connection line had to be long and in large motions, especially when combined with second order drift displacement, it was common for the device cord to fall off the pulley. This inevitably occurred towards the end of an experiment and lead to the test having to be repeated.

For medium scale trials accelerometers could be used but were not very reliable or convenient to deploy and required double integration to obtain displacement.

Although improved versions of these sensor arrangements are still used today they have in general been replaced at both scales by non-contact motion monitoring systems. These are based on active digital cameras which are in fixed locations around the test site and passive (or active) reflective markers which are attached to the model.

If a passive marker system is used the active camera sends out an electromagnetic radiation pulse in the infrared band which is reflected back by the markers and their position in 2D space is recorded. If more than one camera is operational the system software converts each camera reading to a 3D point in space. A continuous time history of each reflective marker's *x*, *y* and *z* coordinates are generated in the output file matrix. If more than one marker is used (two for 2D and three for 3D) further transforms should be used converting the Cartesian coordinates into the required degrees of freedom motion for the hull heave, pitch, surge, roll, sway and yaw.

Because the system is non-contact the WEC is allowed to move freely on a mooring system providing the second order excursion remains within a pre-calibrated measurement zone.

Although a considerable improvement over the previous methods the system is not without flaws. Extreme accelerations are difficult to track and merging markers (when two reflective markers cross in a camera view) cannot be distinguished and lead to erroneous data errors (see Clause 6).

For large scale, phase 3 sea trials, on-board sensors should still be relied upon. There are several systems commercially available based on accelerometers which usually require an axis reference stabilizer, such as a gyroscope. Pitch and roll stabilizers should be of a high quality or signal integrated noise problems are inevitable.

5.3.9 PTO forces

Once the body motions are monitored the forces developed between the two inertial masses of the WEC should be measured. From these two parameters the instantaneous power can be calculated since:

$$\text{Power} = \text{Force} \times \text{Velocity}$$
or
$$= \text{Pressure} \times \text{Mass flow rate}$$

For pneumatic devices this requires the monitoring of the pressure difference across the turbine simulating orifice. If mechanical PTO simulators are used the force transmitted through them should be recorded. It is not actually necessary in either case to know the level of applied damping but recommended that the settings are calibrated.

5.3.10 Mooring forces

Safety and security of equipment at sea is obviously an important aspect of marine operations. Comprehensive documents on this topic already exist. An important element of these activities is that during the modelling phase it is expected that the mooring forces will be studied.

Force transducers can be deployed as in-line measurement sensors. The location along the mooring line to place the sensor requires consideration. The main criteria should be to follow the requests of the mooring design engineers but also to ensure all aspects of the anchorage are revealed. Both bow and stern mooring should be monitored but for symmetric configurations only port or starboard need to be connected for laboratory trials.

A recommended location for a transducer is at the chain stopper on the device. For phase 1 models this can prove difficult since the site will still be in a splash zone and waterproof strain gauges are heavy compared to the weight of the model. It might, however, be possible to extend the mooring past a fairlead to a dry location. For medium and large scale phase 2 and 3 models this is rarely a problem. At the small scale care should be taken that the sensor's own weight does not become a factor in the mooring recordings. At large scale this is not relevant. An alternative approach in small scale trials is to attach buoyant material to a waterproof sensor and attach it in line to either the device or to the weight bearing float, if there is one in the system. The inertia of the system will be influenced.

Although mooring measurements can be conducted at small scale this should only be a guide for mooring designers and should not replace measurements from the medium scale tests. The latter results can more confidently be applied to the mathematical safety codes used by the design companies. Since snatch loading can be present in mooring lines a fast acquisition rate might be required.

NOTE The calibration of the force transducers should be performed before and after the test programme and regular zero load checks made during testing.

5.4 Calibration

5.4.1 General

Two forms of calibration should be performed during WEC development trials:

- the wave climate;
- all deployed sensors.

5.4.2 Wave climate calibration

5.4.2.1 General

This should be performed prior to testing in enclosed tanks for three reasons:

- to obtain the generating system transfer function;
- to produce the required wave spectra;
- to quantify the reflected waves.

5.4.2.2 Tank transfer function

Mechanical wave generation systems have frequency related transfer functions that should be established for all installations. Providing no changes are made within the tank, such as to the downstream energy absorption beach, this should not change over time.

A set of calibration curves for a range of monochromatic waves typical of this procedure can be drawn up by programming the control computer in steps of increasing gain and measuring the response in terms of wave height generated. If the generation system does not have adjustable gain each individual wave height required should be run separately. The wave period should similarly be checked during the same runs.

Water levels can influence the transfer function so tank levels should be checked regularly. This procedure should be followed for single frequency, regular waves and irregular seaways. Before beginning a set of important device trials, it is prudent to confirm that the transfer function is still valid. These checks should be made prior to the deployment of the model and preferably at the proposed test location within the tank.

5.4.2.3 Required wave spectra

A similar approach is taken with real seas when the full time history is run and the summary statistics obtained for each seaway. A graph can then be produced of the theoretical and practical significant wave height such that intermediate seaways can be generated. The spectral shape should also be verified as described previously.

Once the standard wave climates are established for a facility they need only be statistically verified at the model deployment station. If additional specific spectra are required these should be calibrated following the above procedure. Again this should be completed prior to the launch of the model.

5.4.2.4 Reflected waves

The reasons for the occurrence of and methods of reducing reflected waves was described in 5.2. However, they are ever present and should be quantified since they do add a complication to testing in enclosed wave bodies. Even when the model is absent some reflection from downstream beaches contaminates the wave field and should be taken account of.

So as not to lead to an unmanageable amount of calibration the reflected waves should be measured just at the site where the model will be located. Following one of the various methods described in 5.3.7, the absolute, incident and reflected water surface elevation can be obtained. A task specific judgement call is required as to which measurement is the most appropriate to apply during device trials. For point absorber type devices the absolute water surface elevation can be used. For attenuator devices the height will vary along the length, which is more difficult to balance and so it reduces the confidence limit in the results.

For buoyant point absorbers which surge over extreme distances an allowance during analysis for height changes might be required. Variations are easily identified in regular waves by inspecting the response time trace for differences in magnitude of the oscillations.

5.4.3 Sensor calibration

Transducers and other types of sensors may be obtained with or without manufacturers' pre-calibration certificates. In either case it is good practice to pre-calibrate both types, especially if this can be done in situ on the model and connected to the data acquisition equipment and logger. The minimum should be a bench calibration of the complete acquisition system for each sensor.

Wave recorders should also undergo calibration. In the laboratory the common use of resistance probes can be checked reasonably easily by raising and lowering them in still water, thus producing a calibration graph similar to Figure 25. When the step size is known the voltage change can be related to the specified excursions such that the calibration units become distance per unit digital change, i.e. mm/digit.

At sea things are more complicated. Most proprietary wave gauges are factory calibrated but should occasionally be checked. This could involve returning the unit to the manufacturer for service or the technique of deploying a second unit for a short period of time to verify the primary recorder. In general the manufacturer's service recommendations should be followed verbatim, which can be expensive so should be included in the budget planning.

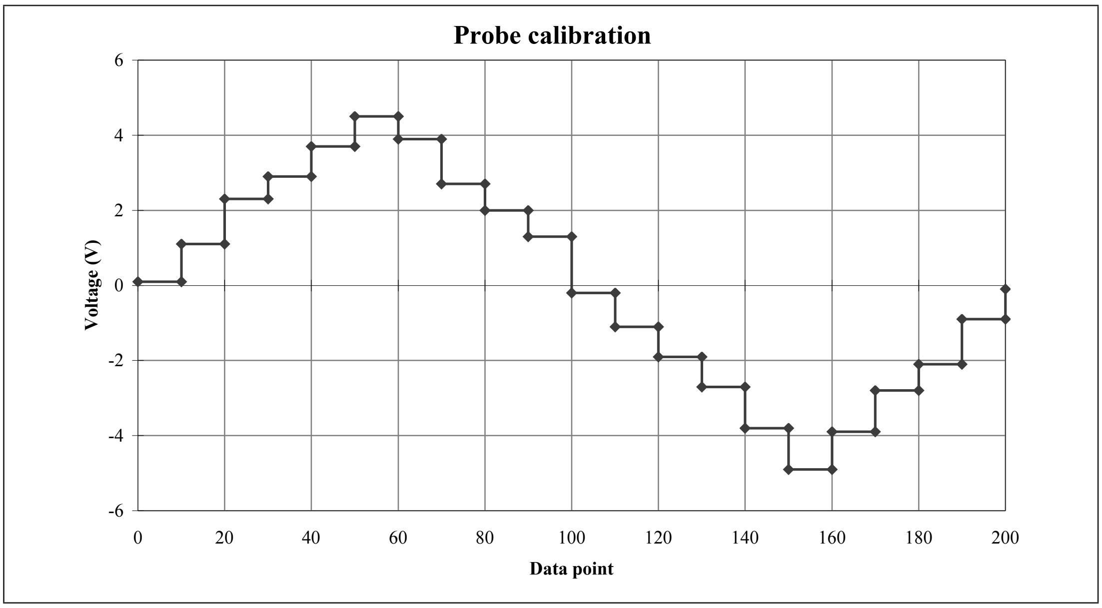

Figure 25 — Wave probe calibration procedure

5.4.4 Measurement quality

The accuracy, resolution and repeatability of sensors should be considered carefully. Three important points for these decisions are:

- the phase of testing underway;
- the purpose of gathering the data;
- the physical parameter being measured.

