5 Numerical and Experimental Modelling of WECs

The design of a wave energy converter relies heavily on results from numerical simulations and experiments with scale models. Such results allow not only fundamental design changes but also the optimisation of selected configurations. For ongoing development, and particularly at an early stage, numerical models give the flexibility of assessing a large number of versions at a relatively low cost. Physical models are then tested in wave tanks to validate the numerical simulations and to investigate phenomena which are not evidenced by the computational packages. This chapter provides an overview on the numerical techniques that have been used to model the hydrodynamics of wave energy converters (WECs), details on wavemaker and wave tank design, guidelines on experimental techniques and finally a case study related to one of the most studied concepts which reached the full-scale prototype stage.

5.1 Fundamentals of Numerical Modelling

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When designing a wave energy converter, and at several stages of development, numerical modelling is pivotal. In this section only the hydrodynamic numerical modelling is considered. It is critical at an early stage, as it allows several iterations of the same concept to be tested in the fastest way possible, but it is equally critical in later stages, when envisaging new generations of machines and/or trying to optimise control routines.

Chapter 3 already focused the differences between working in the frequency or in the time domain. Basically frequency domain solutions of the equations of motion rely on the assumption that the incident waves are the result of the superposition of single harmonic waves. Linear wave theory is used (i.e.: body motions are assumed small when compared with the wavelength) and thus the problem can be split into two other: the diffraction problem, where the body is fixed and subject to an incoming wave field, and the radiation problem, where the body is forced to move in otherwise undisturbed fluid. The velocity potential is obtained the sum of the diffraction potential and all the radiation potentials, which can be associated with the wave exciting forces and moments and with the hydrodynamic coefficients (added mass and damping), respectively. With such results the motions of the body can be derived, and these are usually expressed in a non-dimensional form through the response amplitude operator (RAO). Additional constrains can be introduced by external mass, damping of stiffness matrices (e.g.: to assess the influence of different mooring arrangements or of different power take-off settings).

When non-linear effects are judged to be significant, time domain solutions need to be implemented. There are several ways to derive such models, but in the majority of cases the non-linear analysis is based on direct pressure integration over the body surface at each time step of the simulation (McCabe, 2004). Simplifications, like reducing the body surface to a mean wetted-surface, can be implemented, leading to a considerable reduction in the computational time that is required to run the simulations at the expense of the maximum possible accuracy. The main difference to the frequency domain approach is therefore the possibility of adding non-linear effects in the equations of motion, which are typically linked with convolution integrals that take into account effects that persevere after the motion of the body stops (hence such integrals are sometimes referred to as 'memory functions').

To this date the frequency domain approach as been used in a much larger number of applications than the time domain equivalent. The fact that this book is dedicated to an overview of the several stages of development of wave energy converters lead to the choice of emphasising such approach in this section, as frequency domain models are particularly useful to those who are new to the field and are simultaneously valid tools to the more experienced readers. Firstly an introduction to panel methods is given, while in 5.1.2 details regarding specific studies involving several wave energy converters are addressed.

5.1.1 Introduction to Panel Methods

Panel methods, also referred to as Boundary Element Methods (BEM) in a wider engineering perspective, are computational methods used to solve partial differential equations which can be expressed as integral equations. Typically, BEM are applicable to problems where the Green function can be calculated. A thorough review on panel methods in computational fluid dynamics is presented in Hess (1990). Relevance is given to aerodynamics, but the main assumptions (e.g.: potential flow) and principles are relevant to general fluid mechanics problems. A sub-chapter focusing exclusively in free surface applications is also presented. The two common problems given as examples are:

1. a ship at constant forward speed in an undisturbed wave field;
2. a fixed structure facing incoming regular waves.

Note that an extension of the case described in 2. also includes the problem of an oscillating body in an undisturbed media, which is particularly relevant in wave energy conversion.

In 1., Rankine type sources were originally used and both the submerged portion of the hull and the surrounding free surface were panelised. In 2. the singularities are more complex and only the body is discretised. Newman (1985) developed a practical technique to address such issues and later applied it to a variety of case studies. Many references can be found in the literature, but given the introductory nature of this section Newman's key communications are followed.

A review on the basic principles that rule the application of panel methods in marine hydrodynamics is given in Newman (1992). It is emphasised that many of the common problems in this subject, like wave resistance, motions of ships and offshore platforms, and wave structure / interaction can be addressed following potential flow theory, where viscous effects are not taken into account. The objective is therefore to solve the Laplace equation with restrictions imposed by boundary conditions. The domain is unbounded (with the solution being specified at infinity), so a numerical approach that arranges sources and (optionally) normal dipoles along the body surface can be considered to solve the hydrodynamic problem. Two different representations can be considered, following Lamb (1932): the potential or the source formulation. In the first one, Green's theorem is used, and the source strength is set equal to normal velocity, leaving the dipole moment, which is equal to the potential, unknown. On the other hand, the source formulation relies solely on source terms with unknown strength to describe the potential. In both cases, similar Fredholm integral equations can be solved.

The pioneer work of Hess and Smith (1964) is mentioned by Newman, in which the source formulation was used for three-dimensional bodies of arbitrary shape. For the first time, a linear system of N algebraic equations was derived by establishing boundary conditions at a collocation point on each of the N panels that were used to describe the fluid domain.

Hess and Smith (1964) also derived the analytical expressions for the potential and velocity induced by a unit density source distribution on a flat quadrilateral panel, avoiding numerical integration that could lead to erroneous results when the calculation point is in the vicinity (or on) the panel.

To conclude his keynote paper, Newman (1992) also points out the basic differences between the source and the potential formulation. It is mentioned that the computational effort required for both approaches is roughly equivalent. The differences manly involve:

1. issues linked with thin bodies, where normal dipoles prove to be more stable than sources;
2. the fluid velocity, that in the source formulation can be evaluated from the first derivatives of the Green function, whereas in the potential formulation the second derivatives are necessary. Nevertheless the latter is not robust when using flat panels to discretise a curved surface, given that the velocity field induced by the dipoles changes quickly over distances similar to the panel dimensions;

3. ‘irregular frequencies’, which are related to flawed solutions in problems involving bodies that pierce the free surface. It is a common problem of both approaches but more likely to appear in the source formulation (Yeung, 1982).

When choosing a method to solve a specific problem there are two main versions that can be followed: a low-order method, where flat panels are used to discretise the geometry and the velocity potential, and a high-order method, which uses curved panels, allowing (in theory) a more accurate description of the problem. The high-order method has inherent advantages and disadvantages when compared with the low-order equivalent. Lee et al. (1996a) and Maniar (1995) showed the increase in computational efficiency, i. e., the method converges faster to the same solution when the number of panels is increased in both. The possibility of using different inputs for the geometry, like an explicit representation, also contributes to an increase in accuracy. Another significant advantage relies on the continuity of the pressure and velocity on the body surface, which is relevant for structural design. The main disadvantage is linked with the lack of robustness that the method yields, failing to converge in some cases. Such issues can be particularly severe when a field point is in the vicinity of a panel or near sharp corners.

The concerns associated with the computational burden have been progressively loosing the initial importance as computers evolved. However such issues remain clear when developing a new code, particularly when studying complex problems. It is also clear that the pre-processing, linked with the calculation of the panel representation and relevant parameters, like areas and moments of inertia, and the solution of the linear system itself, are the steps which require the majority of the effort.

Newman and Lee (1992) performed a numerical sensitivity study on the influence that the discretisation has on the calculation of wave loads. The effects of the number of panels and their layout were investigated. Convergence tests were also performed. Such focus on accuracy was clear since the early simulations, but computational limitations were clear. A classic case is the one described in Eatock Taylor and Jeffreys (1985), where the hydrodynamic loads calculated are of ‘uncertain accuracy’. The recent hardware developments allow much more detailed studies.

Typically, increasing the number of panels used in the geometric and hydrodynamic representations will lead to an increase in accuracy. One important exercise that should never be neglected when developing a code is the numerical verification of the results, ensuring that the solution is not divergent or convergent to the wrong solution. Naturally validation, i.e., the comparison with physically derived results, is also a key factor. The computational time required to solve the problem also increases with the number of panels, so an optimal ratio between accuracy and the number of panels can be derived. Equally relevant is the panel layout, which can be solely responsible for invalid solutions.

A few basic qualitative guidelines are pointed out by Newman and Lee (1992). These can be summarised in the following way:

1. near the free surface, short wavelengths demand a proportionately fine discretisation;

2. local singularities, induced by (e.g.) sharp corners, tend to require fine local discretisation;
3. discontinuities on the characteristic dimension of the panels should be avoided; ideally a cosine spreading (also referred to as spacing) function should be used for the panel layout (width of the panels is proportional to the cosine of equally-spaced increments along a circular arc);
4. problems involving complex geometries can require a high number of panels even for simple calculations (e.g.: volume).

Convergence tests are usually the answer to select the optimal discretisation. For representative wavelengths and for the same mesh layout, the number of panels is increased and the output evaluated. For a high enough value, the increase in the number of panels will not lead to a significant change in the solution.

The authors mention the word ‘error’ when comparing different numerical solutions, which according to many references is fundamentally wrong (Roache, 1998; Eça and Hoekstra, 2000). Recently several authors have conducted verification studies using numerical results related to different concepts (e.g.: Cruz and Payne, 2006; Sykes et al., 2007).

Newman and Lee (1992) also mention, using the low-order method (flat quadrilateral panels), a numerical ‘error’ of 0.1 % to 10 %, emphasising the need to validate all the results. The authors are directly associated with the development of a BEM code named WAMIT, at the Department of Ocean Engineering of the Massachusetts Institute of Technology (MIT). This code was initially verified through comparison with analytical solutions. Validation exercises were also conducted using experimental results. Together with these procedures, benchmarking with similar codes also has an important role to ensure that a code does not converge to the wrong answer. Examples of topics studied by this research group include wave loads on offshore platforms, time-domain ship motions, ship interactions in a channel, wave energy conversion and, on a more theoretical level (with implications to all fields), the development of a panel method based on B-splines. This high-order approach is justified by some fundamental differences, namely the possibility of describing more accurately the geometry and the velocity potential. Recent developments are presented in Newman and Lee (2002).

Other research groups have been actively involved in BEM code development. A particular strong one with regard to the study of wave energy conversion can be found at the École Centrale de Nantes (Laboratory of Fluid Mechanics). A complete suite of packages for several seakeeping problems has been under development since 1976 at ECN, resulting in:

1. AQUADYN, for general problems without forward speed;
2. AQUAPLUS, which assumes an encounter frequency for a moving vessel;
3. CUVE, which solves the problem of a vessel with internal tanks.

AQUADYN is a BEM code very similar to WAMIT, in particular to its low-order panel method solver. Several examples of the use of AQUADYN can be found in the literature (e.g.: Brito-Melo et al., 1998). Details about specific studies related to wave energy conversion involving AQUADYN and WAMIT, two of the most prominent BEM codes used in the field, are given in section 5.1.2.

5.1.2 Applications of Panel Methods to Wave Energy Conversion

It is fair to say that Salter's early work regarding wave energy absorption by different shapes, published in a wide audience journal like Nature (Salter, 1974), lead to similar studies in research groups spread worldwide. The first numerical simulations soon followed. A first attempt to numerical reproduce Salter's experiments was made by Katory (1976), in which inconsistent results were obtained (e.g.: the derived added mass matrix was not symmetric). Mynett et al. (1979) presented the first comprehensive numerical study with regard to cam shaped wave energy converters, following the experimental work performed by Salter on such shapes and the theoretical work of Mei (1976) and Evans (1976), where the principles of basic power take-off systems were described and characterised using linear wave theory. A modified hybrid element method, originally derived by Bai and Yeung (1976), was used. The forces, motions and the hydrodynamic efficiency of the device were assessed. The simulations were validated by direct comparison with the available experimental results, allowing the confirmation of the high efficiency of the cam shape in a broad band of wave frequencies. An interesting sensitivity study was also conducted, evaluating the impact of the change of shape, submergence ratio, water depth and the inclusion of a non-rigid support structure. Some key findings can be identified in Figures 5.1 and 5.2, which illustrate the relative influence of such parameters for constant water depth by plotting the efficiency (ε) as function off the non-dimensional frequency. Figure 5.1, where the optimal efficiency (ε_{opt}) is compared for selected configurations, shows the predominant influence of the submergence depth (s) with regard to other parameters like the angle θ, which partially defines the shape. Note that when $\theta = \pi/2$ and $s = 0$ the theoretical limit for a semi-circle is reached, so $\varepsilon_{opt} = 0.5$ for all frequencies. Figure 5.2 shows a similar plot, now comparing the effect of the external damping ratio $\left(\hat{\lambda}'_{22}/\hat{\lambda}'_{33}\right)$, where the index '2' denotes heave and '3' pitch. The two curves per damping ratio correspond to two different values of the external carriage mass (which holds the support system). It is clear that as the ratio decreases so does the efficiency.

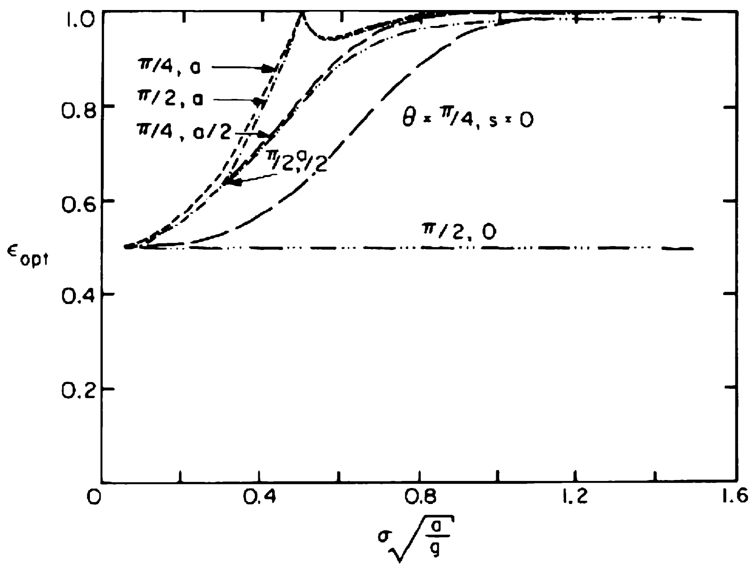

Fig. 5.1. ε_{opt} vs. non-dimensional frequency for different configurations (Mynett et al., 1979)

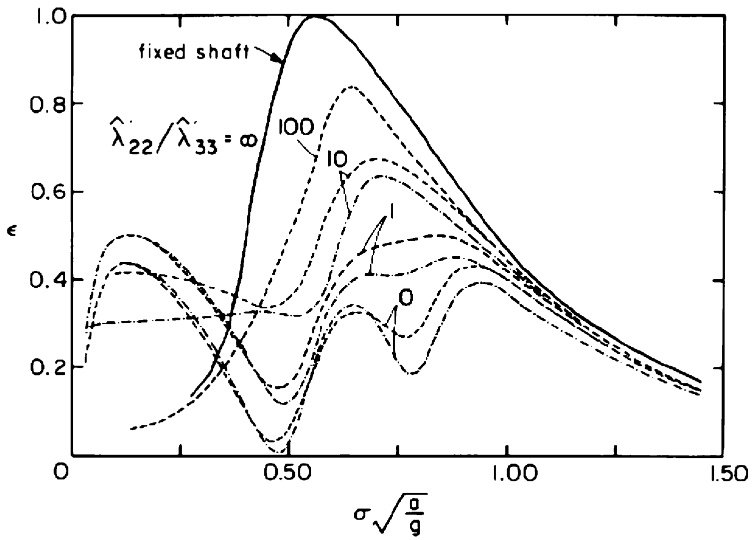

Fig. 5.2. ε_{opt} vs. non-dimensional frequency for different non-rigid supports (Mynett et al., 1979)

Mynett et al. (1979) therefore corresponds to the first numerical study concerning cam (or duck) shapes. In Standing (1980) numerical comparisons regarding the response amplitude operator in pitch and the capture width for a duck string were evaluated by means of a BEM code named NMIWAVE, from the National Maritime Institute, in a direct follow up of Mynett et al. (1979). Most of the subsequent work at the University of Edinburgh was experimental, with different models at different scales being tested in narrow and wide wave tanks, but Pizer (1992, 1993, 1994) applied a pure BEM approach to the duck geometry and in Cruz and Salter (2006) WAMIT was also applied to the same concept.

The use of pure BEM codes to study wave energy converters (WECs) was at first also linked with the study of Oscillating Water Column (OWC) plants. Brito-Melo et al. (1998, 2000a) modified the AQUADYN code originally developed at ECN (Nantes), producing a specific version dedicated to OWCs (AQUADYN-OWC). The major modification was associated with the supplementary radiation problem imposed by the oscillatory movement of the water in the inner chamber, which was solved by modifying the boundary condition through the pressure distribution. The study, conducted in the scope of the development of the Pico plant, showed an increasing level of depth: the initial configuration assumed an isolated structure surrounded by an infinite fluid domain (Fig. 5.3), whilst the final geometry included the neighbouring coastline and bathymetry (Fig. 5.4). Comparisons were made with a 1:35 scale model, validating the numerical results.