During phase 1, conducted in a laboratory, global scale results for comparison between different configurations are paramount so that the accuracy can be relaxed somewhat. This is because results are relative rather than absolute. However, repeatability is important.

By phase 2 the absolute value of the parameter is required so measuring tolerances should be tightened but the resolution is not so critical.

Of more concern, particularly at small scale phase 1 trials, are the ranges of the parameters measured. Sensors should be carefully selected to be appropriate to these limited scales, which can restrict the choice. The accuracy of most gauges and transducers is a function of their full scale deflection.

If an active control system is under investigation during the phase 2 part of the programme then the transducer specifications should become even tighter. This requirement certainly advances into phase 3 when a PTO control of some description will definitely be required. The sensor selection also becomes a multidisciplinary task so the final decision of the actual units should be left to the appropriate engineers. Providing the underpinned principles of calibration are followed a system should function satisfactorily.

One aspect that should be agreed for phase 3 is that of sensor redundancy. For critical components and parameters, dual or back-up sensors should be incorporated when possible. One rationale for this is if the sensor will not be accessible at sea due to either its location or integration in the control circuitry.

Table 6 offers a guide to some common parameters and the overall accuracy from the sensor to the logger.

Table 6 — Calibration accuracy

Sensor	Phase 1	Phase 2	Phase 3
waves	≤ 5%	5%	10%
motion	≤ 10%	5%	10%
force/pressure	≤ 5%	2%	10%
mooring	≤ 15%	10%	≤ 5%
generator			≤ 2%

6 Calculation procedures

6.1 General

Analysis of test results requires as much skill, experience and knowledge as conducting the physical test programme. Although standard mathematical techniques can be employed to validate data and produce the first stage of the analysis for each test run and device configuration investigated, progressing this information into the summary stage will be a bespoke activity requiring imagination, discipline and ingenuity.

6.2 Analysis of tank testing results

6.2.1 General

The two basic approaches are time domain and frequency domain analysis. Both methods have germane usage.

6.2.2 Time domain

6.2.2.1 General

Although spectral methods can be used for monochromatic results, and indeed should be employed on certain occasions, it is usual to produce the various physical parameters from time series. Important information can be obtained directly from raw data records or derived from the combination of two or more parameter signals.

6.2.2.2 Regular raw data

Figure 26 shows a typical time trace of four monitored signals from which considerable relevant information regarding the characteristics of a device can be read directly. Examples of the observations are:

- amplitude of each parameter;
- phase relationship;
- response profile to regular excitation;
- quality of signal;
- resonance proximity;
- signal statistics (root mean squared (RMS), maximum, minimum, mean, standard deviation etc.).

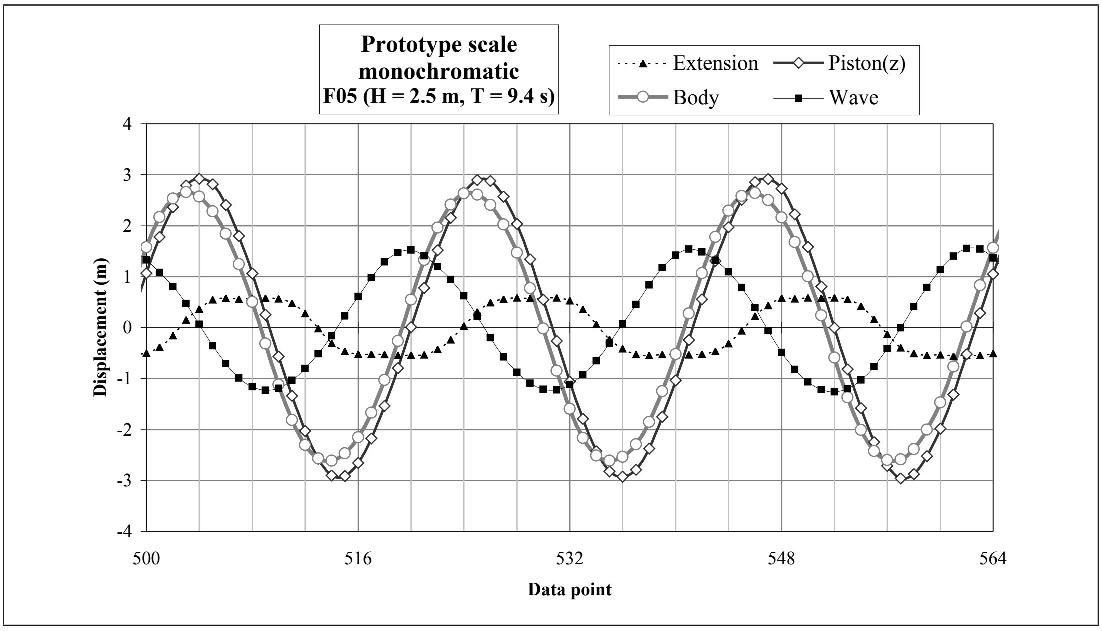

Figure 26 — Time history of measured signals

6.2.2.3 Analysed data

Further insight into device behaviour, characteristic, performance etc. can be revealed when signals are combined, such as shown in Figure 27. In this graph, the differentiated motion signal (i.e. velocity), and the direct force signal product produces the instantaneous power from which the required statistical values can be derived (e.g. mean power).

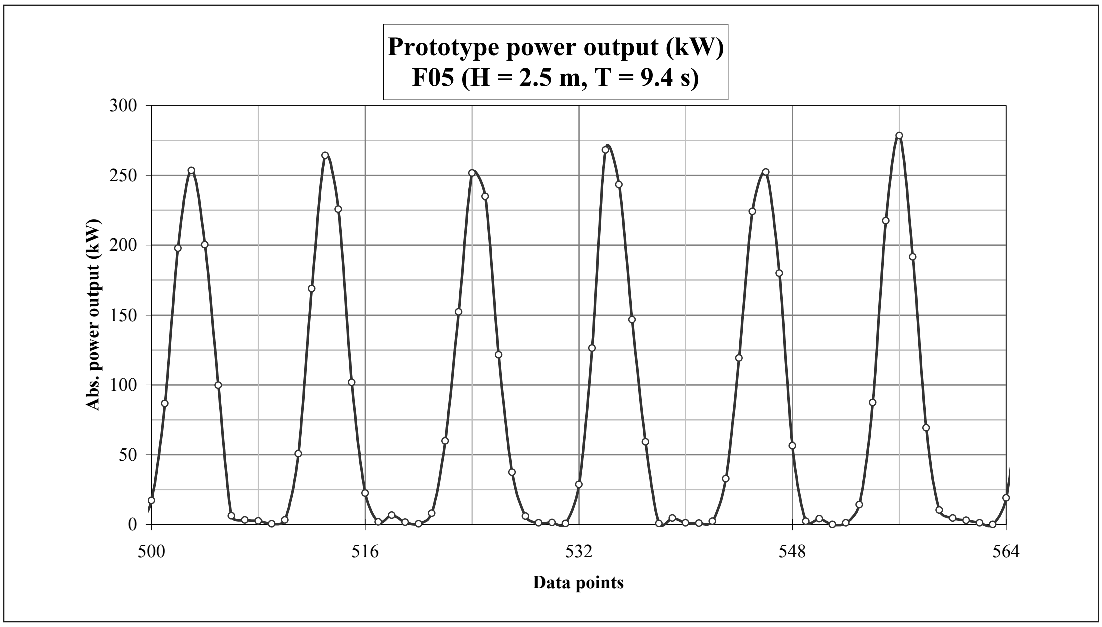

Figure 27 — Time history of power output

A useful continuation of the time history analysis is to compare the measured device performance with the incident wave creating that response. Two primary areas of interest are:

- magnification or response amplitude operator;
- phase relationship.

The method of obtaining these values in regular waves is illustrated in Figure 28.

One wave excitation frequency produces a single measure and plot point of the device response. Multiple frequency runs can then be combined to produce a complete picture of the device behaviour.

6.2.2.4 Summary data

As described in 3.2 a range of wave frequencies should be generated for a particular device configuration, or setting (e.g. damping), to investigate the basic characteristics of the unit. From the above procedure an overall transfer function for each physical parameter under investigation can be generated. These summary plots provide the basic design requirements so the WEC can be optimized. An example of this is shown in Figure 29 depicting three different body motions. Design engineers can evaluate these graphs to ensure the required characteristics are being exhibited.

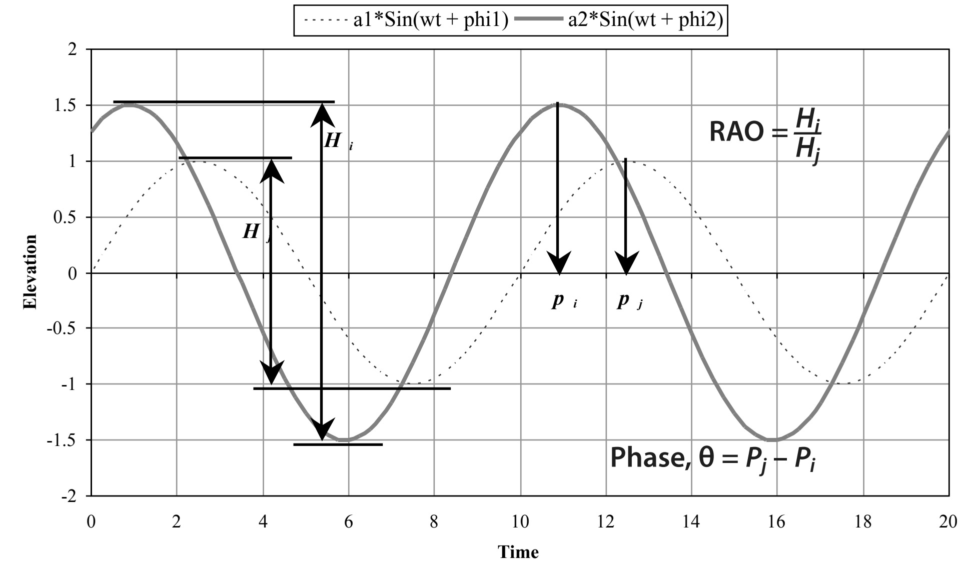

Figure 28 — Phase and magnitude differences

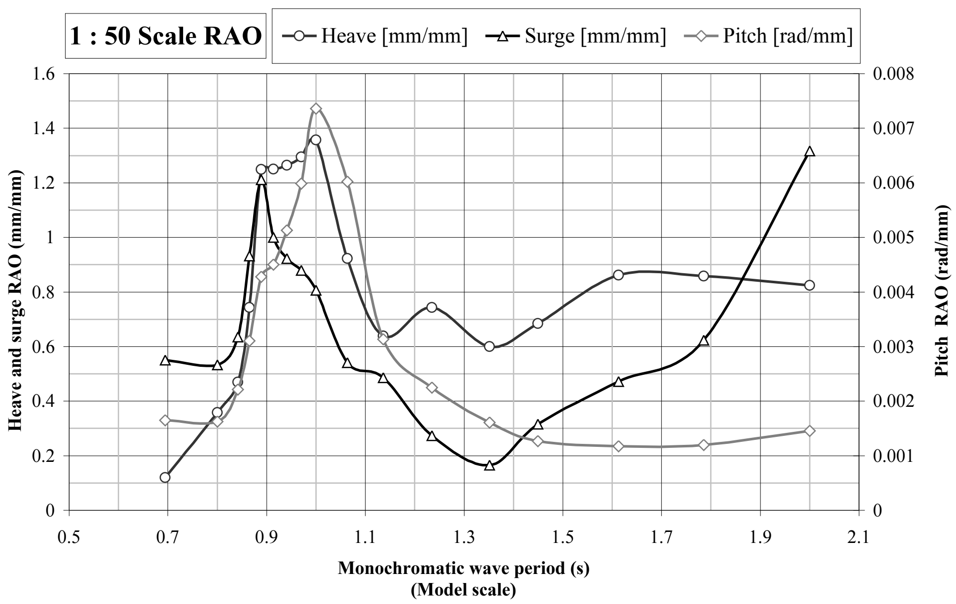

Figure 29 — RAO plots of various motions

This process should then progress a stage further by comparing different device configurations, or settings, to highlight which combination produces the results specified by the design team. An example of this is shown in Figure 30 (and Figure 8). The unit under investigation was a heave mode extraction WEC for which pitch was to be minimized. The governing mass properties were adjusted according to the equations specified in Clause 5 to produce the three uniquely different responses shown in the graph. From such comparisons the design engineer can select the combinations best suited to a particular device.

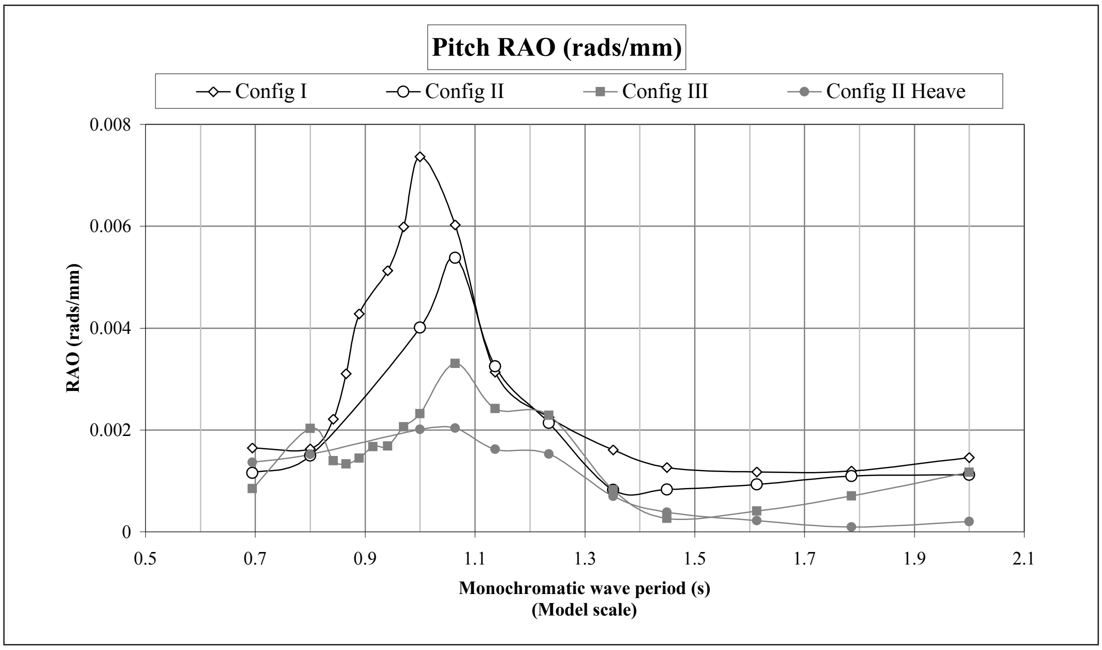

Figure 30 — Pitch RAO for different device configurations

6.2.2.5 Irregular raw data

Response to multi-frequency wave fields can also be analysed by time domain methods. Figure 31 shows the real sea time series equivalent to the monochromatic traces in Figure 26. Less detailed understanding of the behaviour can be extracted from these results but important criteria such as extremes, averages, variance etc. (which are required by designers, especially regarding seakeeping characteristics), can be extracted.

Also critical is the instantaneous power absorption under real wave conditions. Figure 32 shows a plot of the product of the simultaneous PTO velocity and force from Figure 31. Such information is essential for the design of a power take-off system and the power electronics that will convert the supply to an acceptable quality for connection to a national grid, particularly that of dealing with the spikes.

To provide a full set of design criteria these plots can be further analysed to provide information regarding:

- the time period for energy above a set threshold, such as the average;
- the duration and occurrence of zero, or null, energy conversion;
- the duration of spikes;
- the ratio of average to peak.