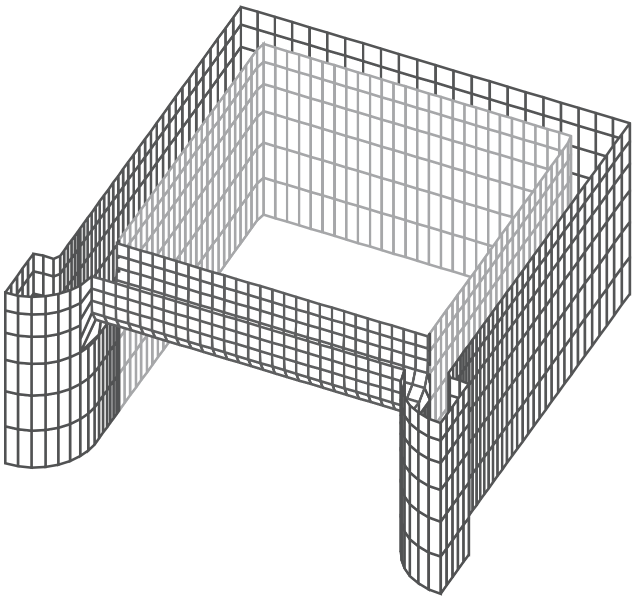

Fig. 5.3. Initial OWC configuration studied (Brito Melo et al., 1998)

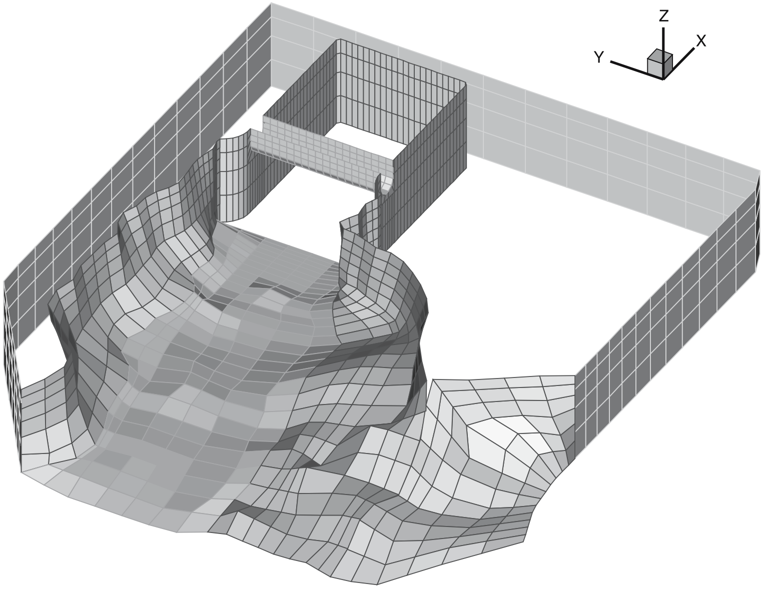

Fig. 5.4. Final OWC configuration studied (Brito Melo et al., 2000a)

Studies involving the integration of OWCs in breakwaters have also been conducted by the same wave power group at the Instituto Superior Técnico (Brito-Melo, 2002b). Such approach required a number of changes in AQUADYN-OWC, most of which due to the presence of the breakwater, and can be useful for the modelling of new OWCs like the one to be integrated in the Porto breakwater (Portugal) in the near future (Martins et al., 2005), or to numerically simulate experiments such as those described in Bocotti et al. (2007).

WAMIT has also been used, in its low-order option, to model OWCs. Lee et al. (1996b) studied three different configurations: a moon pool in infinite water depth, a bottom-mounted OWC and an OWC with extended walls (in the direction of wave propagation). Two approaches were conducted to incorporate the inner free surface effects. Firstly, the source code was modified to take into account a new dynamic boundary condition. Secondly, a virtual surface was fitted to the inner free surface, with predetermined velocity distributions ruling the movement. The study lacks experimental validation but a partial verification exercise was performed, comparing the outputs of both approaches, which were found to be closely correlated. Several numerical problems were identified, like the difficulty in implementing the principles associated with resonance in a linear code, and the influence of thin walls, which can lead to inaccuracies when representing the linear system of equations. Numerical sensitivity exercises were also conducted by evaluating different discretisations of the geometry and by comparing the derived values for the exciting force from direct pressure integration and from the Haskind relation.

Delauré and Lewis (2003) applied WAMIT in the modelling of an OWC, following a similar approach to the second one employed by Lee et al. (1996b), where generalised modes of motion were used to model the inner free surface. The article follows up on a series of contributions from the same authors, where a review on similar applications, parametric studies and benchmarking with experimental results were presented (Delauré and Lewis, 2000a; 2000b; 2001). The agreement between numerical and experimental results was shown to be particularly good for small amplitude waves and for an 'open chamber' configuration (no external damping). One of the results confirms Newman's earlier work (Newman, 1992), by pointing out the differences between the results from the potential and the source formulation, with the latter being judged less suitable for problems involving thin wall structures such as OWC plants.

Returning to the previously mentioned work at the Wave Power Group of the University of Edinburgh, Pizer (1994) used a custom made BEM code, previously developed at the University of Strathclyde during the author's PhD studies, to compare numerical with experimental results from a solo duck (Skyner, 1987); see Chapter 2. In the process of verifying the code, selected analytical results, such as a floating hemisphere, were also used. Recently a WAMIT model was derived to compare results from its high-order module to both the low-order predictions from Pizer and the experimental results from Skyner. The radiation impedance matrix, the exciting force and the non-dimensional capture width were calculated. The results show, as expected, a better agreement with the previous numerical predictions than with the experimental results. Nevertheless the correlation with the latter is at least as good as the previous (i.e., when using the original numerical calculations). Examples are given in Figures 5.5 and 5.6 for the real part of the hydrodynamic impedance matrix and the modulus of the wave exciting force, respectively. Typically the WAMIT curves seem to be vaguely shifted in terms of frequency when compared to the experimental ones. This is particularly clear when trying to identify the maximum / minimum value on each plot, and could be partially linked partially with the discretisation procedure or, as indicated by Payne (2006) in a study of a different concept, to inaccuracies in the description of the mass matrix. Sensitivity studies show that the outputs are strongly influenced by changes in this matrix, particularly in the moments of inertia. In the duck case the differences are most likely due to the presence of the vertical flat mounting struts from which the model is connected to the test rig. With regard to the non-dimensional capture width, the influence of the control parameters on the location of the peak value is not only clear but expected. In addition Pizer (1992) pointed out that in further studies regarding conservation of energy, Nebel (1992) came across unaccounted losses, which could be linked with the properties of the flow or a physical problem with the test rig.

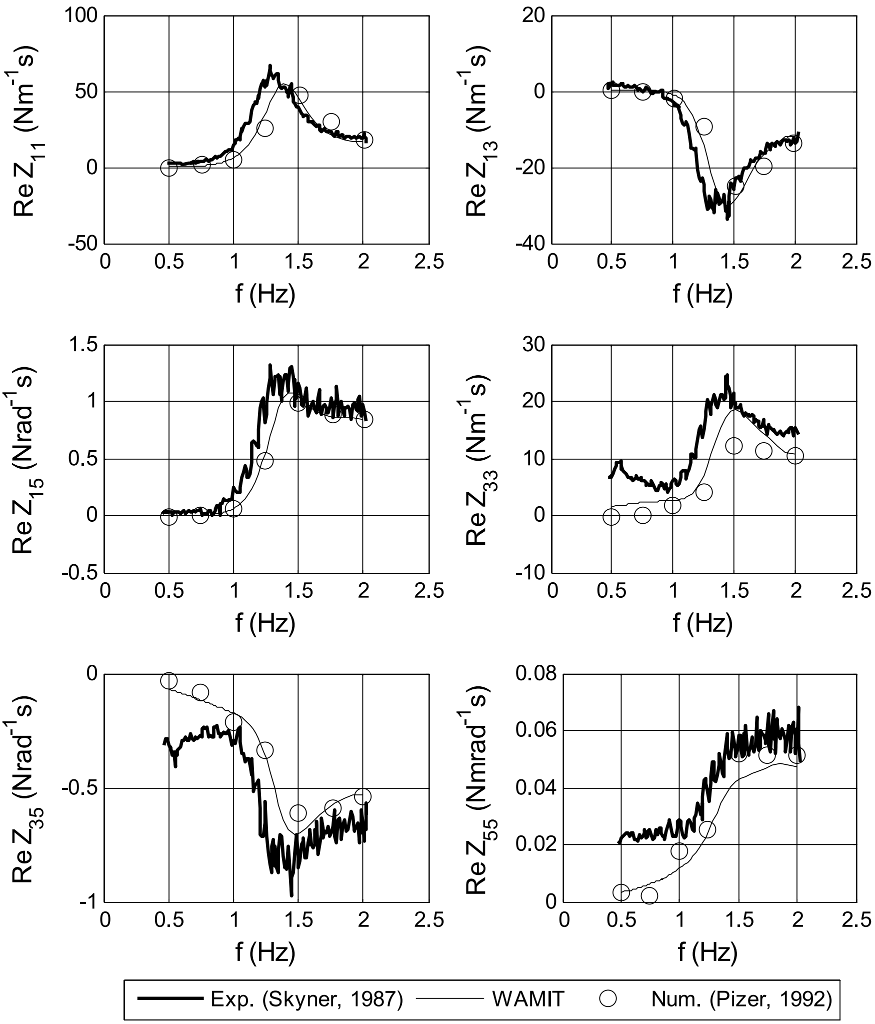

Fig. 5.5. Real part of the hydrodynamic impedance matrix – duck model results

Within the same research group, Payne (2006) used WAMIT to perform the hydrodynamic modelling of a sloped IPS buoy, comparing the results with those from two experimental models: a one degree-of-freedom model (Fig. 5.7) and a freely floating model (Fig. 5.8). The one degree-of-freedom version was developed by Lin (1999). WAMIT results, particularly in terms of the body motions, showed a shift in the frequency with regard to the experimental equivalents, a tendency that was linked with the influence of the discretisation of the inertia matrix. A numerical sensitivity study to quantify the influence of the radii of gyration

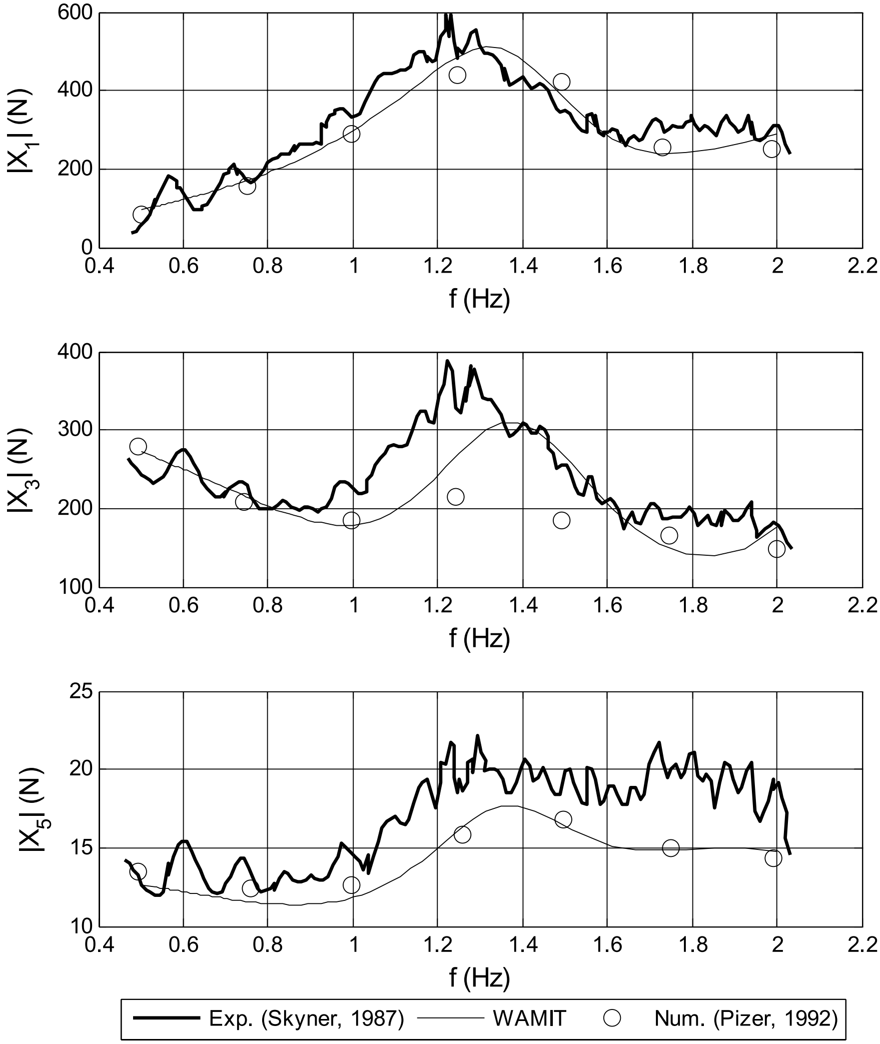

Fig. 5.6. Modulus of the exciting force (1- surge; 3- heave; 5 – pitch) – duck model results

was conducted to confirm that effect. The complexity of the model, namely the dynamometer that acts as the power take-off system and the inability to fully describe all the physical phenomena in a linear code can also be indicated as partially responsible for such discrepancies. An extensive review on the application of BEM codes to wave energy research, both in theoretical studies and when comparing numerical and experimental results, is also available in Payne (2006).

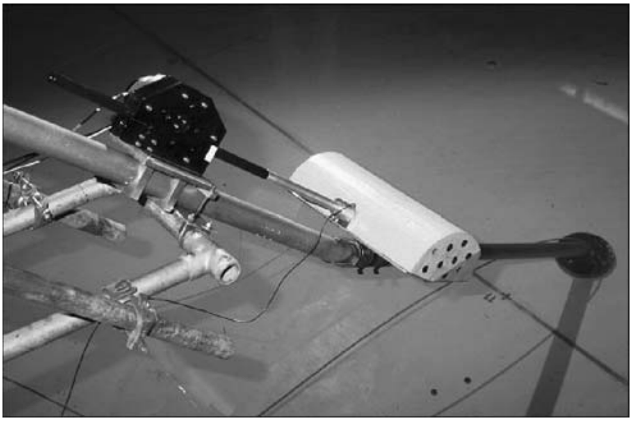

Fig. 5.7. One degree-of-freedom experimental model of the slopped IPS buoy (Lin, 1999)

To conclude, and to emphasise the importance of BEM modelling, particularly at the early stages of development, two examples related to full-scale concepts which will be addresses later in Chapter 7 can be given. Firstly, the Archimedes Wave Swing (AWS), for which the first numerical calculations were performed by Pinkster (1997), who derived the hydrodynamic coefficients for selected geometries. The AQUADYN code was also extensively applied to the AWS, allowing the recalculation of the hydrodynamic coefficients and also the exciting force for a wide range of configurations (Alves, 2002; Prado et al., 2005). Figure 5.9 shows one of the early numerical discretisations of the AWS pilot plant. Recently results from AQUADYN were used to estimate the wave profile directly above the full-scale pilot plant, which was installed in late 2004 offshore Póvoa de Varzim in Northern Portugal (Cruz and Sarmento, 2007). Starting from a library of hydrodynamic coefficients related to nine scenarios for different levels of tides and floater positions, the aim was to characterise the sea state at the actual pilot plant's location using the available pressure sensors. Two approaches were performed: a first one purely based in linear wave theory, neglecting the presence of the device, and a second one, based on the results from AQUADYN, which allowed a detailed quantification of the effects of the presence of the plant on the wave profile directly above it. Comparisons with a Datawell Waverider buoy located at a certain distance from the plant validated the methodology.