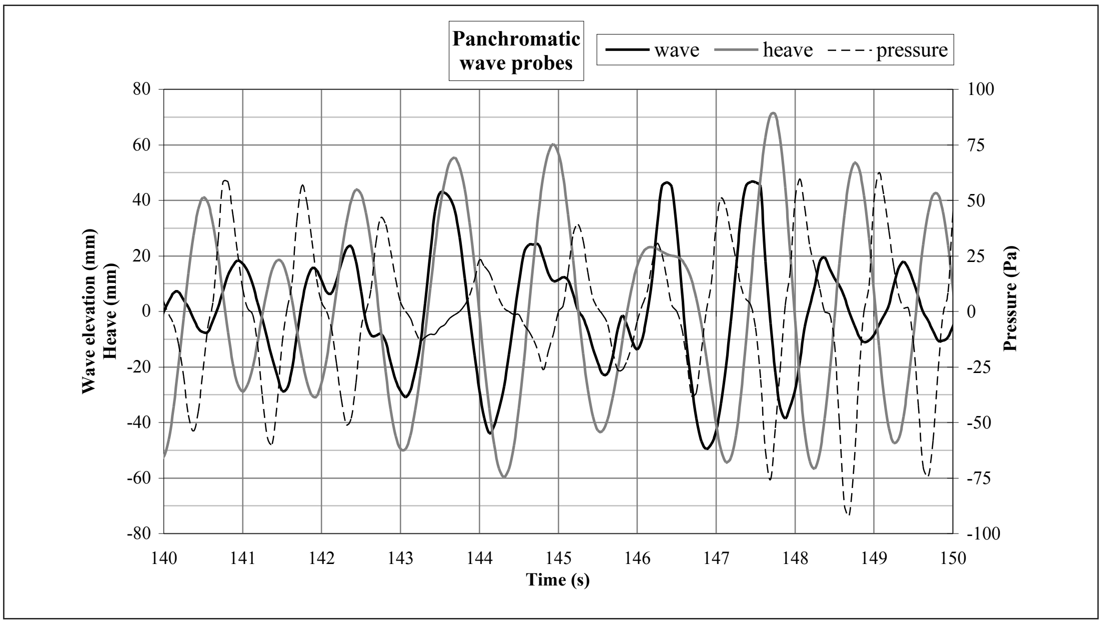

Figure 31 — Panchromatic time history of measured signals

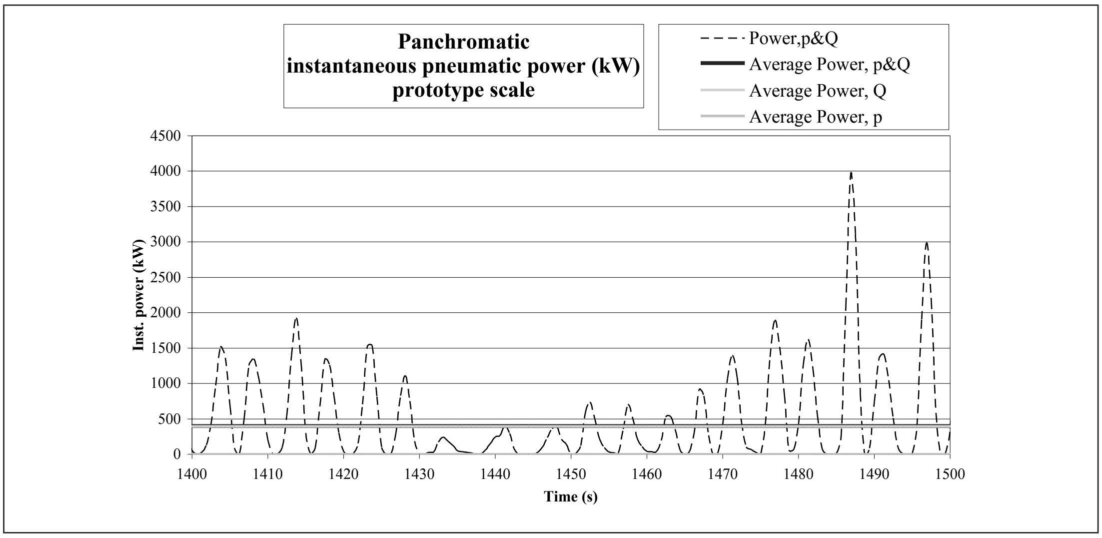

Figure 32 — Instantaneous power output from panchromatic trials

Time series analysis is also required to aid mooring design. Figure 33 shows details from two different mooring line configurations. Both are exposed to the same, or similar, seaways. The first is a well designed system with pretension and compensation buoys. The peak to average tension ratio is approximately 3 : 1 and no snatch loads are present. In the second plot, representative of a slack moored catenary type mooring the maximum to average tension ratio is approaching 10 : 1 and in this record snatch forces become present. This information can be combined with the regular wave second order work to verify and calibrate mooring design computer packages.

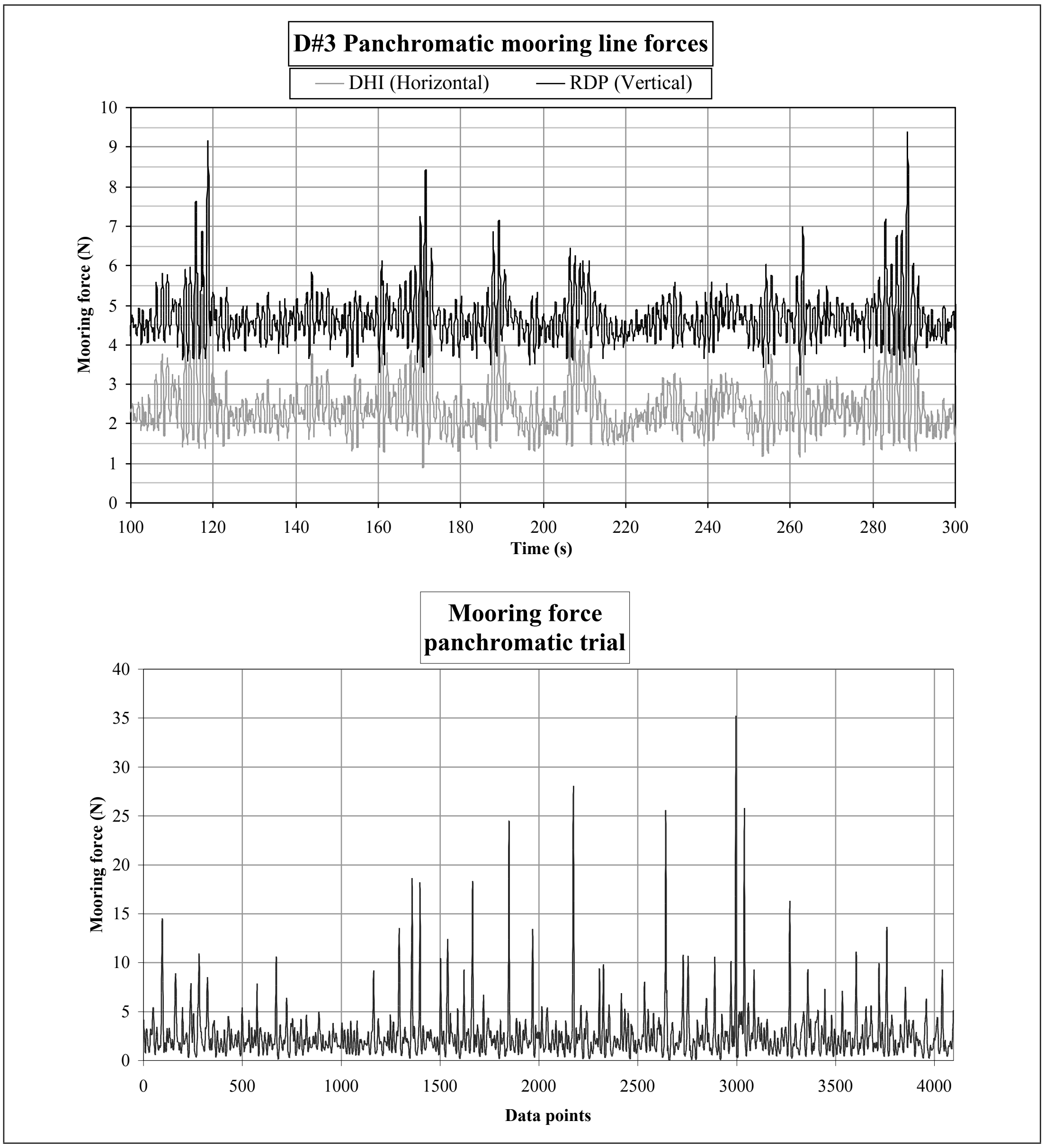

Figure 33 — Panchromatic time trace of mooring loads

6.2.3 Frequency domain

6.2.3.1 General

Analysis of irregular signals can also be undertaken by a spectral approach, since the excitation waves can be represented by a frequency spectrum.

The principle behind this technique is that an irregular signal is the super-position of a series of regular waves which can be decomposed into frequency components. Figure 34 illustrates this technique graphically.

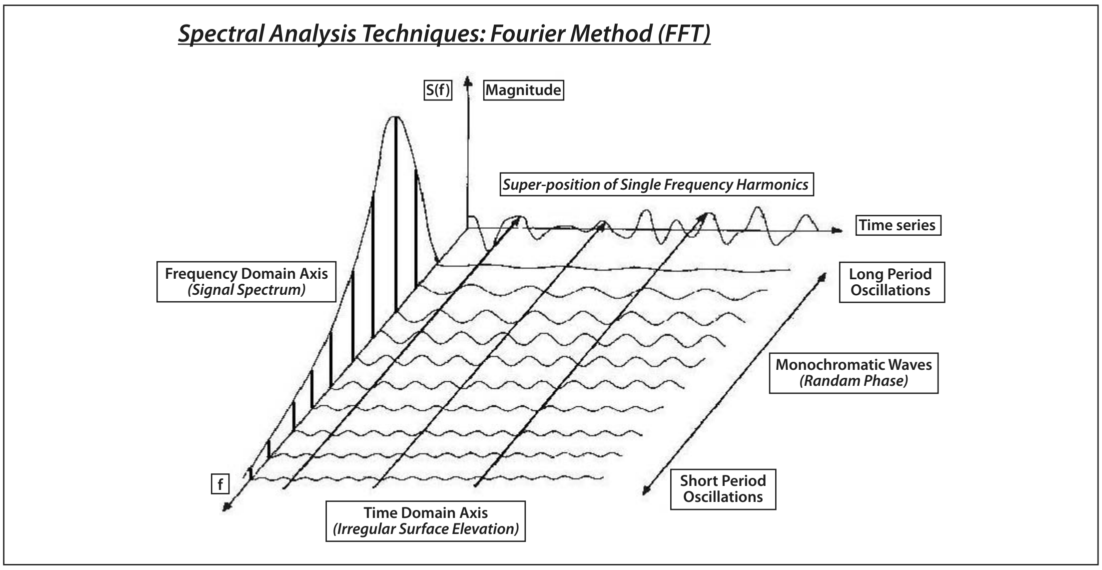

Figure 34 — Depiction of irregular signal components

Theoretically each wave frequency can vary randomly in amplitude and phase but in ocean sea states it is more usual that amplitudes vary according to governing physical laws of energy transfer whilst phase is regarded as random. This means that when superimposed the regular waves produce an irregular oscillation as shown in Figure 34 on the time series axis. Along the frequency axis the spectral energy density that these monochromatic harmonics are derived from is depicted.

6.2.3.2 Fast Fourier analysis

Any of the measured physical parameter signals, as shown in Figure 31, can be processed into a series of frequency ordinates by the reversal of the procedure described above. That is, an irregular time series is measured and the spectral profile obtained by harmonic analysis.

The recommended algorithm used for computer based analysis is the Fast Fourier Transform (FFT), which is an efficient method for producing the discrete Fourier series. The spectral ordinates can be viewed as amplitude values (m) or energy density values (m^2/Hz) or the appropriate units for the parameter being analysed (e.g. pitch (rad^2/Hz), energy (W^2/Hz)).

There are two particular characteristics of spectral analysis that should be considered when applying it to a data set.

- The analysis technique relies on decoupling of the signal into harmonic components, which might not occur in nature. This methodology introduces the factor of periodicity into the analysis when evidence suggests it might not have existed in the original signal.
- For various mathematically imposed limitations the amplitude/energy density values are estimates calculated from the original signal. Frequency step size, ordinate leakage, etc. affect the accuracy and, therefore, confidence that can be placed on the results.

However, although the individual amplitudes of the harmonic components can differ the overall variance produced by the spectral method should not vary significantly from the variance calculated from the time series.

This last statement has several caveats that should be accommodated when conducting this work since ancillary application can influence the result accuracy. Examples of these are:

- filtering;
- smoothing;
- windowing;
- length of original signal;
- number of degrees of freedom applied (segmenting).

6.2.3.3 Spectral application

Harmonic analysis is less universally used as an analysis tool than time series analysis but does have several important contributions to add to the evaluation and understanding of the process governing device performance.

Since monochromatic waves can't be expected in the ocean it offers a useful tool to investigating the excitation and response of a device once the laboratory is left, i.e. phase 3 and beyond. Its use to produce the RAOs of a device was described in Clause 5. Direct spectrum comparisons can also reveal important information. In Figure 35 the relationship between the wave spectra and the power conversion of a typical buoyant WEC in three different seaways is shown.

The conditions have been selected to illustrate seas with a peak period below the device resonance ($T_p < T_D$), coincidental with the device natural period ($T_p \approx T_D$) and the peak energy period above the device eigen frequency ($T_p > T_D$). As can clearly be seen the peak in the power production does not migrate with the wave energy peak by as much as might be intuitively expected. Indeed the period of maximum power absorption varies little from seaway to seaway. It is also shown that the magnitude of the peak in the resonant case is an order of magnitude greater than both cases either side of resonance.

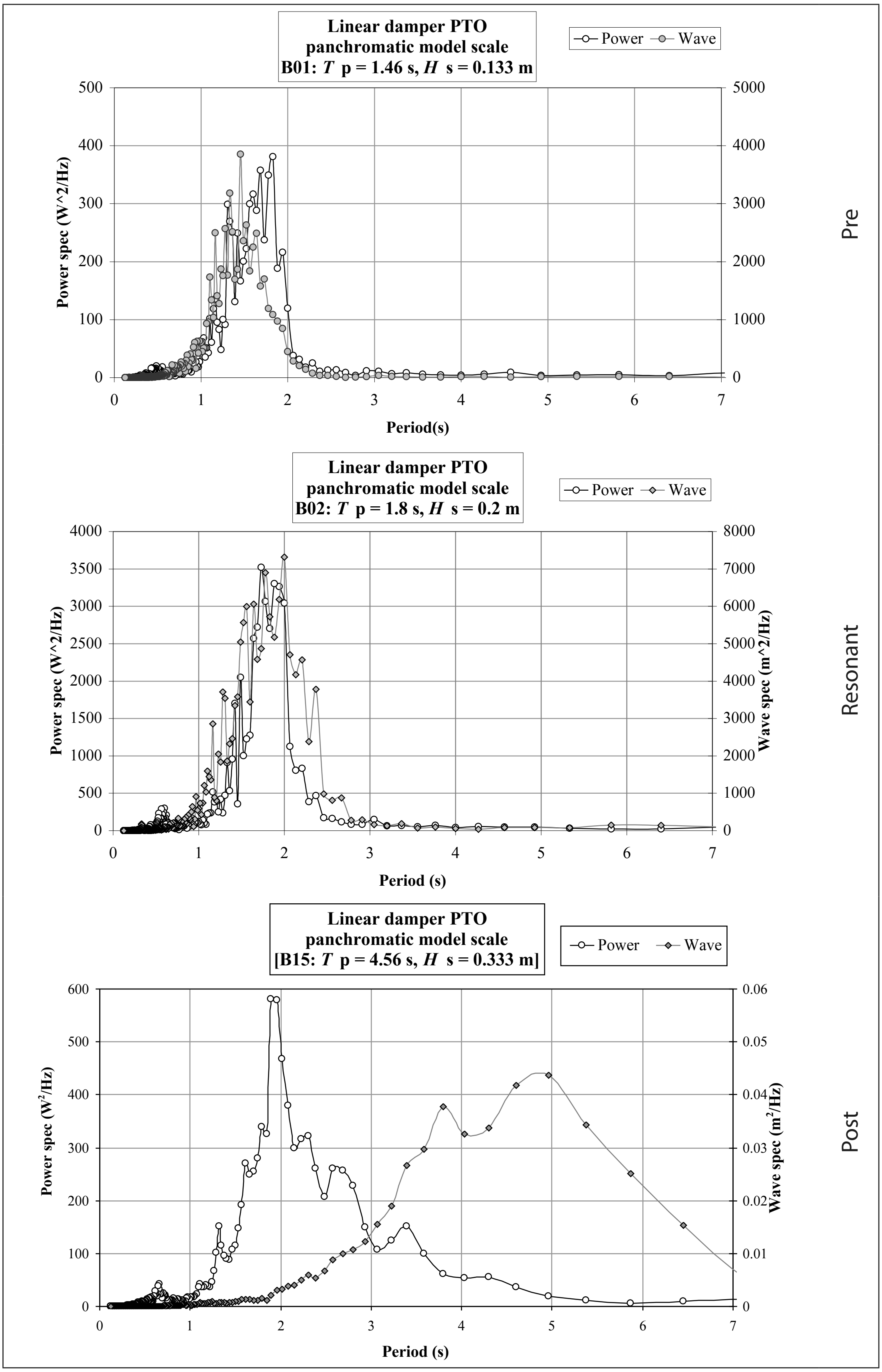

Figure 35 — Wave and power spectra relationship

This detailed information can support the summary device specification presented from the time series analysis and from which the power matrix performance scatter diagram has evolved, see Figure 36.

Significant wave height (H_{sig}, m)	Power period (T_{pow}, s)																
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	–	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	–	–	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	–	–	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	–	–	–	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	–	–	–	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	–	–	–	–	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	–	–	–	–	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	–	–	–	–	–	750	750	750	750	750	750	750	750	676	613	584	525
7.5	–	–	–	–	–	–	750	750	750	750	750	750	750	750	686	622	593
8.0	–	–	–	–	–	–	–	750	750	750	750	750	750	750	750	690	625

Figure 36 — Power matrix

This diagram is at present being proposed as an industry standard for describing the power conversion characteristics of wave energy converters such that they can be equitably compared.

To be of value the method of derivation of the power value in each element of the power map should be displayed in combination with this information.