In a similar way, and also from an early stage, the Pelamis wave energy converter (WEC) has been developed using a variety of computer codes, of different scope and complexity. In the basis of all the developed tools is the computation of the hydrodynamic coefficients, exciting force and motions in several degrees-of-freedom using a linear BEM code named 'Pel_freq'. A detailed description of the complete software suite is given in Retzler et al. (2003), where validation exercises are described at several scales, though initial comparisons with results from a

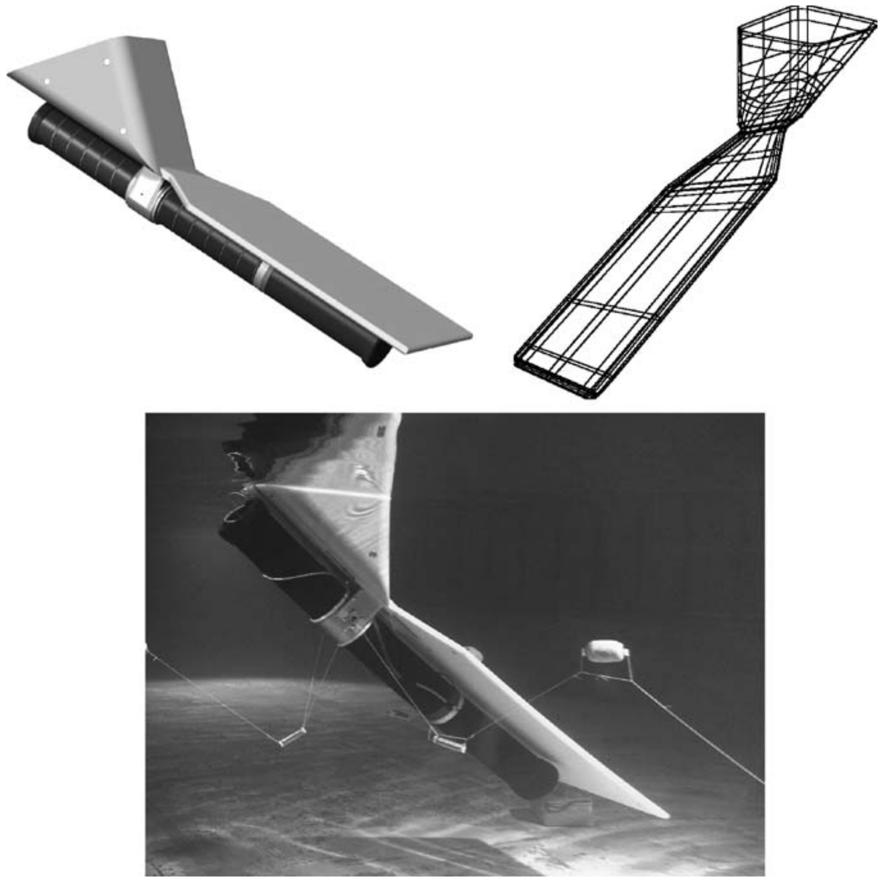

Fig. 5.8. Freely-floating model of the slopped IPS buoy (Payne, 2006): SolidWorks model (top left), MultiSurf model (top right) and experimental model (bottom)

1:35 scale model were already presented in Yemm et al. (2000). An updated version of the 2003 article is given in Pizer et al. (2005). It is emphasised that the outputs of the frequency domain code are extensively used as inputs in the time domain simulation also developed by Pelamis Wave Power (formerly Ocean Power Delivery) (linear and nonlinear), and in interfaces with other numerical tools for selected problems (e.g.: mooring load analysis). A case study related to the modelling of the Pelamis WEC, a concept already mentioned in Chapter 3 (and described in detail in Chapter 7), is given in section 5.4.

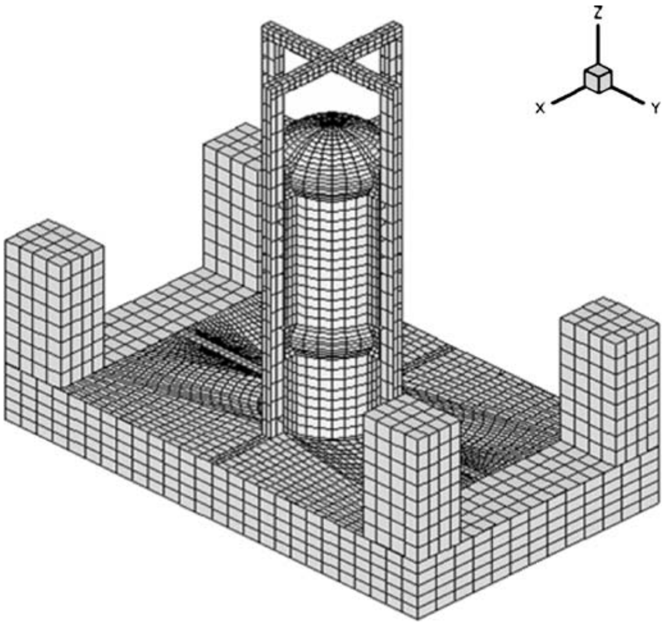

Fig. 5.9. AQUADYN's discretisation of the AWS geometry (Alves, 2002)

5.2 Wave Tank and Wavemaker Design

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Most modern tanks use two types of wavemakers. Flap paddles are used to produce deep water waves where the orbital particle motion decays exponentially with depth and there is negligible motion at the bottom. Typical applications are the modelling of floating structures in deep water and the investigation of the physics of ocean waves. Often the hinge of the paddle is mounted on a ledge some distance above the tank floor.

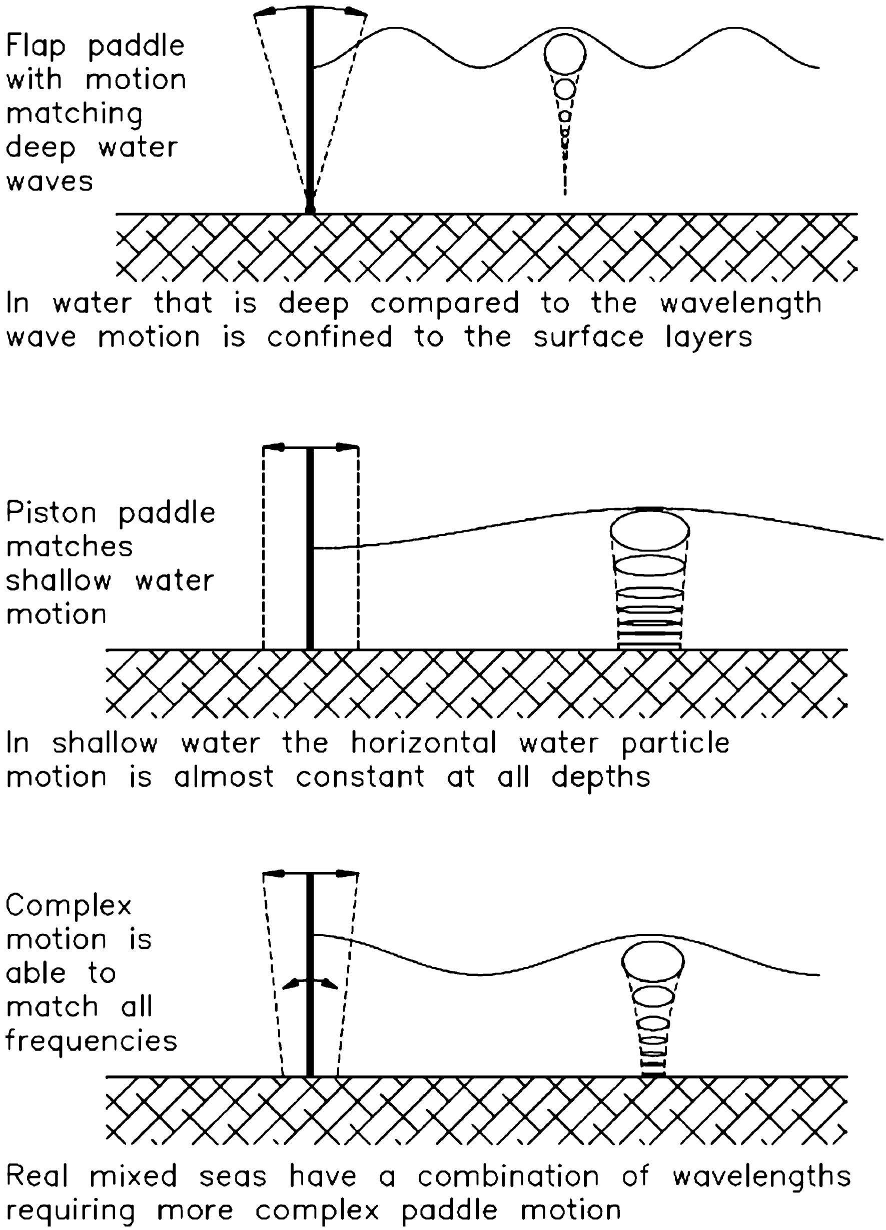

Fig. 5.10. Description of the motion of a wavemaker

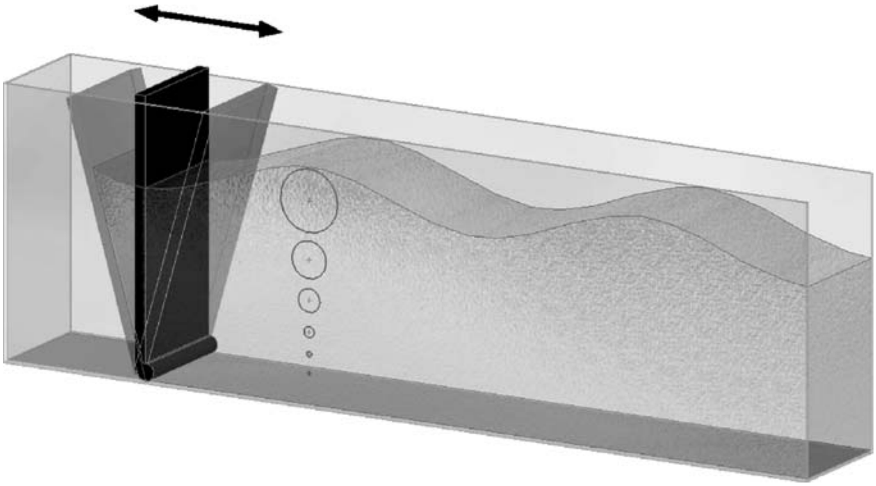

Fig. 5.11. Schematic of a flap paddle

Piston wavemakers are used to simulate shallow water scenarios, where the water depth is roughly smaller than half a wavelength. Here the orbital particle motion is compressed into an ellipse and there is significant horizontal motion on floor of the tank. This type of paddle is used to generate waves for modelling coastal structures, harbours and shore mounted wave energy devices.

Most early wave tanks were custom designs produced in the laboratory where they were used, hence there are many unique and innovative designs. These include displacement pistons, sliding wedges and other more complex machines like double hinged flaps. The design goal is to try to match paddle motion to the water motion and minimise the evanescent waves immediately in front of the paddle. These unwanted waves decay naturally but reducing their amplitude minimises the

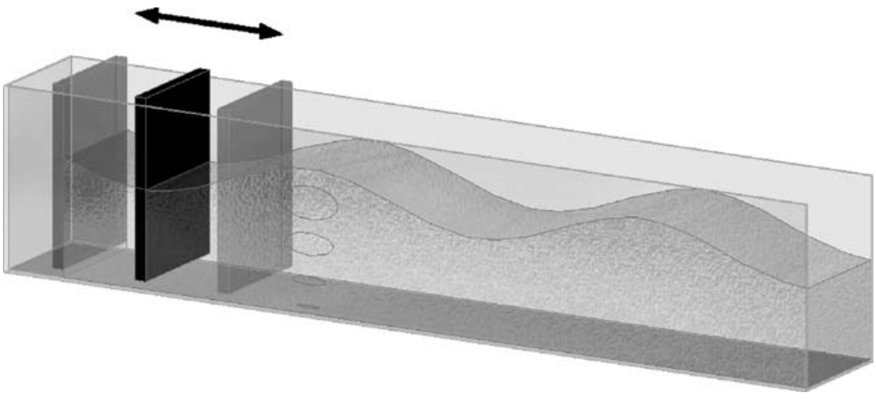

Fig. 5.12. Schematic of a piston paddle

unusable space in front of the paddle. All paddles will have an optimum frequency where the horizontal motion is very close to the motion of the water. This is the frequency where the inertia of the water, or added mass, is lowest. As the frequency is increased the mismatch between the paddle and the water motion causes the added mass to increase. This effect can be seen in a wave tank where a piston wavemaker generates high frequency waves, although the motion is small, the paddle moves a block of water that appears to be attached to it. It takes a few wavelengths for the natural wave to transform from this motion and travel down the tank. High frequencies do not require high power but can exert very high inertial loads on the structure. At low frequencies the volume displaced by the paddle limits the wave height. A piston will displace twice as much water as a flap, with the same stroke, so the wave will be approximately twice as big. Although the loads are low the design focus becomes the paddle stroke and preventing leakage round the structure (see Figures 5.13 and 5.14).

The type of research to be conducted in the tank determines the choice of tank size and wavemaker. First determine the sea state that is to be modelled; how deep is the water and what is amplitude and frequency range in the open ocean? The open full-scale sea wave spectra should be split into component wave fronts so that the amplitudes at different frequencies can be determined. The next step is to set the scale factor for the tank and models. There are many arguments that big is better however model scale is ultimately determined by the available budget. For most tanks this is in the range between 1/10 to 1/100 scale. The wavemaker type will depend on the relationship between the waves and the water depth. If the water depth is less than half the wavelength, or will be varied, a piston should be chosen.

5.2.1 Tank Width

The choice of tank width depends on the proposed model tests. The most straightforward tank is a single paddle in a narrow flume that represents a 2D slice, with the model fully blocking the width of the tank. This type of model is relatively easy to analyse because the waves and flow act in a plane. Visibility is excellent and models are readily accessible. It is a very good and economic tank for early investigations. A slightly wider tank with a single paddle can have a 3D model subjected to long-crested waves that pass round the sides so that 3D edge effects can be observed. The main difficulty is that as the width increases the frequency of the resonant cross wave becomes very close to the working frequency of the tank. For example a $0.7\,m$ deep tank $1.2\,m$ wide will have a cross wave of $0.78\,Hz$. The most realistic mixed seas have to be modelled in a wide tank with multiple individually controlled paddles. Software control of the paddles will allow a full range of waves and wave spectra to be generated. The width of the tank depends on model width and the angle of waves required on either side. For a line of paddles the angular spread is limited by the angle from the model to the tip of the line of straight paddles. One way round this is to build the bank of paddles in a curve (see Fig. 5.21).

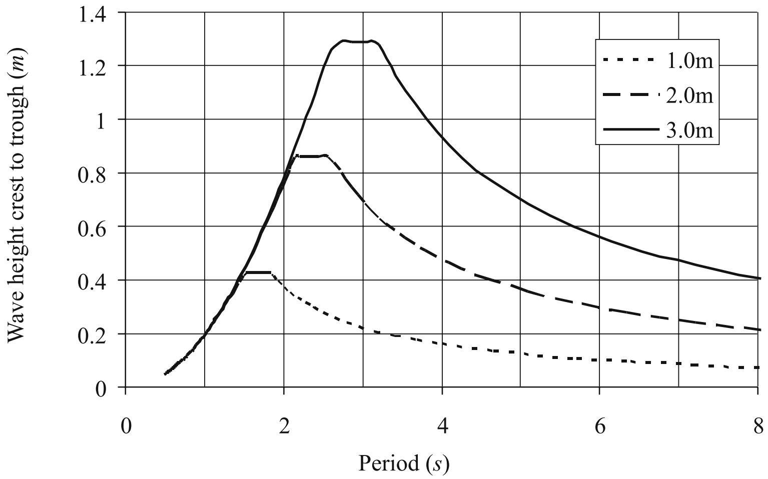

Fig. 5.14. Theoretical wave height for a 0.5, 0.75.1.0 *m* deep piston paddles with a stroke of +/– 0.5 x water depth

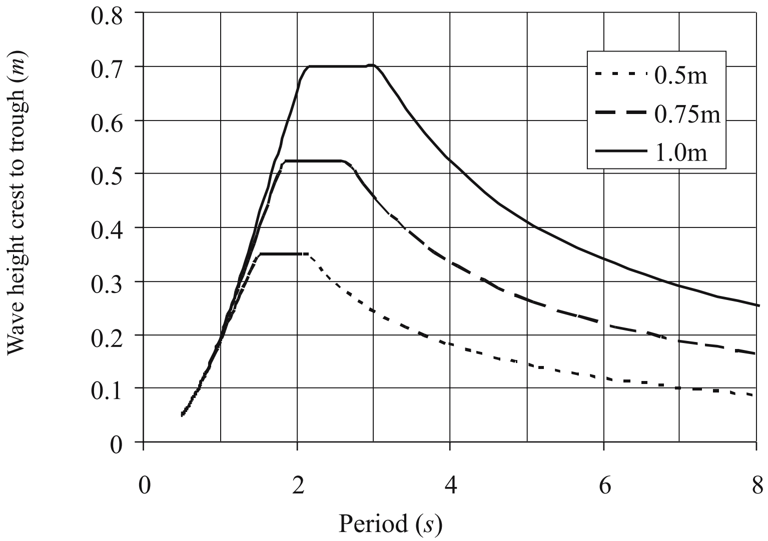

Fig. 5.13. Theoretical wave height for a 1, 2, 3 *m* deep flap paddles with a stroke of +/– 17 degrees

5.2.2 Tank Length

The tank has to have enough length to allow for three distinct areas. First there is the paddle and enough space for the evanescent waves to decay. Waves from a well-controlled paddle need to travel approximately twice the hinge depth of the paddle to become fully developed. The model zone depends on the size and motion of the model. Towing tanks are the extreme example where the length has to be sufficient to allow the carriage to accelerate, run and the slow down. For wide tanks the combination of width and length determines the angle of waves that approach the model. Finally there is the wave absorbing beach which has to be at least half the length of the design wavelength to achieve 90 % absorption.