At present most power maps are theoretically generated but if, as will eventually be the case, the matrix is produced from measured, empirical data a further layer of evaluation will be required for the following reason.

6.2.3.4 Spectral variation

The spectral approach can sometimes be useful to explain unexpected differences in performance characteristics during sea trials. Figure 37 shows the average power output from a WEC in real seas. The abscissa depicts each time the selected sea state occurred over a set period of time. The ordinate (therefore each grey histogram) represents the power absorption for that time slot. The variation in levels is obvious. Below each highlighted black histogram is the actual frequency component mix that produced those same summary statistics. For the left hand example, the real sea resembles a classical Bretschneider and the WEC performance is similar to the scaled laboratory results. For the middle example a twin peaked spectra was present with zero input frequency ordinates at the peak period. Very little power was produced in these wave conditions even though the summary statistics produced the same H_{m0} and T_{02} combination. The example to the right has a JONSWAP type narrow spectrum with a higher peak close to the peak period for the Bretschneider. These wave conditions produced a slightly higher power production.

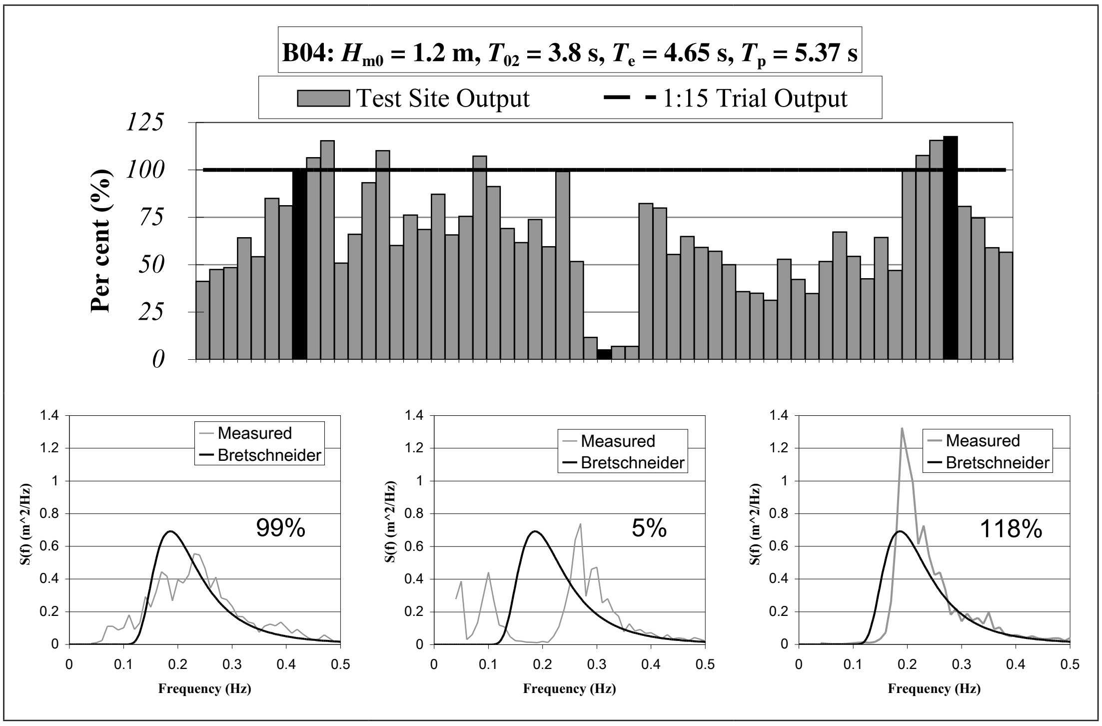

Figure 37 — Real sea trial power output levels

Without the application of the spectral approach to the data analysis this type of information would not be revealed to the device designers.

6.2.4 Signal validation

6.2.4.1 General

Before any detailed analysis is conducted a pre-processing code should be implemented to validate the various signals being monitored. The simplest form of this type of quality check is to compare statistical values of similar, or consecutive, records. Large variations can be indicators of measurement error.

If typical characteristics of the physical parameter are known error traps can be implemented on an individual signal. Often this is improved if an analysed, rather than raw, trace is used since the error can be enhanced. A further modification can be to apply the check to the product of more than one signal, though this method does not isolate the problematic channel.

Figure 38a (displacement) shows a raw signal with small errors that would be difficult to detect. Figure 38b (velocity) depicts the differential of that signal in which the problem becomes more obvious and Figure 38c (power) is the product of the error signal and a second, clean, trace (not shown) in which an error has now become evident and can easily be identified digitally.

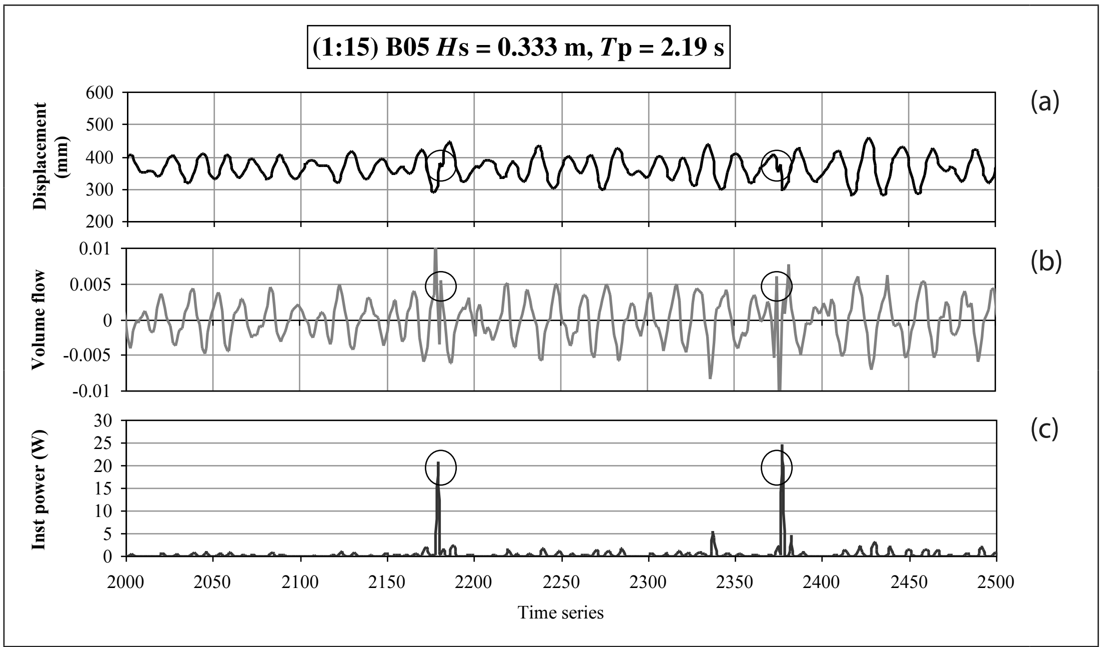

Figure 38 — Time series error analysis

If such monitoring errors are not detected significant and misleading differences can be incorporated in the summary records, and in particular the power statistics.

6.2.4.2 Signal decontamination

Several mathematical techniques exist to improve signal quality but how and which to apply is a judgement decision. Problems can present themselves in various forms and each requires a different approach for the best solution. Basically the solutions involved are frequency filtering or time series smoothing.

There can also be gaps in the time series, which should be compensated for. This can necessitate a data set being completed by zeroes or perhaps spline filling but care should be taken or the signal can become distorted.

a) Smoothing

High frequency noise or jitter on a signal can be smoothed in the time domain, taking care not to introduce phase shift. Figure 39 shows an example of a raw and smoothed signal and the improvement in the processed trace. A consequence of smoothing can be a reduction in the amplitude, which can also be seen in Figure 39.