5.2.3 Paddle Size

The angular motion of a flap paddle is determined by the quality of the control system. With position feedback it is reasonable to run up to +/–12 degrees. With force feedback or other 2^{nd} order correction they will run well up to a displacement of +/–18 degrees. Piston paddles can move larger distances and are typically designed with a stroke of 50–100 % the water depth. A paddle for generating solitons will require a total travel distance of at least twice the water depth.

The first analysis of wave generation was published by Biesel and Suquet (1951) and provides solutions for relationship between wave height, stroke and force for hinged and piston wave generators. This was refined by Gilbert, Thompson and Brewer (Gilbert et al., 1971) who produced design charts that give engineering solutions for wavemaker design. The analysis is based on linear theory and takes no account of breaking waves. Higher frequency waves are limited by breaking; for regular waves the limiting steepness is 1 : 7 so the linear wave height curve is combined with the breaking wave limit. This tends to overestimate the size of the maximum breaking wave so a practical solution is to truncate the top 15 % of the curve. The paddle will create waves above this height but they will by unsuitable for research but useful for demonstrating the tank to visitors. Lower frequency waves are limited by the displacement of the paddle. As an approximate guide a flap paddle should extend about 35 % of the hinge depth above the waterline.

5.2.4 Multiple Paddles

A bank of individually controlled paddles can produce angled waves by setting a phase difference in the drive signal to each paddle. The most common layout is a rectangular tank with a straight line of absorbing paddles facing a beach on the opposite side. At first this seems a restricted arrangement but the hard sides can be used to reflect waves towards the model so the virtual angle that the paddles cover is greater than the physical width. Computer driven paddles are very versatile and can generate waves at 90 degrees to the paddles. 3D wave tanks are notoriously complex experimental environments and there is a strong argument for keeping a simple layout of one generating side, one absorbing side and two hard reflecting sides. Several large tanks have paddles along two sides in a *L* shape with beaches on the opposite sides. This is especially useful if there is current flow in the tank so waves can be run across and with the current flow. This arrangement leads to a complicated geometry where the two banks of paddles meet and waves get absorbed as they run along the beach which adversely affects the working area of the tank. Full computer control of the paddles allows the paddles to be laid out in any configuration leading to tanks with paddles arranged in a curve. Many coastal tanks have movable paddles that can be arranged around a model to provide waves from an appropriate direction.

Desired angle/frequency and the available budget determine the choice of paddle width. Multiple paddle wavemakers can generate angled waves up to a limit, which is determined by the paddle width and the wavelength. Normally this limit can be set where the apparent wavelength of the angled wave at the paddles is 2–4 times the paddle width. Near this limit the paddles generate a "ghost" wave at 90 degrees to the main wave. Figure 5.15 shows the operating envelope for various width paddles in 1 *m* deep water. Waves to the right-hand side of the curves are not possible. For example a bank of paddles, each 500 *mm* wide, will be able to generate a 1 *Hz* wave at 40 degrees but 700 *mm* paddles will not.

5.2.5 Drive and Control Systems

Early paddles used a crank to produce sinusoidal motion. An adjustable mechanical arm altered the stroke and the motor speed controlled the frequency. Some tanks had segmented paddles and angled waves could be produced by setting the phase of the cranks on a common drive shaft. This system could not be used for random waves and was time consuming to adjust. In the 1950s larger machines used a hydraulic drive with servo valve and electrical control system that could be directly driven with an analogue voltage. Most of the big naval towing tanks had direct servo hydraulic drives capable of generating long crested random waves.

With servo control it was possible to control the paddle motion from a signal generated in the control room. Single frequency waves were produced with a sine wave generator. Complex spectra were generated using a bank of adjustable filters to allow selected frequencies from a white noise source.

In the late sixties transistor amplifiers meant that direct drive electrical servo systems became possible. The size and reliability of electronic drives improved dramatically in the 1990s so that they are now competitive with hydraulic machines for all except the largest wave paddles. The control has become more sophisticated with specialised digital controllers available to correct for absorption of reflected waves and 2^{nd} order harmonics.

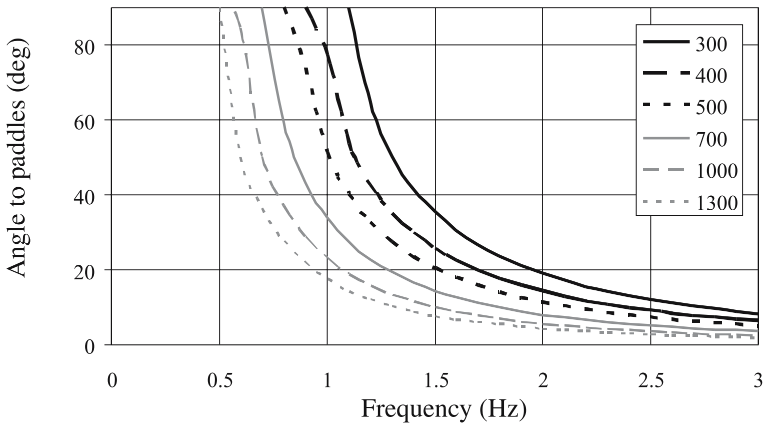

Fig. 5.15. Limiting angle for different width paddles in 1.0 *m* deep water

All modern tanks have wave generation software to drive the paddles. Data for the paddles is either pre-computed or generated in real time. A commonly used technique is to sum individual sine waves to create complex seas. Frequency, amplitude, angle and phase define a wave front. Summing individual wave fronts generates multi-spectral seas. Built-in functions allow regular sine waves, long crested multi spectral waves and mixed seas to be defined, each with a single line of text. Standard functions include the Pierson Moskowitz, Cosn, Cos2n, ISSC, Bretschneider, Neumann, Mitsuyasu and JONSWAP spectra, RMS merging, amplitude merging and freak waves.

5.2.6 Absorbing Wavemakers

Waves reflect off the surfaces of the model and from the sides of the tank. All tanks have resonant frequencies and often these lie within the working frequencies that are generated in the tank. A good beach will absorb much of the energy after it has passed the model but has little effect on cross-waves or models reflected from the model. This can be a major limitation on towing tanks where the productivity of the whole facility is determined by the settling time after a run has been completed. Active absorbing wavemakers dramatically increase the performance of a tank by prolonging the time that an experiment can run without the build up of spurious waves and also by decreasing the settling time between runs.

Traditional wavemakers work with a position feedback control system. This has the disadvantage that the swept volume of the paddle is dependent on the water level in front of the paddle. So the wave height generated is dependant on many factors including the size of an incoming wave or a poor quality beach.

During the first trials of the Duck wave energy converter Professor Stephen Salter found that wave height could vary by 30 % which made it very hard to measure the absorption of the device. Early experiments were unstable because waves were reflected back from the models and interacted with the wavemakers to create an uneven wave field. He overcame the problem by inventing a force feedback absorbing wavemaker that absorbed incoming waves by measuring the force on the front of the paddle and controlling the velocity (Salter, 1981). Now the absorption control is calculated by a digital controller so absorption is totally predictable and can be optimised for specific experimental conditions.

Other researchers have implemented wave absorption using different techniques such as measuring the incoming wave with a wavegauge mounted to the front of the paddle. This signal is brought into the paddle controller and the motion is modified to absorb and damp out the unwanted wave.

5.2.7 Absorbing Beaches

The wave, after it has passed the model, has to be absorbed. There are a wide variety of beach designs and the best summary is given in Ouslett and Datta (1986).

This survey assessed the performance of about 48 wave absorbers and several research papers. One factor that is common to many of the sloping beach designs is some form of innovative porosity mechanism, usually to channel the water flow caused by the wave advancing up the beach to be transferred back without affecting the wave. Similarly surface roughness is often used with the intention of tripping the wave over. The significant conclusions of the survey report are:

- A reflection of up to 10 % is to be expected even for well designed beaches and that the % reflection tends to increase with reduced wave height.
- It does not appear possible to attain reflection coefficients below 10 % for absorbers shorter than 0.5 to 0.75 of a wavelength.
- A porosity of 70 % in one case was shown to decrease the reflection coefficient by 2 %.
- Most beaches surveyed have a steepness of between 1:6 and 1:10 at the waterline.

Absorption, especially in a wide tank, is surprisingly difficult to define. It is dependant on amplitude, angle, and frequency. Many of the mechanisms that ultimately dissipate the energy rely on the Reynolds number so similar beaches will have different characteristics as the scale is altered. Another difficult with beaches is that they appear, in a tank, to be less effective than they are. A wave reflected from a beach that absorbs 90 % of the energy will be 31 % the height of the original wave.

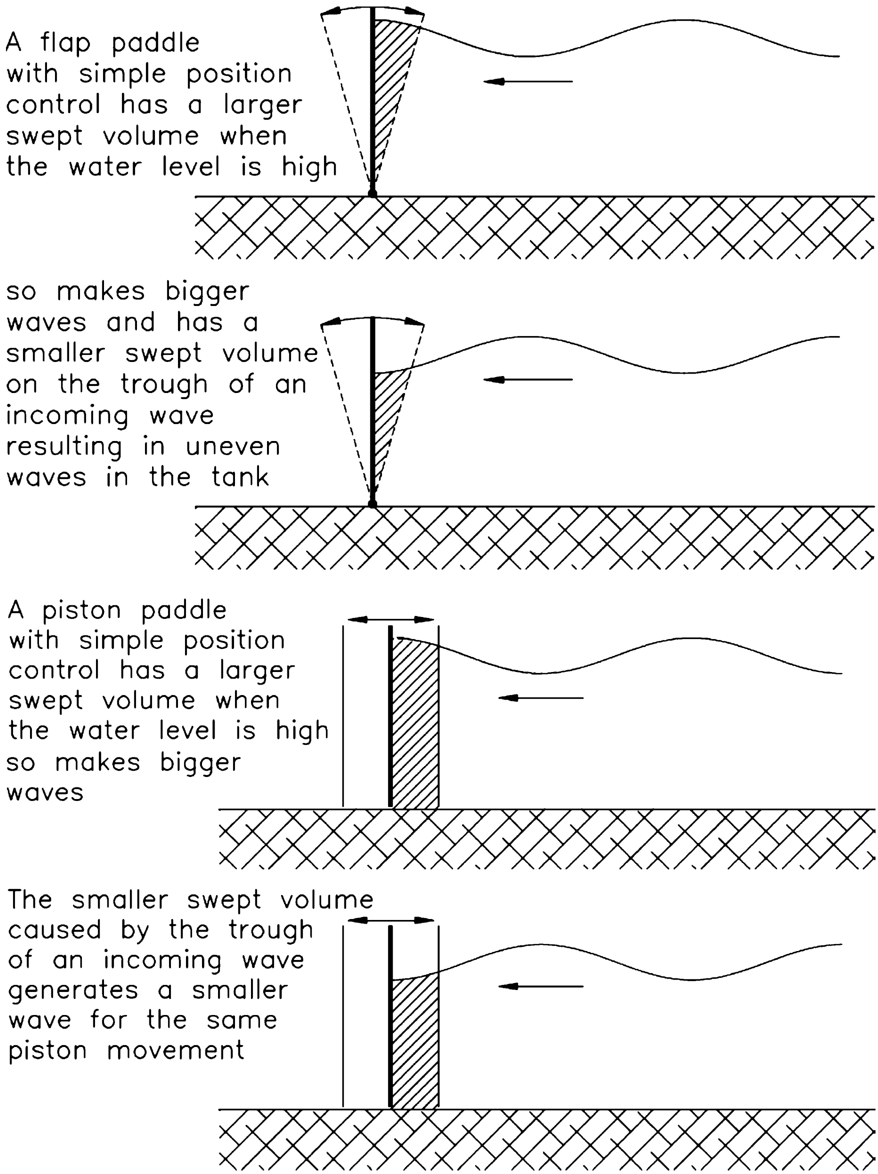

Fig. 5.16. Absorption mechanism: flap (top) and piston paddle (bottom)

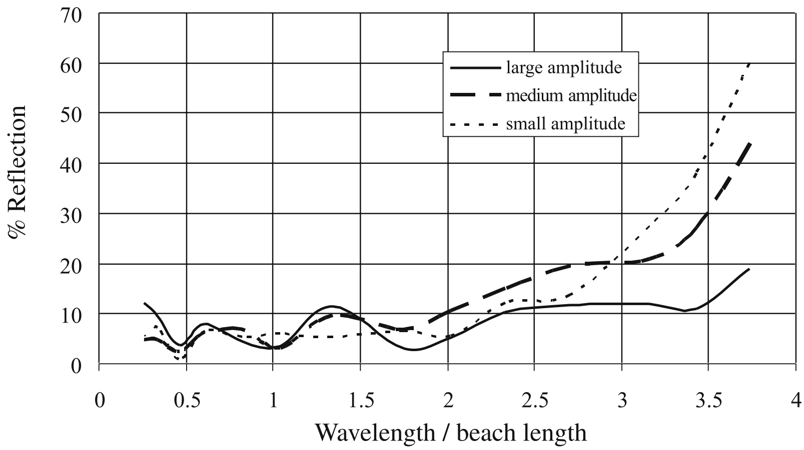

Fig. 5.17. Wave reflection for 6 *m* long beach tested in 3.0 *m* water depth

Sloping beaches do not have to run the full depth of the tank and can be sloped at up to 30 degrees without degrading performance. A typical wave tank beach will have a steep underwater section with a curved transition to a very gentle 6 degree slope meeting the waterline. Very little structure is required above the waterline as by this stage the wave has broken and its energy is dissipated. It is useful to allow water to run over the end of the beach so it does not cause back waves by surging back down the slope. Ripples caused by the wave breaking can affect smaller tanks. These can be reduced by covering the surface with an absorbent layer of foam or mesh material.

The loads on a beach can be high and it is particularly important to design for the up-thrust which can be just as high as the down-thrust. Beaches are also subjected to fully reversing cyclic loading so can fail in fatigue rather than by direct loading. It is very important to consider the mounting points where the entire structural load is transferred to the body of the tank.

Sloping beaches do not work so well in variable depth tanks. An alternative is to use mesh filled wedges. Multiple layers of plastic mesh dissipate the waves as they flow past and create eddies on the millions of sharp edges and ideally present the same impedance to waves as would unobstructed water in an infinitely long tank. The flow velocity varies for different waves so the foam density should increase progressively with depth and with distance down wave. There is a full description of the method of construction in Taylor et al. (2003).

5.2.8 Examples of Wave Tanks

To conclude this section a selection of photographs from different wave tanks is presented. Firstly, Fig. 5.18 shows an eight piston paddle arrangement in a wave tank at the University of Manchester, while Fig. 5.19 presents a similar tank but

Fig. 5.18. Wave tank at the University of Manchester (small displacement piston paddle)

with flap paddles at the University College London. Many more could be given as an example but two stand out by their unique character: the impressive 50 by 30 *m* (5 *m* deep) wave basin at the Ecole Centrale de Nantes (Fig. 5.20), which often receives several developers in the wave energy area, and the Edinburgh curved tank (Fig. 5.21), an uncommonly shaped fully-functional wave tank which replaced the Edinburgh wide tank in 2003. In contrast to the linear array of the majority of multi-directional wave tanks, the absorbing-wavemaker paddles are placed in a 90-degree arc in an attempt to improve the angular spread of the generated three-

Fig. 5.19. Regular waves at the University College London

Fig. 5.20. $50 \times 30 \times 5\ m$ wave basin at Ecole Centrale de Nantes

dimensional sea states, and to minimise cross-tank seiches. The lessons from this tank are expected to provide valuable input to the design and construction of a fully circular wave tank, as proposed in Salter (2001).

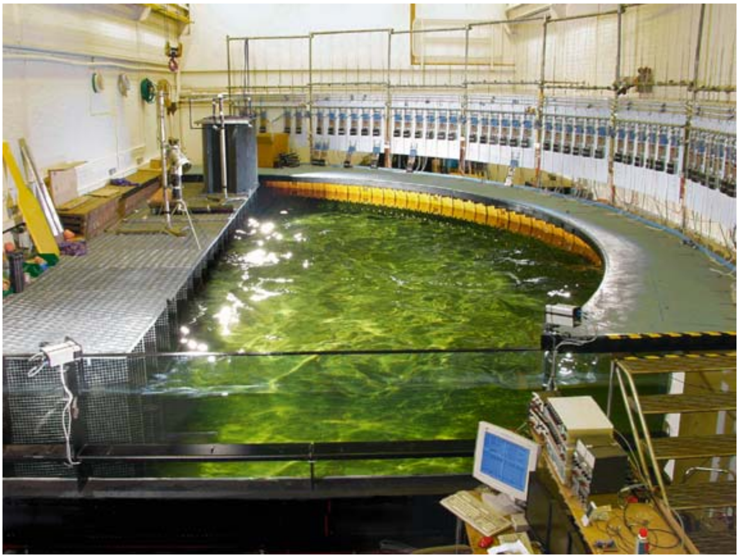

Fig. 5.21. Curved tank at the University of Edinburgh (Taylor et al., 2003)

5.3 Guidelines for Laboratory Testing of WECs

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This contribution is adapted from Sarmento A and Thomas G (1993), "Laboratory Testing of Wave Energy Devices", Wave Energy Converters Generic Technical Evaluation Study, Annex Report B1, Device Fundamentals/Hydrodynamics. C.E.C., Brussels.