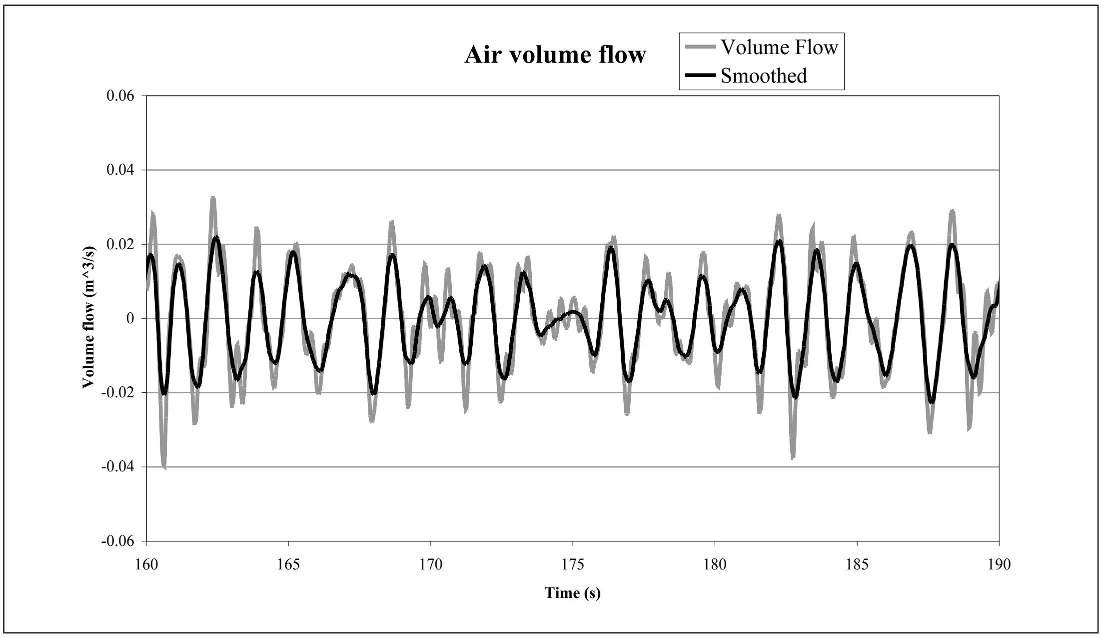

Figure 39 — Smoothing noise from a signal

b) Filtering

Although similar to smoothing this method separates frequencies by allowing some to pass and attenuating those that are unwanted. Initially applied in the frequency domain, filtering can be particularly useful to remove low frequency oscillations that can be masked in the time history. Electrical analogue filters can be incorporated in the hardware or digital numerical filters in the software, but each should produce the same effect. Unfortunately no electronic filters have ideal characteristics as they tend to reduce a problem rather than remove it completely. There can also be difficulties 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.

Band pass filters which are applied to the high and low frequency conditioning are particularly useful.

Figure 40 shows a raw data signal and the resultants when the two fundamental types of filter are applied. The left hand trace has allowed the high frequency components to pass but removed the low frequencies. The right hand time trace has removed the high frequency elements. The difference between the resultants is clear and the dangers of such powerful tools being applied incorrectly is obvious.

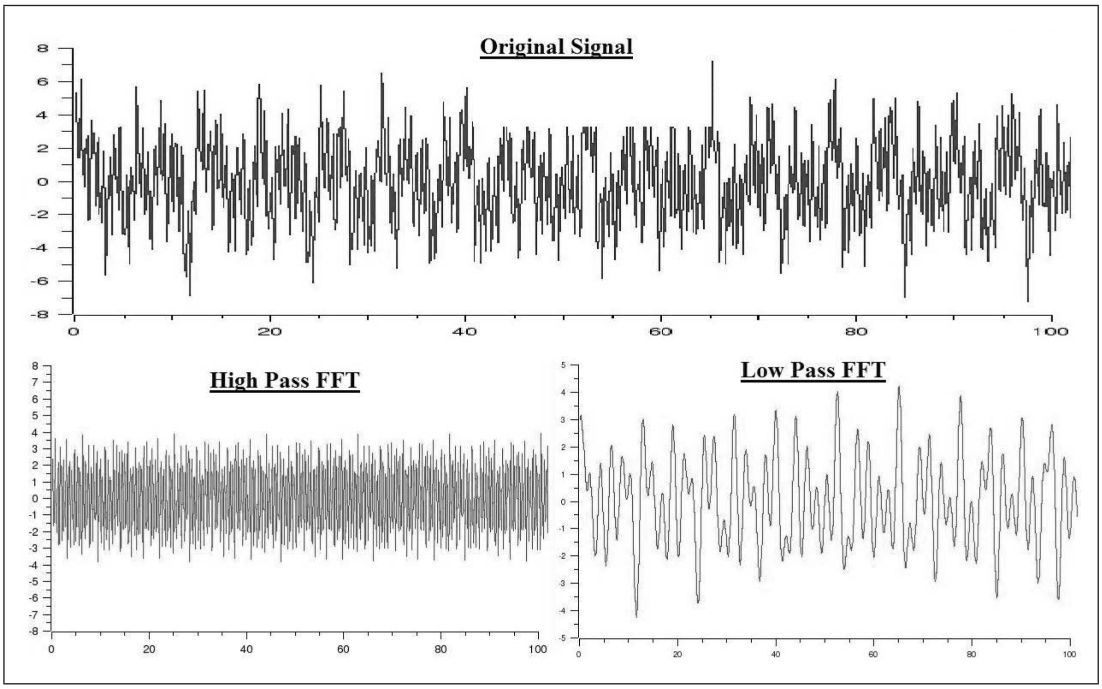

Figure 40 — The effect of filters applied to a signal

c) Windowing
The efficiency of digital filters can be improved by the application of windows to the time series filter kernel. Not only can the Sinc function become manageable for computing but the pass band and stop band characteristics are enhanced. The characteristics are shown in Table 7.

Even with improved quality filters there will be the inevitable alteration to the original signal in phase and amplitude that might require correction prior to continued application.

Table 7 — Filter classification

Filter used for…	Filter implemented by…
Time domain *(smoothing, mean trend removal)*	Moving average
Frequency domain *(separating frequencies)*	Windowed Sinc

d) Manual
It is not uncommon in laboratory studies that jumps occur in the time trace, as seen in Figure 41. This problem is usually detected in the processed signal as described above. These errors are more difficult to correct and often lead to either repeated trials

or manual adjustment to the data set. Ideally this problem should be avoided as the solution is not trivial and can be time-consuming.

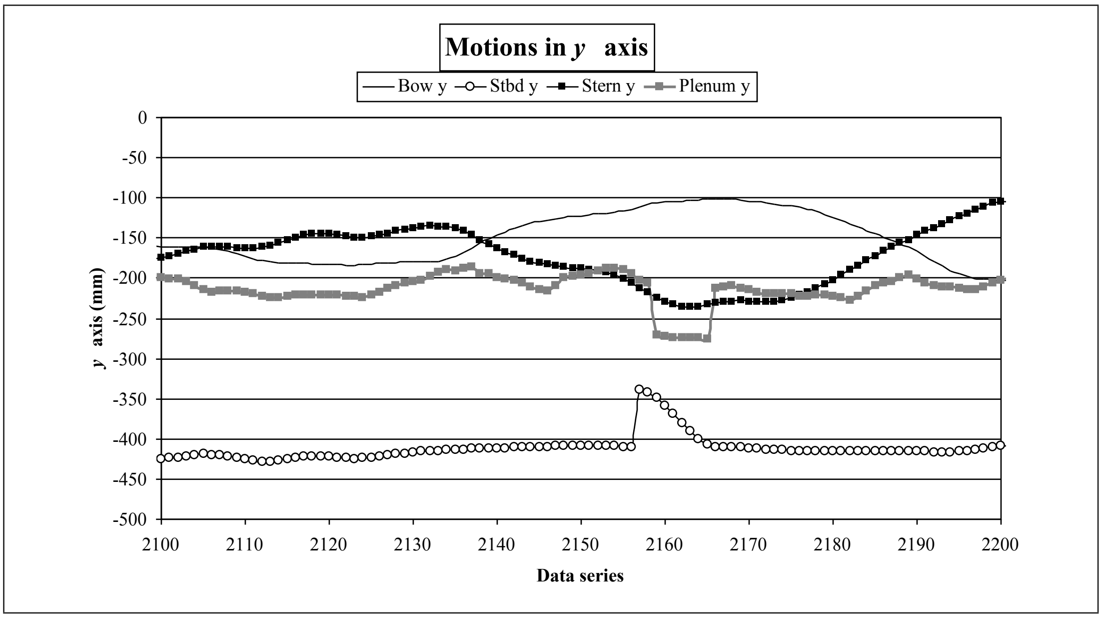

Figure 41 — Example of data discontinuity

6.3 Extrapolation of results

6.3.1 General

One of the primary reasons that scale model testing is conducted is that there are rules that enable it to be done. Physical laws of similarity and similitude can be applied such that the fundamental behaviour of a process can be observed, even when the theory governing the situation is not well defined or even poorly understood. The physical model behaves as an analogue computer that introduces all the parameters and interactions that would occur at full size. Most wave energy converters seem like simple devices but there are usually quite complex hydrodynamic interactions.

However, as with all engineering solutions, there are conditions that should be followed. In this instance the principle consideration is that not all physical processes scale to the same laws. The consequence of this fact is that the dominant relationships are compared and the appropriate similitude law adopted.

For wave energy physical modelling there are two main criteria to consider, Froude and Reynolds. Froude equates inertial forces whilst Reynolds relates viscosity. Because of their derivation both of these two criteria cannot be matched in the same model. Since inertia dominates the majority of the forces experienced in wave energy device operation Froude scaling is selected as the primary law to match between the model and the prototype.