5.3.1 Introduction

Tank testing, in both narrow and wide tanks, has played an important role in the progress of wave energy studies and is widely agreed to be essential for the calibration and validation of mathematical and numerical models. Most devices have been tested extensively either to validate a mathematical model or to supply vital information during the design process.

It must also be acknowledged that certain phenomena, of which device survivability is a good example, are not yet well understood from a theoretical viewpoint and good experimental programmes are vital to facilitate progress to be made in these important areas. Good laboratory experiments can also identify and isolate particular problems, often device specific, which are not addressed by contemporary theoretical models and thus provide an important input into the next generation of models.

There are however two fundamental characteristics of tank testing which do not have direct analogies in the modelling programmes. Wave tanks can be expensive to construct and this is especially so for wide tanks, with many wavemakers capable of generating multidirectional seas; in addition, they cannot easily be moved from one site to another and cannot be usefully employed without suitable wave-generating software and the availability of personnel with sufficient accumulated expertise to perform the required experiments. This means that established wave tanks are substantial investments in both materials and expertise and it is important to have the correct strategies for the maximum utilisation of such facilities.

Wave tanks have often been built for specific work programmes, but have been successfully used for purposes outside their original remit. So, for example, a facility originally intended for the testing of structures for the offshore oil industry can be used for studies on fish cages in the nearshore region and perhaps also for wave energy converters (WECs) in much deeper water offshore. However, despite the ability of wave tanks to perform a range of tasks, there are aspects of tank testing which are specific to WECs. A major one of these is that the standard testing practice for an offshore structure is to monitor the behaviour of a model under specified wave conditions and perhaps measure the pressures and forces on the structure or mooring systems; this can be an immensely difficult task, but for wave energy devices there is the added difficulty of including a simulator of the power take-off mechanism.

It is readily acknowledged that an Oscillating Water Column (OWC) was one of the first devices to pass successfully through all three stages of demonstration, prototype and full-scale generation. This situation has arisen because of the twin reasons that the power take-off mechanism, an air turbine, is sufficiently developed for immediate use and that OWCs can be built at shoreline sites with the relative ease of construction in a more benign environment than that of the proposed offshore WECs. A consequence of this progress is that OWCs have already been subjected to wide-ranging model testing programmes and this has not been the case for most WECs (one of the exceptions is presented as a case study in section 5.4). Recent experimental work has demonstrated that there are specific difficulties associated with the model testing of OWCs; furthermore some, but not all, of those problems which are presently being encountered by OWCs will be of direct relevance to offshore WECs at comparable stages of their development. These problems can be due to both device geometry and power take-off characteristics.

The purpose of this contribution is to outline progress to date and to identify those problems which have caused, or are likely to cause, greatest difficulty in testing programmes. Recommendations are then made with regard to the funding and laboratory practice requirements of future research programmes.

5.3.2 Laboratory Testing

Historical Perspective

Despite drawing heavily upon the theoretical expertise which originated in the fields of naval and commercial ship hydrodynamics, together with that of the offshore structures industry, the laboratory programmes for the testing of WECs have tended to develop in isolation of the better established industries. This may seem to be surprising, especially to the uninitiated to whom all structures designed to operate and survive in forty metres of water must seem to demand similar testing requirements.

This point seems even stranger upon further reflection, given that there are a number of large commercial and semi-state organisations which provide comprehensive testing facilities to the ship-building and offshore industries. In a similar manner wave energy has generally not utilised (though there are some exceptions) the facilities supported by national or European programmes.

There are three principal reasons for this relative degree of isolation and each is indicative of factors which have been, and continue to be, associated with the development of wave energy devices. The first is that funding has never been supplied to the wave energy community in a way which matched that of the offshore industry and even daily rates at commercial testing stations were prohibitively expensive, although in the long term this has probably not proved to be a disadvantage. The second is that the requirements of testing are different for the both cases; wave energy devices are inherently more complicated especially when the power take-off mechanism is also taken into account. Thirdly, wave energy requires wide tanks to act as development facilities, not just as testing facilities, and this demands considerable access to tank time.

The lack of suitable funding is exemplified by the construction one of the best known wide tank, constructed at the University of Edinburgh by Professor Stephen Salter in 1978 (see Chapter 2). When this tank was commissioned, some considerable surprise was expressed at the technological achievements which had been made, but astonishment greeted the cost for which the facility had been built - this was a small fraction of that which commercial organisations stated would be required. This success has epitomised much of the progress of wave energy, in which achievements have not been matched by funding. It must also be acknowledged that despite financial shortcomings the results from most experimental programmes, where these have been openly reported, appear to be acceptable.

Laboratory Practice

Most laboratory programmes have followed the same course as the parallel theoretical studies, in which the initial work has been in two dimensions (2-D) and then extended to three dimensions (3-D). The terminology Narrow Tank is usually reserved for experiments which investigate genuinely 2-D phenomena and Wide Tank refers to the 3-D case, which usually allows for the possibility of directional seas. Regular and irregular waves can be used in both cases. The relative ease of construction, combined with lower running costs, means that most institutions either possess or have ready access to a narrow tank.

Working in a narrow tank has many advantages and the use of 2-D models and investigations can often be readily justified on both scientific and engineering grounds. The best quality experiments are often carried out in narrow tanks for the very simple reason that specialist experimental equipment regularly operates better on the relatively small scale and the degree of control over the experimental conditions is generally very good. Much of the sophisticated experimental equipment, such as absorbing wavemakers (to act as wavemakers and/or beaches) and cylindrical wave gauges work best in narrow tanks and it must be recognised that the development of this equipment, again with an important input from Professor Stephen Salter, has been of enormous benefit to the wider community who conduct water wave experiments.

Moving to a wide tank introduces a number of difficulties which are not present in a narrow tank. One estimate has placed the cost per annum of running a wide tank at ten times that of a narrow tank, personnel excluded, and the increase in experimental difficulty is of a similar magnitude. There is a much greater level of uncertainty in a wide tank and wavemakers, beaches and wave probes; all have been causes of concern to experimentalists. As section 5.2 showed, such concerns have been progressively minimised over the years and there are now a considerable number of wave basins where large scale experiments can be conducted with confidence.

5.3.3 Shortcomings of Existing Practices

Fundamental Deficiencies

There have been many fundamental deficiencies in the testing programmes which have been completed to date. It is tempting to lay most of the blame upon the device teams, but to do so would be most unfair as they have been generally unwilling victims of circumstances beyond their control rather than the perpetrators of misdeeds. The point made earlier that the results of most experimental programmes seem to be acceptable is an important one and is mainly due to the enthusiasm and dedication of device teams.

The most obvious criticism of previous programmes is that insufficient funds were available and these were stretched as far as possible. This only tells part of the story as insufficient time is also a crucial factor and the way in which that time is used. Commercial tank testing is usually allocated a daily rate and this is entirely inappropriate for device development; the base rate should be measured in months rather than days and the device teams should be present to oversee tests whenever possible. This should not exclude the possibilities of sub-contracting device tests but there is a requirement that the sub-contractors are familiar with the expected behaviour of wave energy devices as well as being familiar with their tank facility. The concept of a wave tank as a development tool is an important one and needs an appropriate level of funding.

Monitoring

Much of the past experimental work has taken place under the cloak of secrecy as device teams have sought to hide their work from competitors. This approach is in many ways understandable, but it has not necessarily meant that experimental expertise is always employed. Indeed there are sometimes uncertainties in published results which are difficult to assess and lack of specialist experimental knowledge amongst device teams has been all too evident. There are two principal reasons for the laissez-faire approach. The first is that there are not yet standard practices for the testing of wave energy devices; the second is that there has been insufficient independent monitoring.

The question of establishing standard practices is a difficult one to deal with, particularly as experimental programmes have often been primarily used to confirm theories or concepts rather than be used as genuine device design tools. Testing has often been completed, in rather short time periods, by the device teams themselves without the benefit of expert advice. One crucial feature here is that research to date has been under funded for the level of progress attained and corners have been cut to match the meagre budgets.

The lack of suitable monitoring procedures is in many ways indicative of the fact that wave energy conversion is a rather new technology. Testing for the offshore engineering industry is a tightly controlled process, with testing often carried out at considerable expense by independent specialist laboratories, with specified standards laid down by government regulations, insurance requirements or industry standards. Exacting standards are not required for device development, but it is important to establish standard laboratory practices for device testing; this would ensure confidence in experimental results and enable comparisons between the performances of different devices at model scale.

Scale Effects

One of the most commonly acknowledged difficulties of conducting experiments with wave energy devices is the presence of scale effects. This occurs because if only one experiment, or series of similar experiments using the same single facility, is chosen to investigate the behaviour of a device then the model scale chosen will not usually be appropriate for all of the phenomena which are associated with the hydrodynamic behaviour.

The initial testing of a device, in either a narrow or wide tank, usually utilises Froude scaling which is governed by the wave kinematics. Although this is a sensible approach to adopt, the range in magnitude of WECs can present problems. For instance, the horizontal dimension of a broad bandwidth terminator may be a hundred metres or more, whereas a point absorber type buoy might have a diameter of at most ten metres. The difficulty which arises is that small scale viscous effects, due to the laboratory scale chosen and which will not appear at full-scale, can corrupt the model tests and not permit simple comparison between model tests for devices which were carried out using the same facility.

There are also a number of phenomena which cannot be appropriately scaled in standard narrow or wide tank tests. In preliminary model tests these may seem to be relatively unimportant when compared to the determination of the basic hydrodynamic behaviour and to a certain extent, this is true. However, all of the effects are associated with either real fluid or nonlinear effects and some of them possess a potentially catastrophic capability. These include nonlinear wave effects, which culminate in both engulfment and impact forces, vortex shedding from cables and structures, and turbulence.

Finite Channel Width Effects

The principal purpose of wide tank testing is to reproduce open sea conditions at model scale in order to monitor and test device performance. However, even for wide tanks the influence of the channel walls on the hydrodynamics can be appreciable and the behaviour which occurs in the tank can be more representative of a motion within a finite domain than the desired open sea conditions. The phenomenon has already been recognised at a fundamental level and the notation 21/2-D has been used to describe the modelling of 3-D models in relatively narrow wave flumes.

It was thought that the solution was simply to widen the tank, but theoretical work has shown that a wave tank can often provide a poor replacement for the open sea when a single vertical cylinder, or an array of such cylinders, is placed in a channel and subjected to a regular incident wave train even in comparatively wide tanks. The influence of the channel walls is considerable in many ways, particularly with regard to the pressure distribution over the cylinder, or cylinders', surface and to the reflected and transmitted waves in the tank.

It seems likely that similar conclusions will hold both for bodies which possess more general geometries and for irregular waves, although these have not been extensively studied, and such results have important implications for the laboratory testing of WECs. However, recent work suggests that the implications are very important and the testing of arrays in particular will require considerable care to isolate tank effects from interactions between the array members.

Lessons from OWC Testing

Detailed experiments using scale models of OWCs have identified many problems which need to be addressed. Some of these are of a generic nature and have been included above, but while most are presently specific to OWCs they may have wider applications in the long term.

Testing of offshore WECs requires that the model is placed in the working area of a wave tank, which may be quite small even for large tanks, and essentially this lies between the wavemakers and the beach (at a few selected wavelengths from both). All of the advanced testing for OWCs has been concerned with shore-mounted devices so that a wavemaker is present but the absorbing beaches are replaced by models of the coastline which includes the OWC. The OWC under test is usually strongly site specific and it becomes necessary to model the bathymetry in the vicinity of the site to a degree of acceptable scale and accuracy, but this will often require very small device models due to the limitations enforced by the physical dimensions of the tank. Very small scale models will not allow the hydrodynamic losses and wave breaking to be well represented by the model and this affects the capacity of the model tests to simulate the influence of significant wave height. A further difficulty is that the removal of beaches will most certainly lead to problems of unwanted reflections.

The minimisation of hydrodynamic losses does not generally require detailed simulation of the bathymetry, power take-off or control procedures. The essential requirement is for larger model scales and this means that different scale tests are required for different phenomena. A further example of this is the importance of wave breaking and impact tests, which should include wave breaking. Scale effects are recognised as being extremely important and require considerable study.

Power take-off mechanisms are not generally simulated in detail. A good model of a turbine is to use a device which dissipates the pneumatic energy of the air such that the flow versus pressure characteristic does not deviate much from that of the turbine to be used in the prototype. Such a simulating device could have a nonlinear characteristic as in the case of an orifice plate or an approximately linear characteristic as in the case of a rotating disk or a porous plug.

Although the three-dimensional nature of the physical modelling has already been stressed, there are certain aspects of OWCs which can be suitably modelled in the first instance by two-dimensional models. These include the impact forces mentioned previously and also the testing of control procedures, for which linear waves will suffice at an initial stage but will eventually require irregular waves.

5.3.4 Results and Conclusions

Funding

The cost of constructing major wave tank facilities, i.e. wide tanks, together with the funding levels required to maintain equipment and support personnel on an ongoing basis, is very considerable. If such facilities are to be financially justifiable then they must be able to regularly attract funding and not be subjected to long periods of enforced idleness. Commercial alternatives do exist nowadays, but a major step forward could still be achieved if a large scale wave tank was built to be benefit of the wave energy community, possibly with the support of the EU. This, along with funding for the early stage developers, would allow the appropriate testing of different concepts by the tank operating crew, providing independent validation and certification of the device. Narrow tanks are considerably less expensive to build, require little general maintenance and have low running costs; all device teams should have ready access to a narrow wave tank.

There are many advantages to the funding of centres of testing expertise, of which one should be associated with offshore devices and another with OWCs. An agreed common approach to testing would be required and this would be a major step forward. The host facility would provide an element of neutrality and thus ensure that test results of different devices could be fairly compared. There are two important points which must be addressed: the first is that the wave energy community must have universal confidence in the testing centres and the second is that the wider community must have an input mechanism into the management and policy of the testing centres

Testing Programmes

It is not possible at this stage to determine how an agreed testing programme would be constructed, although certain elements can be readily identified. The validation of linear theory for the prediction of device performance in regular waves is clearly the first task once the appropriate model scale of the testing programmes has been established. At the opposite end of the wave amplitude scale to linear waves are extreme waves and the device response to extreme wave should be tested to assess prospects for storm survivability. The testing procedures for the central region, involving irregular seas, will be more difficult to determine and cannot be done at this stage. One of the major reasons for this is that WECs will almost certainly become more site specific than they are at present and consequently they will be designed to operate best within certain sea conditions; this means that spectra will be device and site specific. An approach is to use generic spectra to study the basic device response to irregular waves and site specific spectra for details of device behaviour at the proposed site. However, this is a difficult subject to resolve; it will require general agreement within the wave energy community, but the task should be given an urgent priority.

Scale Effects

The importance of scale effects in laboratory experiments has already been identified. An attempt is made here to categorise the various fluid-structure interactions which occur and to suggest a suitable scales for experimental investigation of the mechanisms. The suggested scales are the minimum values which should be used and larger scales are often more desirable, but there is a balance to be drawn between financial cost, available facilities and meaningful results. The list below utilises the experience accumulated under several development programmes.

Offshore Device Behaviour

This does not require detailed knowledge of the local bathymetry; constant depth testing can be employed and device considerations will dominate the experimental regime. The appropriate scale is usually dependent upon tank size and wave-making capacity, but too small a scale can introduce small-scale viscous effects into the hydrodynamic interaction processes.

- Suggested Scales: *1 : 50* (First Choice), *1 : 100* (Second Choice)

Validation of Numerical Models / Optimisation

The design of a WEC requires the use of scale models to validate the numerical predictions carried out by frequency and time domain models. Furthermore, there are critical aspects like survivability that need to be addressed. The experiments should naturally include the highest level of detail possible, but it is recognised that at this stage not all important factors can be taken into account. The most noticeable example is the power take-off mechanism, which is either not modelled or at best a simulator is used. Another important question is whether the influence of nonlinear wave effects upon the capture width can be accurately assessed. If alternative configurations should be tested, this is the ideal scale to do so.

- Suggested Scales: *1 : 20* (First Choice), *1 : 33* (Second Choice)

Nonlinear and Hydrodynamics

There are a number of hydrodynamic mechanisms which are either difficult to model at small scale or are not yet understood from a theoretical viewpoint. Examples are engulfment and impact forces, viscous losses and turbulent effects. Almost all are potentially catastrophic, but most can be modelled using 2-D tests in the first instance and another common feature is that as large a scale as possible should be used.

- Suggested Scale: *1 : 7* or *1 : 5*

Component Testing

The ideal scale for component testing will strongly depend on the type of WEC, particularly with regard to the power take-off mechanism. An extreme example can be found in the experience from OWCs: for turbines the major issues concern the influence of turbulence and the importance of water particles in the air flow to the turbine. Additional blade problems can also arise and stall is one important factor. The modelling difficulties are great and the flows, for OWCs, are very complicated. Hydraulic systems will need testing at considerably larger scales than linear generators.

- Suggested Scales: *1 : 5*, *1 : 2*, *1 : 1*

5.3.5 Recommendations

As there are a number of recommendations and these are both of a generic and a technical nature, it has been decided that the list will be divided into a generic list concerning standard practices and a more technical list; all recommendations are important. Very serious consideration should be given to the generic list before further investment in the testing of wave energy devices is undertaken.

Generic

1. Access to wide tank facilities is still limited and strongly conditioned by financial motives; a standard facility should be supported by future wave energy programmes; sufficient funds should be available to enable device teams to conduct experiments at the specialist centres.
2. Such facility should focus the study of offshore devices and array interaction; additionally OWC R&D should continue to be encouraged, especially when integrated in costal defence mechanisms such as breakwaters.
3. Standard testing procedures should be established for all WECs, but this will require a high degree of agreement from device teams. This should include linear waves in regular seas to validate mathematical models and extreme waves to test storm survivability; agreed generic spectra should be used, in conjunction with site specific spectra as necessary.

Technical

4. The applicability of all aspects of 2-D and 3-D testing should be assessed, particularly with regard to losses, forces and impact pressures. This also should include the influence of flume width on both genuine 2-D tests and those best described as 21/2-D (i.e. 3-D tests in wave flumes).
5. The importance of scale effects in model tests is not fully understood. A detailed comparison of experimental tests should be undertaken with two different scale models, say 1 : 10 and 1 : 100 to assess this phenomenon.
6. A comparison should be made of the regular and irregular wave testing requirements with regard to the evaluation of losses, forces and impact pressures.
7. The influence of different power take-off simulators in model experiments should be considered.
8. Detailed experimental studies to monitor time-domain simulation models should be undertaken.

5.4 Case Study: Pelamis

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The role of numerical and experimental modelling in the development of the Pelamis WEC is discussed in this section. A detailed description of the concept is given in Chapter 7, but a short summary is desirable prior to the presentation of the models that have been built by Pelamis Wave Power (formerly Ocean Power Delivery) over the last years. The Pelamis WEC is an offshore, floating, slack-moored wave energy converter consisting of a set of slender semi-submerged cylinders linked by two degree-of-freedom hinged joints. The power take-off (PTO) consists of hydraulic cylinders mounted at the joints, which pump fluid via control manifolds into high-pressure accumulators for short-term energy storage. Hydraulic motors use the smooth supply of high-pressure fluid from the accumulators to drive grid-connected electric generators. A response inclined to the horizontal can be induced by controlling of the PTO to give different levels of restraint in each joint axis. The inclined response offers an effective hydrostatic stiffness reduced from a vertical response, resulting in a natural frequency controllable through the PTO with minimal reactive power requirements.

The wave loading and response is limited in large seas by the inherent design characteristics of the machine. The machine's overall length is chosen to be comparable to the wavelengths for which maximum power capture is desired. In longer waves the segments move with smaller phase differences, thus relieving the load on the structure and the power systems. In small and moderate seas, the wave loading is dominated by the strong dynamic buoyancy force. In high waves the dynamic buoyancy limits as the cylinder sections become locally submerged, and the weak inertial force becomes more important. The rate of rise of wave loading with wave height therefore reduces as the wave height becomes comparable to the cylinder diameter. These two features – frequency and amplitude limits – protect the machine in long and high storm waves.

Numerical and experimental modelling has been at the core of the Pelamis development programme since its inception. The culmination of the numerical and experimental modelling programmes was achieved with the construction, installation and test of a full-scale prototype, 120 *m* long and 3.5 *m* in diameter, with a rated power of 750 *kW*, at the European Marine Energy Centre (EMEC) in Orkney, Scotland. The several stages of development are detailed in the following subsections.

5.4.1 Numerical Simulation

The PEL suite of software, developed by Pelamis Wave Power over a number of years, is used to model the hydrodynamics of the Pelamis and allow the analysis of results. It comprises three main programs of increasing computational complexity: Pel_freq, Pel_ltime, Pel_nltime; see Table 5.1. Approximate CPU times are shown for a set of 50 wave spectra representing the sea-states for an average year. Recently the possibility of using real seas spectra from single point measurement devices was also included in the simulation. Each of the main programs is fully configurable with respect to geometry (i.e. tube lengths & diameters, ballasting, roll-bias), control applied at the joints (linear impedance for **Pel_freq** but arbitrary for others), and waves (Figures 5.22 and 5.23).

Table 5.1 The PEL Suite main components

Program	*Body Dynamics*	*Hydrodynamics*	*Control*	*CPU*	*Applications*
Pel_freq linear frequency domain	linear	3D freq. dep. coef. 2D freq. dep. coef.	linear	1 sec	large parametric studies with simplified control
Pel_ltime linear time domain	linear	3D impulse response 3D freq. dep. coef. 2D freq. dep. coef.	Arbitrary non-linear	2 hrs	power absorption in small and moderate seas
Pel_nltime non-linear time domain	non-linear	2D freq. dep coef.	Arbitrary non-linear	4 days	survivability in large seas

A time-domain model of the Pelamis power take-off system was developed and included as an optional routine within **Pel_ltime** and **Pel_nltime**. It includes all effects associated with the real hydraulic system to enable accurate power prediction studies and allow detailed control algorithms to be developed within the context of the entire machine operating in representative conditions. The separation of control routines and the models of physical systems allows for the easy translation of control programmes between simulations and actual hardware.

Control subroutines sample joint angles from the existing hydrodynamics subroutines just as a real controller samples transducer signals. A control algorithm is then applied and the output is passed to the PTO model in a similar format to that of the real controller. The PTO subroutine then models the physical hydraulic system and provides the resulting applied joint moment to the rest of the program. Other useful signals such as chamber and accumulator pressures and flows are also output for analysis. Effects included: fluid compressibility, valve characteristics, delays, flow losses, friction, accumulation, generation characteristics.

A finite element model of the mooring system has been integrated into the time-domain simulations. This allows the effect of the mooring on both power capture and survivability to be examined and included in numerical studies. The model is generally definable to allow different mooring configurations to be examined.

In addition several auxiliary programs perform pre- and post-processing tasks in relation to the PEL suite. These are summarised in Table 5.2.

The PEL hydrodynamics simulation has been verified using tank test data, while the power take-off models were verified using laboratory test rigs. Offshore engineering consultants WS Atkins carried out an independent verification of the hydrodynamics modelling of the PEL suite.

In addition to the PEL suite, PWP has made use of the commercial simulation package ‘Orcaflex’. Orcaflex is a marine dynamics program originally designed for static and dynamic analysis of flexible pipeline and cables. The OrcaFlex Pelamis model is built up from a combination of several types of component (buoys, lines, spring-dampers, winches) placed within an environment with seabed, waves, wind and current all specified by the user. Wave types available are Airy wave theory, Stokes’ 5th order theory, Dean’s stream function theory and Fenton's cnoidal theory, all of which have been tested on the Pelamis model.

Orcaflex was used in particular to analyse the mooring system under extreme events. For example, the sensitivity to wave height and period of the mooring system was examined using controlled test cases with a single Dean stream wave with small precursor. A maximum wave height of $28.6\,m$ is the maximum expected within the 100 year storm spectrum according to a HR Wallingford report in a sea state characterised by $H_{m0} = 15.4\,m$, $T_{02} = 14.6\,s$. Worst case snatching and extreme loading events were also simulated to test the mooring design.

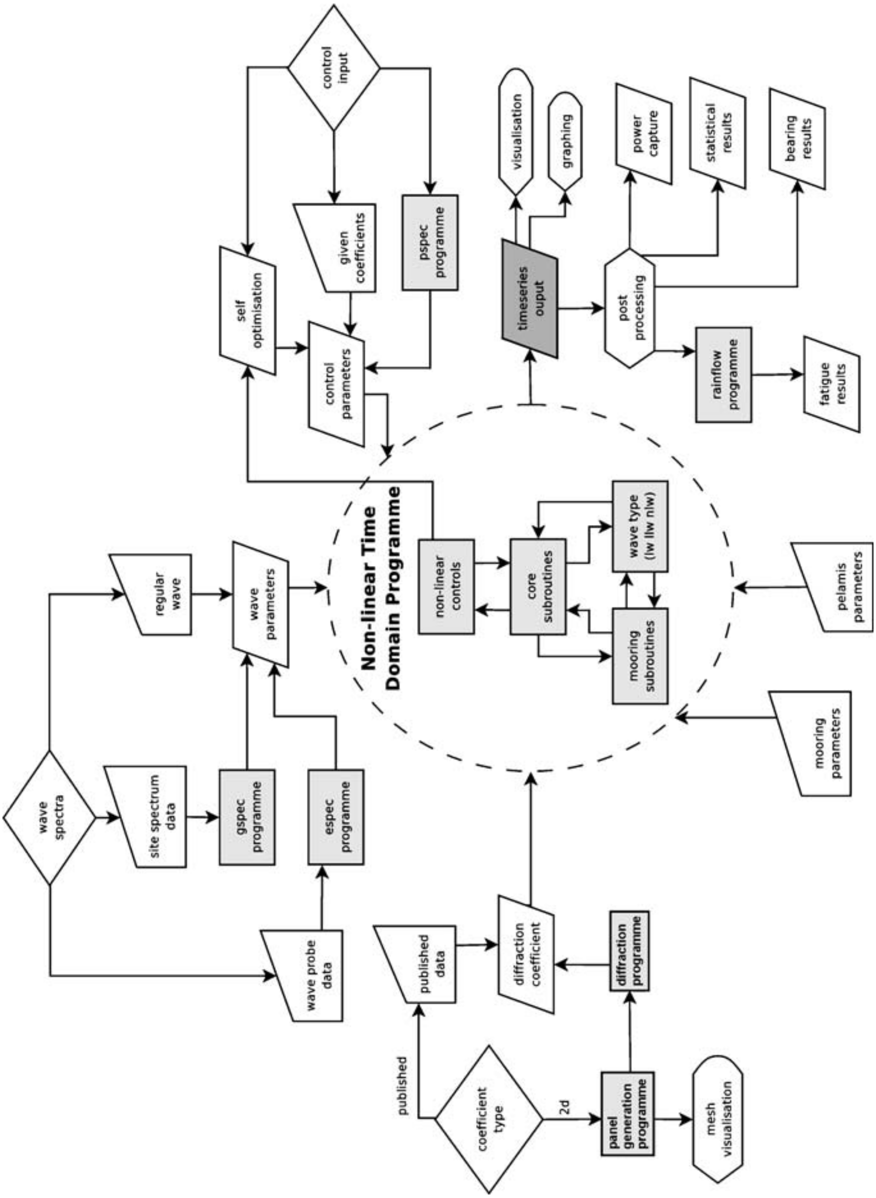

Fig. 5.22. Flow Chart for Non-Linear Time Domain Analysis

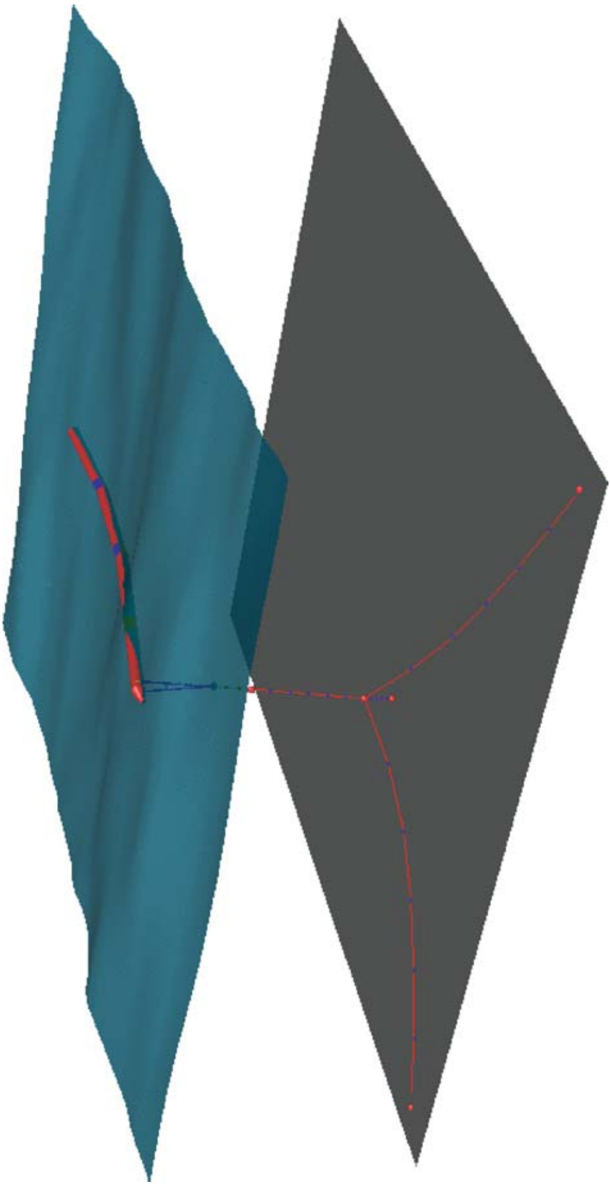

Fig. 5.23. Screenshot of the 3d visualisation interface of the PEL suite, developed by PWP

Table 5.2 Auxiliary Programs

Program	*Description*
Dpg **Viewmed** **Dpm**	A 3-D linear frequency domain wave diffraction program developed at the University of Strathclyde provides a high accuracy model of the interaction of infinitesimal amplitude waves with a rigid body. The **dpg** program generates a flat panel representation which may be viewed with the **viewmed** program. The panel representation is then used by the **dpm** program to evaluate wave diffraction, radiation, and hydrodynamic interaction coefficients for the rigid sections of Pelamis, as required by the PEL suite of programs. 2-D hydrodynamic coefficients may also be approximated by selecting a long enough cylinder, for use in the strip theory PEL programmes.
Gspec	Facility for generating wave spectra files for use by PEL time domain programs or the pspec program. The spectra can be directly read in as spectral components or generated from specified parameters using a prescribed spectral form (ie PM-spectra). The measured spectra may then be transformed to a different water depth under the assumption of no power loss, or by applying a power filter to account for dissipation due to sea-bed friction. The frequency components of the spectra can be re-sampled to provide a set of frequencies from which the time domain realisations may be efficiently evaluated.
Espec	Decomposes experimental wave records to provide corresponding wave spectra data files for PEL suite, allowing comparison between numerical and experimental results for mixed seas. Spectral components are evaluated to correspond to the three wave models used in the PEL suite: linear, second-order or Lagrangian.
Pspec	Iteratively runs the frequency domain model to select optimal controls to achieve response within specified constraints. Output powers are weighted with respect to site-specific wave data to give annual average power prediction.
Rainflow	Carries out rainflow analysis of time-series for evaluating fatigue damage fraction for various structural components and features.
Visualisation	Provides 3-D animation of time-domain simulation of waves, Pelamis, and mooring. The user can zoom and change viewpoint etc during animation.
Graph	General graphing program for time-domain simulation. Outputs time-series of any variable e.g. joint angles & moments, hydraulic system pressures, absorbed and generated powers, mooring forces.

Fatigue analysis was also carried out on the mooring components using the rainflow facility available within Orcaflex applied to line tension results from a set of eighteen wave spectrum simulations chosen to represent the EMEC Orkney site. Tests have also shown that primary mooring line and tether annual damage agree reasonably with those produced from model testing.

In order to verify the performance of Orcaflex in modelling the Pelamis, the system has been modelled to replicate the 20th scale tests performed in Nantes. Nine test cases were used for correlation – six regular waves, a short term spectrum wave group and a longer steep spectrum. Further checks were also performed to assess the performance of different types of wave modelling etc, with some limitations being identified.

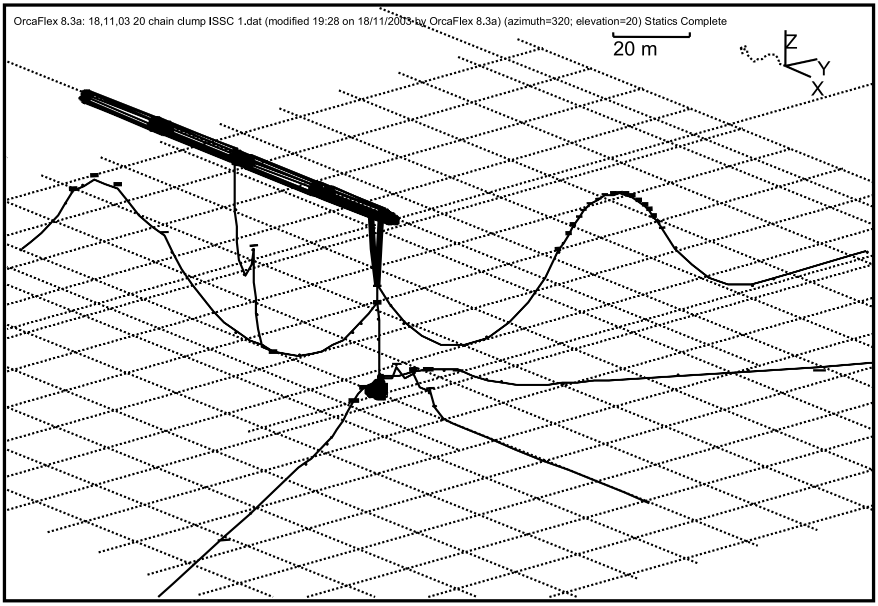

Fig. 5.24. Screenshot from the Orcaflex simulation package showing the full-scale Pelamis prototype mooring set-up

5.4.2 Experimental Modelling

Physical models have been constructed at the 80th, 50th, 35th, 21st, 20th and 7th scales. They have tended to grow in scale as the modelling budget increased, and as the demands for more detailed data and greater functionality became evident.