It is, however, important to know that there will be some forces present that are not to scale and their influence on the results should be qualified if not quantified. This is particularly the case in small scale wave energy models, circa $\lambda < 1:50$, that have large wave frequency, first order, excursions, especially heave. Such physical combinations produce the worst deviations from full scale results and are the primary rationale for the progressive increase in scale through the phases. This approach not only applies checks to the scale effect but, since different facilities support different scales, the laboratory effects also.

6.3.2 Froude and Reynolds similitude

The actual equations for these two criteria are:

Froude: $$Fr = \sqrt{\frac{\text{inertia force}}{\text{gravity force}}} = \frac{v}{\sqrt{gL}}$$

v = velocity
g = acc. due to gravity
L = length scale

Reynolds: $$Re = \sqrt{\frac{\text{inertia forces}}{\text{viscosity forces}}} = \frac{\rho v L}{\mu} = \frac{vL}{\gamma}$$

ρ = density
v = velocity
L = length
μ = coeff. dynamic viscosity
γ = kinematic viscosity

These similitude criteria, as shown in Table 8, produce the following important relationships which should be applied during the model design and the data analysis extrapolation to full size prototype values.

Table 8 — Similitude scaling ratios

Characteristic	Dimension	Froude	Reynolds
		Geometric	
Length	[L]	λ	λ
Area	$[L^2]$	λ^2	λ^2
Volume	$[L^3]$	λ^3	λ^3
Rotation	$[L^0]$	—	—
		Kinematic	
Time	[T]	$\sqrt{\lambda}$	λ^2
Velocity	$[LT^{-1}]$	$\sqrt{\lambda}$	λ^{-1}
Acceleration	$[LT^{-2}]$	—	λ^{-3}
Volume Flow	$[L^3T^{-1}]$	$\lambda^{5/2}$	λ
		Dynamic	
Mass	[M]	λ^3	λ^3
Force	$[MLT^{-2}]$	λ^3	—
Pressure	$[ML^{-1}T^{-2}]$	λ	λ^{-2}
Power	$[ML^2T^{-3}]$	$\lambda^{7/2}$	λ^{-1}

6.3.3 Scale application (Froude)

The factors by which a physical parameter should be multiplied to convert from model to prototype scale can be read from Table 8. There are two important considerations when applying this:

- certain parameters have large multiplicands (e.g. power, $\lambda^{7/2}$)
- the extrapolation is dependant on the scale, λ.

$\lambda = 100$	Power $\propto 100^{3.5}$	$\propto$10,000,000
$\lambda = 50$	Power $\propto 50^{3.5}$	$\propto$884,000
$\lambda = 15$	Power $\propto 15^{3.5}$	$\propto$13,000
$\lambda = 4$	Power $\propto 4^{3.5}$	$\propto$128
$\lambda = 2$	Power $\propto 2^{3.5}$	$\propto$12

The figures above indicate why certain groups are concerned with prototype projections from small scale results. The governing similitude laws dictate that these calculations are valid but small differences can become significant in the prediction of absolute value. The percentage error will remain constant across the scale ranges. A particular cause of discrepancy can be non-linear, or higher order, effects that are not in kinematic or dynamic similarity.

The multiplicands also show why even the large scale models used at benign site sea trials do not produce significant amounts of electricity. Even a quarter scale 1 MW device would produce only 10 kW at the design rating. This means connection to a grid has little value but has the advantage that manageable resistive load banks can be used to burn off the generated power.

6.3.4 Scale evaluation

A crucial element of the recommended development protocol is that extensive comparisons of the results between the scales are made at the conclusion of each phase change. This procedure serves five main purposes:

- it verifies the smaller, previous model results;
- it validates the application of the similitude law to wave energy device development;
- it highlights if weaknesses exist in physical model testing methodology;
- it checks the importance of various physical properties and processes to device behaviour and performance;
- it reduces the uncertainty of the results.

To date there is little practical evidence to support the accuracy of predictions since only a small number of devices have achieved full/large scale sea trials and of those not all followed a progressive modelling path or designs went through significant changes between phases.

Some data does exist for validation purposes. It should be remembered that not all physical properties will conform to the same scrutiny even when extracted from the same set of tests. A sensitivity matrix of all parameters should be referenced when reviewing the data.

Figure 42 shows three phases of results at small, medium and large scale. These are normalized power production of a WEC in several different seaways, represented by the horizontal base of the pivot plot. Each sea state is coded with a different shading by the peak period and the benign ($\lambda = 1:4$) results were selected when the scatter diagram element resembled a Bretschneider spectra. This classical shape had been used during the small and medium scale tests.

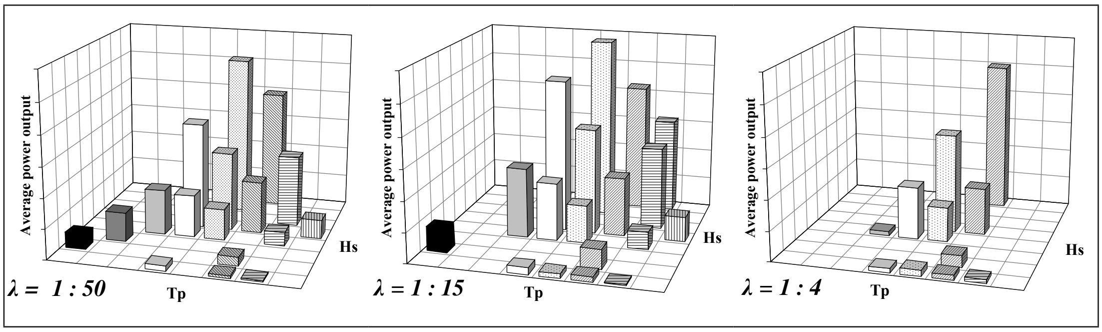

Figure 42 — Device power predictions from the three phases

These results are from a pneumatic type device so the power represents an exacting parameter which contains several factors that have unknown scale effects, e.g. air compressibility, viscosity. Reference to the three plots reveals close similarity at the different scales, which does support small scale trials.

The conclusion of these comparisons, once more data has been made available, could be that the intermediate scales can be skipped. However, endorsements from developers who have been, or are engaged in, large scale sea trials, suggest phase 3 is valid for the experience gained in bringing together a multidisciplinary team and several differing technologies in a fully functional device. This practical skill is achieved with the added benefit that the rehearsal is not prohibitively expensive.

7 Reporting

7.1 General

The basic requirement and rationale for model testing wave energy devices has been outlined in this document. The importance of a phased technology readiness level approach has been described and examples of how test schedules for each phase can be constructed are included. Equally as important as completing the device development programme is the reporting of the activities and results within each phase.

It is to these data sets that stage gate criteria will be applied during the most important evaluation stage.

The question of commercial confidentiality will obviously become a concern in the content of these reports but that should influence the distribution rather than the production.

The actual test schedule flow diagram for each specific trial set will dictate the main part of the reporting procedures and provide the data for the downstream activities such as analysis and presentation. However, the other elements required to configure a test programme should also be described following Clauses 3, 4, 5, and 6.

Each report will be formatted for the device under test and the phase of the trials. However, there should be some underlying principles and minimum inclusions to all the technical reports. A liberal use of photography, diagrams and graphs in a report is encouraged together with the following information.

7.2 Purpose of tests

- Phase and scale use.
- Objectives of trials.
- Plan and schedule.
- Type of model.
- Type of tests.

7.3 Facilities

- Type (flume, basin, benign site).
- Specification of tank.
- Wave generation capability.
- Beach and paddle characteristics.
- Pre-calibration of waves.

7.4 Model

- Technical specifications and material selection.
- Scale calculations of geometry and mass properties.
- Method of validation (dry and wet).
- Special features.

- Selected mooring (including characteristics).
- PTO specification and characteristics.
- Instrumentation:
  - Specification and selection of sensors.
  - Calibration curves of all sensors.
  - Measuring accuracy (static and dynamic).
  - Location on model and in water (i.e. wave probes).

7.5 Waves and seaways

- Height and period of monochromatic waves.
- Directions selected.
- Duration of panchromatic seaways generated.
- Summary statistics of all sea states.
- Spectral shapes selected.
- Short crest seaways definition ($2Cos^n$).
- Calibration evidence of all wave fields.

7.6 Data acquisition

- Monitoring equipment specification (rates, duration, ranges).
- Description of hardware (analogue to digital logger, transducers).
- Brief of software (MatLab, LabVIEW, Excel).
- Synchronization of measurement signals.

7.7 Test programme

- Set-up procedures.
- Special investigations.
- Description of tests conducted.
- Note on model changes.
- Failure modes.

7.8 Data analysis

- Examples of raw data.
- Description of validation methods and routines.
- Examples of analysed data.
- Description of formulae and equations implemented.
- Full entry of summary data.
- List of approximate methods and simplifying assumptions.

7.9 Extrapolation of results

- Scale factors implemented.
- List of approximate methods and simplifying assumptions.
- Comparison of model scale results.
- Decision gate criteria.

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