The most elaborately controlled and instrumented model so far has been the 20th. Recently, a 21st scale model similar in detail has been tested (optimisation of the next generation of Pelamis machines). The scale is appropriate for power testing in readily available wave tanks, and for survival testing in the large wave basin at Ecole Centrale de Nantes. Figure 5.25 shows a motorised joint axis and the strain-gauged spider that connects it to the orthogonal axis. Moment, angle and velocity are measured in all 6 joint axes. In addition, pressure is measured around the foremost cylinder, mooring and tether line tensions, tether line angle and roll moment, and wave height down the length of the model. The model joints are controlled by a microcontroller that, via the motors, can apply arbitrary spring and damping, and model the full-scale ram characteristics, including the stepwise application of moment. Figure 5.26 shows the front two cylinder sections of the model, connected by a joint, covered with a neoprene rubber fairing. The electrical cables exit the joint to the right.

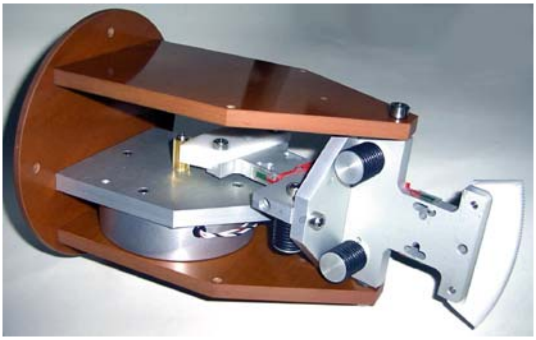

Fig. 5.25. Motorised joint axis and the strain-gauged spider

Fig. 5.26. Detail of the 20th scale model

The 20th model has been used to test joint control strategies under power and survival regimes, mooring configurations and failure modes. It has provided measurements of response amplitude operators and power performance, envelopes of joint moments and angles, and mooring loads and structural pressures in extreme waves. Figure 5.27 shows the comparison between the output of the numerical simulation and the experimental results obtained for the capture width.

The 7th scale Pelamis was a technology demonstration model, large enough to include representative systems in but small enough to handle and transport without large cost and to fit into large tanks such as l'Ecole Centrale de Nantes. It employed a hydraulic power take-off system functionally similar to the full-scale system and served as a platform for developing the control hardware and software used in the full-scale machine.

The PTO system was developed independently prior to construction of the 7th and full-scale Pelamis with the use of laboratory test rigs. The 7th scale PTO test rig, initially actuated by hand, was later adapted for actuation by a ball-screw operating under closed-loop control to perform the role of the waves. Pre-prototype hydraulic circuit and component test assemblies were designed and constructed for ad hoc experimentation. The 7th scale test rig was used for a set of tests designed to demonstrate the operation of the Pelamis PTO, test implementations of basic control algorithms, and to verify the mathematical model developed for computer simulation.

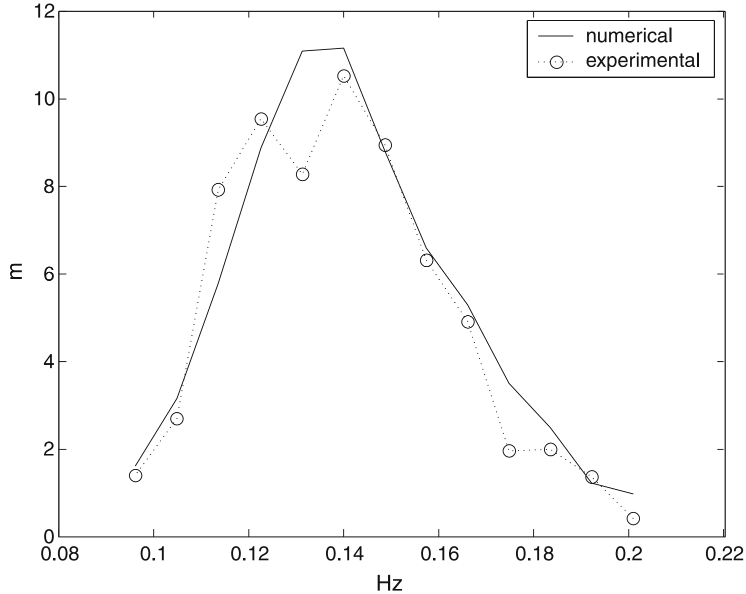

Fig. 5.27. Comparison of PEL simulation and 20th scale model experimental measurements of capture width

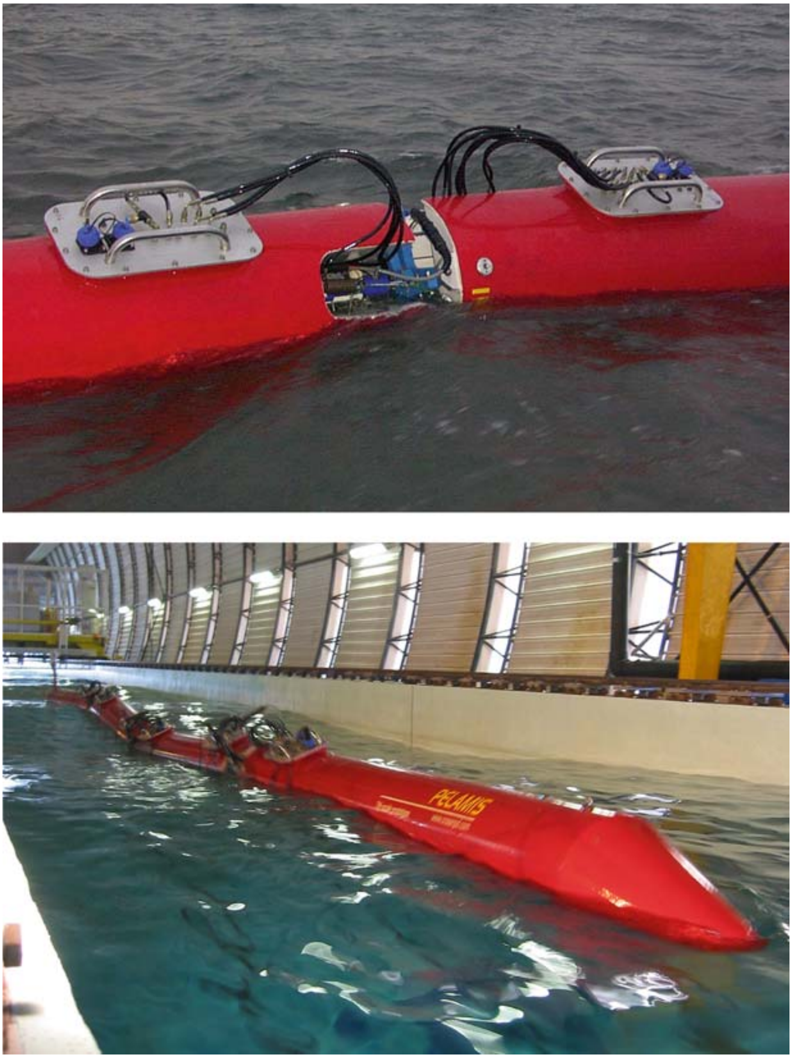

Fig. 5.28. Photographs of the 7th scale model joint during a sea-trial and the whole machine in the narrow towing tank at l'Ecole Centrale de Nantes

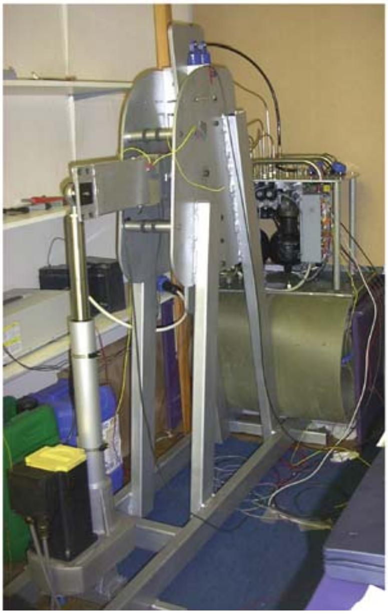

Fig. 5.29. Top: a fully assembled 7th scale power pack positioned upside down from the orientation in which it is installed. The rams are connected to the manifold via flexible hoses fitted to ports extending through the hatch. Bottom: the 7th scale test rig, fitted with a ballscrew actuator under position control, being used to test a 7th scale power pack.

The 7th scale rig provided an essential platform to develop an understanding of the various practical issues surrounding the operation of the PTO such as valve timing, compressibility, delays, and measurement. The lessons learnt and techniques developed during these small-scale experiments fed directly into the full-scale design. Experimental results from the test rig were also be used to verify the numerical models included in the PEL simulation suite.

A full-scale joint test rig was constructed in the winter of 2002 and used for further verification and adaptation of the full-scale PTO, and for extensive operational and cycle testing for assessment of components. Figure 5.30 shows the full-scale rig, where the actuation structure can be immediately spotted (see right-hand side of the photograph). Such land demonstration of the full-scale power take-off mechanism should be encouraged and supported via governmental grants. Even though the capital cost is high, the risk of skipping such stage (and eventually the cost) and embarking in the construction of a full-scale prototype is much higher.

Figures 5.31 and 5.32 show cycling pressures in the eight ram chambers (push and pull) of an axis of the 7th and full-scale joint rigs, respectively. The experimentally measured pressures are shown along with those resulting from running the same position signal and control signals through the PTO simulation. The agreement is extremely close.

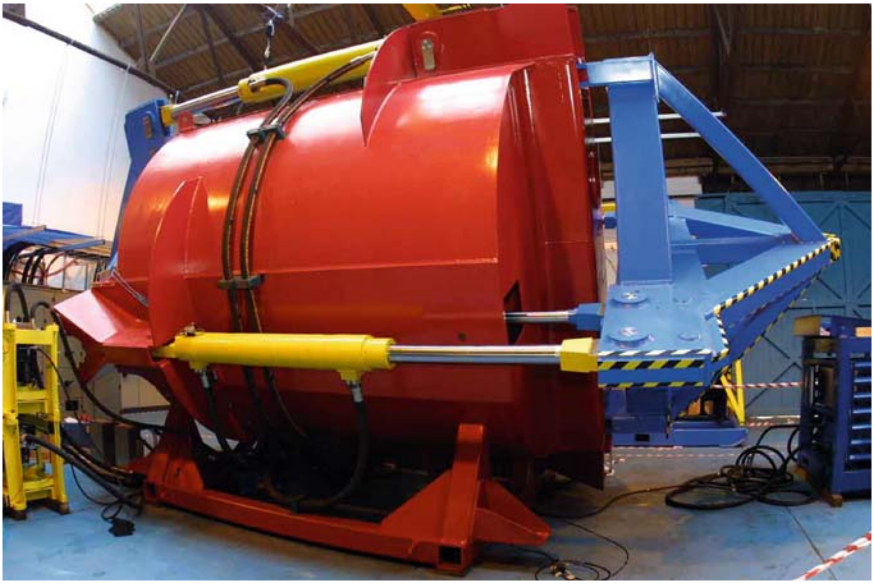

Fig. 5.30. The full-scale joint rig and associated control system: see the power take-off rams within the rig and the outer rams which are used for load simulation

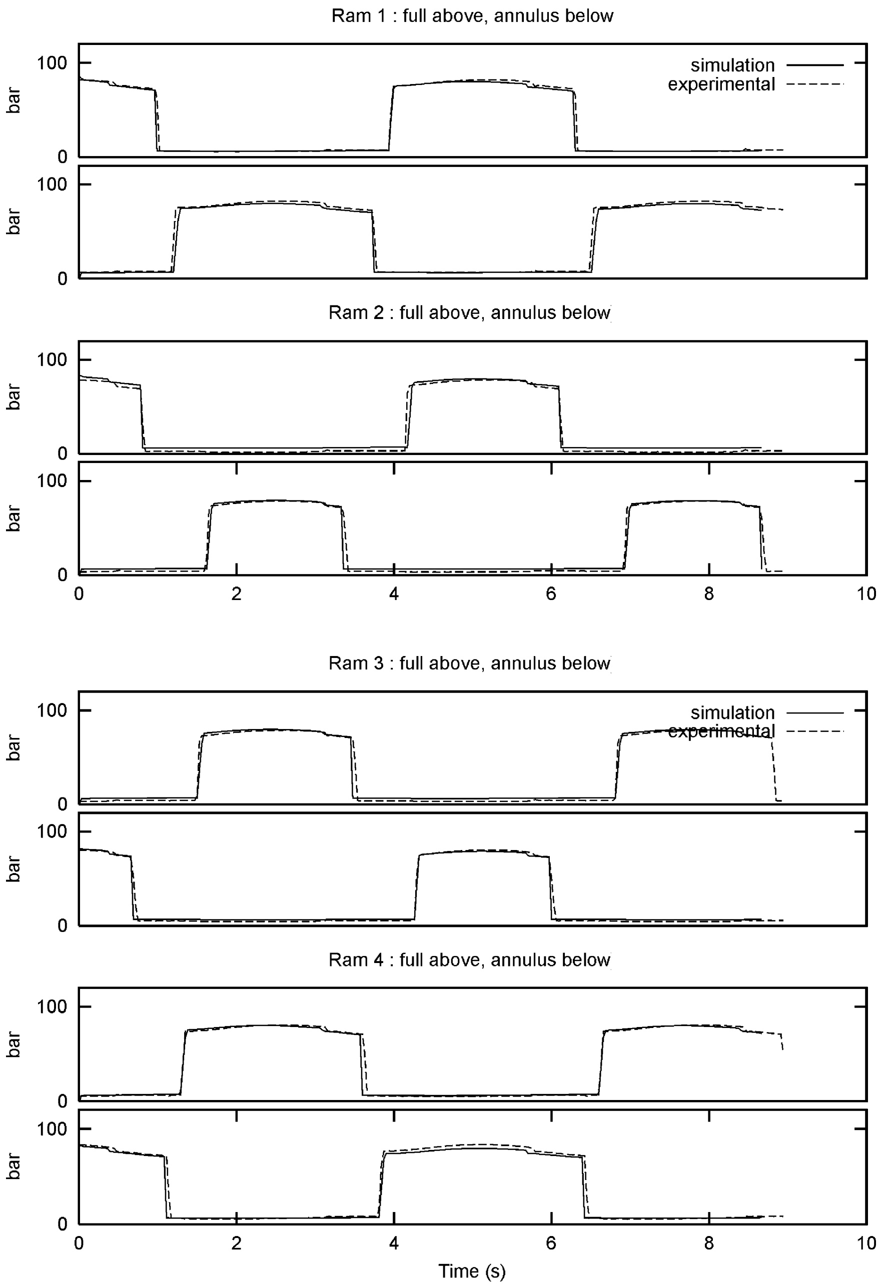

Fig. 5.31. Pressures for each ram chamber, for one axis: 7^{th} scale rig

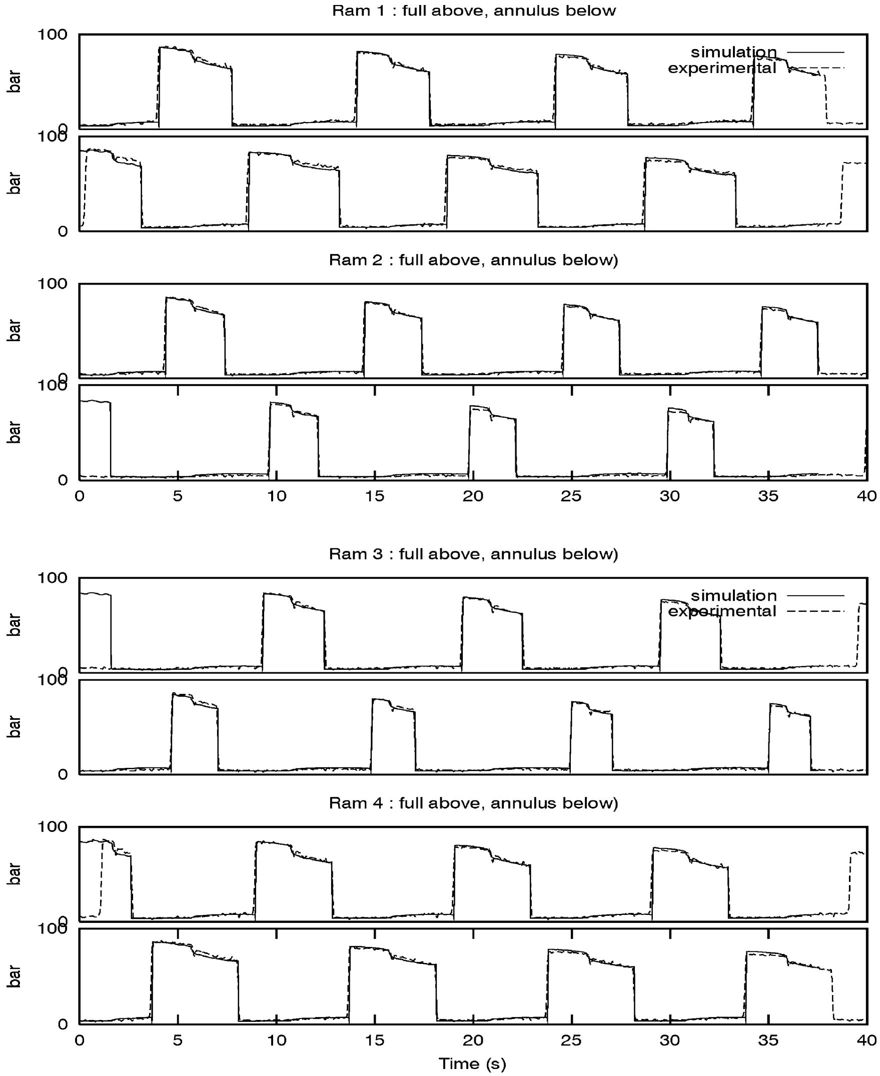

Fig. 5.32. Pressures for each ram chamber, for one axis: full-scale rig

5.4.3 Outcomes

The PEL suite has been of enormous use in every aspect of the Pelamis development programme. It will continue to be used in the future to further optimise the design of the machine and its control algorithms.

PEL also plays a vital role in project development where the likely yield of specific sites must be assessed and the machine configuration adapted. The power table, used to describe the power absorption characteristics of a specific machine configuration with respect to wave height and period of spectra, is derived using PEL. It is envisaged that this method of quantifying machine performance with respect to specific sites will become the standard for assessing the viability of projects, similar to the power curve currently used in the wind industry.

The verification of the prototype Pelamis by WS Atkins, which provided enough confidence for the machine to be granted insurance at a commercial rate, was made possible by exhaustive analysis using the PEL suite. This included:

- Fatigue analysis of stress in key components
- Simulation of partially flooded conditions
- Complete simulation of control and power take-off system including all pertinent effects
- Analysis of behaviour under systems failures

The development and testing of control algorithms is largely dependent on the PEL simulation. The virtual machine provides a platform that is not only com-

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

Fig. 5.33. The power table for a given Pelamis configuration as derived using the frequency domain element of the PEL simulation suite

pletely risk free but repeatable, and tests can be run iteratively for optimisation purposes. Furthermore, changes to the PTO systems, moorings, and the machine configuration can be made in conjunction with related control algorithm changes. A holistic approach to the development of the Pelamis is made possible with minimum cost and/or risk.

A remaining weakness of the PEL suite is that results are inaccurate for the largest waves. Orcaflex provides us with less detailed simulation capability in large waves. While numerical work continues in this area, physical model testing remains vital for the survival regime.

5.5 Discussion

In this chapter the importance of numerical and experimental modelling when developing a wave energy converter was emphasised. Each section could be expanded into a single chapter, but given the scope of this book the main objective is to provide a starting point for those who are novices to the wave energy field.

In 5.1, frequency domain modelling is presented at the expense its time domain equivalent. This is due to the number of applications using both approaches and to the ease-of-use that frequency domain tools provide. In addition, the number of numerical models which directly implement solutions of the Navier-Stokes equations are still a rarity, but their use could increase in the near future. A good starting point for those interested in the field is given in the review conducted by McCabe (2004).

Section 5.2 gives insight to both tank and wavemaker design. The different options that allow the accurate simulation of both shallow and deep water waves are detailed. The influences of geometrical parameters like tank width and paddle size were also studied, and considerations regarding the absorption of reflected waves were presented.

Section 5.3 is intrinsically linked with 5.2 as it provided generic guidelines for the use of experimental facilities. Continuous validation of numerical simulation by means of experiments in wave tanks is essential and it is fundamental that such notion is clear to both developers and researchers.

Finally, section 5.4 demonstrated the integration of numerical and experimental modelling programmes in a commercial environment, by exemplifying the progress made when developing the Pelamis WEC. Several stages that eventually lead to a full-scale prototype were described.

References

Alves M (2002) Incident Wave Identification. MARETEC/AWS Internal Report 2/2002. Lisbon, Portugal

Bai K, Yeung R (1976) Numerical Solutions of Free-Surface Flow Problems. Proc 11th Sym Naval Hydrodyn. London, UK, pp 609–641

Baltazar J, Falcao de Campos JA, Bosschers J (2005) A Study on the Modelling of Marine Propeller Tip Flows using BEM. Congreso de Métodos Numéricos en Ingeniería. Granada, Spain

Biesel F, Suquet F (1951) Les apparails generateurs de houle en laboratoire. La Houille Blanche, 6, 2, 4, and 5. Laboratory Wave Generating Apparatus English version Project report 39. St Anthony Falls Hydraulic Laboratory, Minnesota University

Boccotti P, Filianoti P, Fiamma V, Arena F (2007) Caisson breakwaters embodying an OWC with a small opening – Part II: a small scale field experiment. Ocean Eng 34(5–6):820–841

Brito-Melo A, Sarmento A, Clément A, Delhommeau G (1998) Hydrodynamic Analysis of Geometrical Design Parameters of Oscillating Water Columns. Proc 3rd Eur Wave Energy Conf, Vol. 1. Patras, Greece, pp 23–30

Brito-Melo A, Hofmann T, Sarmento A, Clément A, Delhommeau G (2000a) Numerical Modelling of OWC-shoreline Devices Including the Effect of the Surronding Coastline and Non-Flat Bottom, Proc 10th Int Offshore Polar Eng Conf, Vol. 1. Seattle, USA, pp 743–748

Brito-Melo A, Sarmento A (2000b) Numerical Study of the Performance of a OWC Wave Power Plant in a Semi-Infinite Breakwater. Proc 4th Eur Wave Energy Conf. Aalborg, Denmark, pp 283–289

Cruz J, Payne G (2006) Preliminary numerical studies on a modified version of the Edinburgh duck using WAMIT. Proc World Maritime Technol Conf. MAREC stream, Paper 027. London, United Kingdom

Cruz J, Salter S (2006) Numerical and Experimental Modelling of a Modified Version of the Edinburgh Duck Wave Energy Device. J Eng Maritme Env – Proc IMechE Part M 220(3):129–148

Delauré Y, Lewis A (2000a) An Assessment of 3D Boundary Element Methods for Response Prediction of Generic OWCs. Proc 10th Int Offshore Polar Eng Conf, Vol. 1. Seattle, USA, pp 387–393

Delauré Y, Lewis A (2000b) A comparison of OWC response predicton by a Boundary Element Method with scaled model results. Proc 4th Eur Wave Energy Conf. Aalborg, Denmark, pp 275–282

Delauré Y, Lewis A (2001) A 3D Parametric Study of a Rectangular Bottom-Mounted OWC Power Plant. Proc 11th Int Offshore Polar Eng Conf, Vol. 1. Stavanger, Norway, pp 584–554

Delauré Y, Lewis A (2003) 3D hydrodynamic modelling of fixed oscillating water column by a boundary element methods. Ocean Eng 30(3):309–330

Eatock TR, Jeffreys E (1985) Variability of Hydrodynamic Load Predictions for a Tension Leg Platform. Ocean Eng 13(5):449–490

Eça L, Hoekstra M (2000) An Evaluation of Verification Procedures for Computational fluid Dynamics. IST-MARIN Report D72-7

Evans DV (1976) A theory for wave-power absorption by oscillating bodies. J Fluid Mech 77(1):1–25

Evans DV, Jeffrey DC, Salter SH, Taylor JR (1979) Submerged cylinder wave energy device: theory and experiment. Appl Ocean Re 1(1):3–12

Evans DV (1981) Power from Water Waves. Annu Rev Fluid Mech 13:157–187

Evans D, Linton CM (1993) Hydrodynamics of wave-energy devices. Annex Report B1: Device Fundamentals/Hydrodynamics, Contract JOU2-0003-DK. Commission of the European Communities

Falnes J (2002) Ocean Waves and Oscillating Systems. Cambridge Univ Press

Gilbert G, Thompson DM, Brewer AJ (1971) Design curves for regular and random wave generators. J Hydraulic Res 9(2):163–196

Haskind M (1957) The exciting forces and wetting of ships in waves. Izv Akad Nauk SSSR. Otd Tekh Nauk 7:65–79

Havelock T (1942) The damping of the heaving and pitching motion of a ship. Philos Mag 33(7):666–673

Hess J (1990) Panel methods in computational fluid dynamics. Annual Review of Fluid Mechanics, Vol 22, pp 255–274

Hess J, Smith A (1964) Calculation of nonlifting potential flow about arbitrary three-dimensional bodies. Journal of Ship Research, Vol. 8, pp 22–44

Hughes SA (1993) Physical Models and Laboratory Techniques in Coastal Engineering. World Scientific

Jeffrey DC, Keller GJ, Mollison D, Richmond DJ, Salter SH, Taylor JM, Young IA (1978) Study of mechanisms for extracting power from sea waves. Fourth Year Report of the Edinburgh Wave Power Project. The University of Edinburgh

Katory M (1976) On the motion analysis of large asymmetric bodies among sea waves: an application to a wave power generator. Naval Architecture, pp 158–159

Lamb H (1932) Hydrodynamics, 6th edn. Cambridge University Press

Le Méhauté B (1976) An Introduction to Hydrodynamics & Water Waves. Springer-Verlag

Lee C-H, Maniar H, Newman JN, Zhu X (1996a) Computations of Wave Loads Using a B-Spline Panel Method. Proc 21st Sym Naval Hydrodynam. Trondheim, Norway, pp 75–92

Lee C-H, Newman JN, Nielsen F (1996b) Wave Interactions with Oscillating Water Column. Proc 6th Int Offshore Polar Eng Conf, Vol. 1. Los Angeles, USA, pp 82–90

Lee C-H, Farina L, Newman J (1998) A Geometry-Independent Higher-Order Panel Method and its Application to Wave-Body Interactions. Proc 3rd Eng Math Appl Conf. Adelaide, Australia, pp 303–306

Lin C-P (1999) Experimental studies of the hydrodynamic characteristics of a sloped wave energy device. PhD Thesis, The University of Edinburgh

Linton CM (1991) Radiation and diffraction of water waves by a submerged sphere in finite depth. Ocean Eng 18(1/2):61–74

Maniar H (1995) A three-dimensional higher order panel method based on B-splines. PhD Thesis, Massachusetts Institute of Technology

Martins E, Ramos FS, Carrilho L, Justino P, Gato L, Trigo L, Neumann F (2005) CEODOURO: Overall Design of an OWC in the new Oporto Breakwater. Proc 6th Eur Wave Energy Conf. Glasgow, UK, pp 273–280

McCabe AP (2004) An Appraisal of a Range of Fluid Modelling Software. Supergen Marine Workpackage 2 (T2.3.4)

Mei CC (1976) Power Extraction from Water Waves. J Ship Res 20:63–66

Mei CC (1989) The Applied Dynamics of Ocean Surface Waves. Adv Ser Ocean Eng, Vol. 1. World Scientific [revised edition in 2005]

Mynett AE, Serman DD, Mei CC (1979) Characteristics of Salter's cam for extractgin energy from ocean waves. Appl Ocean Res 1(1):13–20

Nebel P (1992) Optimal Control of a Duck. Report of the Edinburgh Wave Power Project. Edinburgh, UK

Newman JN (1976) The interaction of stationary vessels with regular waves. Proc 11th Sym Naval Hydrodynam. London, UK, pp 491–501

Newman JN (1977) Marine Hydrodynamics. MIT Press

Newman JN (1985) Algorithms for the free-surface Green's function. J Eng Math 19:57–67

Newman JN (1992) Panel methods in marine hydrodynamics. Proc 11th Australasian Fluid Mech Conf, Keynote Paper K-2. Hobart, Australia

Newman JN, Lee CH (1992) Sensitivity of Wave Loads to the Discretization of Bodies. Proc 6th Behav Offshore Struct (BOSS) Int Conf, Vol. 1. London, UK, pp 50–63

Newman JN, Lee CH (2002) Boundary-Element Methods in Offshore Structure Analysis. J Offshore Mech Artic Engin 124.81–89
Ogilvir TF (1963) First- and second-order forces on a submerged cylinder submerged under a free surface. J Fluid Mech 16:451–472
Ouslett, Datta (1986) A survey of wave absorbers. J Hydraulic Res 24:265–279
Payne G (2002) Preliminary numerical simulations of the Sloped IPS Buoy. Proc MAREC Conf. Univ Newcastle upon Tyne, UK
Payne GS (2006) Numerical modelling of a sloped wave energy device. PhD Thesis, The University of Edinburgh
Pinkster JA (1997) Computations for Archimedes Wave Swing. Report No. 1122-O. Delft University Technology, Delft, The Netherlands
Pizer D (1992) Numerical Predictions of the Performance of a Solo Duck. Report of the Edinburgh Wave Power Project, Edinburgh, UK
Pizer D (1993) The Numerical Prediction of the Performance of a Solo Duck. Proc Eur Wave Energy Sym. Edinburgh, UK, pp 129–137
Pizer D (1994) Numerical Models. Report of the Edinburgh Wave Power Project, Edinburgh, UK
Pizer D, Retzler C, Henderson R, Cowieson F, Shaw M, Dickens B, Hart R (2005) PELAMIS WEC – Recent Advances in the Numerical and Experimental Modelling Programme. Proc 6th Eur Wave Energy Conf. Glasgow, UK, pp 373–378
Prado MGS, Neumann F, Damen MEC, Gardner F (2005) AWS Results of Pilot Plant Testing 2004. Proc 6th Eur Wave Energy Conf. Glasgow, UK, pp 401–408
Retzler C, Pizer D, Henderson R, Ahlqvist J, Cowieson F, Shaw M (2003) PELAMIS: Advances in the Numerical and Experimental Modelling Programme. Proc 5th Eur Wave Energy Conf. Cork, Ireland, pp 59–66
Roache PJ (1997) Quantification of Uncertainty in Computational Fluid Dynamics. Annu Rev Fluid Mech 29:123–160
Roache PJ (1998) Verification and Validation of Computational Science and Engineering. Hermosa Publishers
Roache PJ (2003) Error Bars for CFD. 41th Aerospace Sci Meet. Reno, USA
Romate JE (1988) Local Error analysis in 3-D Panel Methods. J Eng Math 22.123–142
Romate JE (1989) The Numerical Simulation of Nonlinear Gravity Waves in Three Dimensions using a Higher Order Panel Method. PhD Thesis, Universiteit Twente
Salter SH (1974) Wave Power. Nature 249:720–724
Salter SH (1978) Wide Tank User Guide. Fourth Year Rep, Vol 3(3). Edinburgh Wave Power Project
Salter SH (1981) Absorbing wave-maker and wide tanks. Proc Directional Wave Spectra Applicat. Am Soc Civil Eng, pp 185–202
Salter SH (2001) Proposals for a combined wave and current tank with independent 360° capability. Proc MAREC 2001. IMarEST, Newcastle, UK, pp 75–86
Sarpkaya T, Isaacson I (1981) Mechanics of Wave Forces on Offshore Structures. Von Nostrand Reinhold Company
Skyner D (1987) Solo Duck Linear Analysis. Report of the Edinburgh Wave Power Project. Edinburgh, UK
Sykes R, Lewis A, Thomas G (2007) A Physical and Numerical Study of a Fixed Cylindrical OWC of Finite Wall Thickness. Proc 7th Eur Wave Tidal Energy Conf. Porto, Portugal
Standing MG (1980) Use of Potential Flow theory in Evaluating Wave Forces on Offshore Structures. Power from Sea Waves. In: Count B (ed) Proc Conf Inst Math Appl. Academic Press, London, pp 175–212

Sumer BM, Fredsøe J (1997) Hydrodynamics around Cylindrical Structures. Adv Ser Ocean Eng 12. World Scientific

Taylor J, Rea M, Rogers DJ (2003) The Edinburgh Curved Tank. Proc 5th Eur Wave Energy Conf. Cork, Ireland, pp 307–314

Van Daalen E (1993) Numerical and Theoretical Studies of Water Waves and Floating Bodies. PhD Thesis, University of Twente, The Netherlands

Vugts JH (1968) The Hydrodynamic Coefficients for Swaying, Heaving and Rolling Cylinders in a Free Surface, Report No. 112 S. Netherlands Ship Research Centre TNO

Yeung RW (1982) Numerical methods in free-surface flows. Annu Rev Fluid Mech 14:395–442

Yemm R, Pizer D, Retzler C (2000) The WPT-375 – a near-shore wave energy converter submitted to Scottish Renewables Obligation 3. Proc 3rd Eur Wave Energy Conf, Vol. 2. Patras, Greece, pp 243–249