The Oscillating Wave Surge Converter

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ABSTRACT

The Oscillating Wave Surge Converter (OWSC) is a novel shoreline or near-shore wave energy converter. The concept has developed from an analysis of the performance of the LIMPET shoreline oscillating water column. This analysis showed that the hydrodynamics of shoreline wave energy converters are highly non-linear and that they have a qualitatively different response to similar devices that are sited in deeper water. In particular, the water particle motion in shallow water is predominantly horizontal, with elongated wave troughs and heightened wave peaks. The OWSC is designed to couple strongly with the horizontal particle motion, permitting large amplitudes of motion of the working surface whilst minimising energy losses in associated water particle motions.

The OWSC consists of a paddle rotating about a horizontal axis above the water surface and perpendicular to the direction of wave propagation. The paddle hangs at the mouth of a gully, effectively forming a 'water column' between the paddle and gully back wall. Thus, the OWSC is similar to the Japanese 'Pendulor' system; however the OWSC uses resonance of the water column rather than harbour resonance as its operating principle.

A limited study of geometric parameters using a two-dimensional wave-tank model has been performed. Results from these experiments have shown that the 'water column' has an effect on the paddle dynamics and OWSC performance, with the OWSC having a higher power capture than both a shoreline oscillating water column (OWC) and Pendulor in shallow water. The potential for the OWSC in the shoreline and near-shore regions is also discussed, with implications for construction costs and the price for electricity generated by the OWSC. Potential control strategies for the OWSC are also discussed, together with their likely effect on operation and performance.

KEY WORDS: wave power; shallow water; ocean energy; shoreline; near-shore.

INTRODUCTION

The development of technologies capable of economically generating power from renewable sources of energy is a key objective of modern industrialised society. These renewable sources include wind, solar, hydroelectric, marine current and wave power. Currently, none of the technologies associated with these renewable energy sources are developed sufficiently to provide a solution to the world's energy needs; nor, indeed, is it clear that any one technology could provide a total solution in the future. The relatively low power densities associated with renewable energy sources and the significance of location on performance means that it is likely that a diversity of renewable power technologies needs to be developed.

The development of modern wave power technologies started in the wake of the 1970's oil crisis as a potential replacement for fossil fuel power stations. In the UK this translated into a design brief for a 2 gigawatt power station. As the difficulties associated with this brief became apparent and as the price of oil fell, interest in wave power faltered. However, research on smaller scale plants continued with a large number of alternative designs being developed. Unlike wind-power, wave-power technologies have not yet reached a common conceptual design and a large diversity of designs remains. Indeed, part of the challenge in wave power research is in reaching a generally accepted conceptual framework.

At Queen's University Belfast (QUB) research into wave power has progressed via a 75kW prototype shoreline oscillating water column (OWC) (Whittaker, Beattie, Raghunathan, Thompson, Stewart and Curran 1997) to LIMPET (Heath, Whittaker and Boake 2000), a 500kW commercial-scale OWC. OWC technology is inviting because of its simplicity of operation and low component count. However air turbine efficiency has so far been found to be disappointingly low (Folley, Curran, Boake and Whittaker 2002), and in shallow water the hydrodynamics of the water column are problematic (Folley and Whittaker 2002, Muller and Whittaker 1994). Consequently, the wave energy research team at QUB have utilised the knowledge and understanding developed from the design, testing and construction of two full-scale wave energy converters to propose a new type of shallow water wave energy converter; this they named the Oscillating Wave Surge Converter (OWSC).

THE OSCILLATING WAVE SURGE CONVERTER CONCEPT

In its most primitive form the Oscillating Wave Surge Converter (OWSC) consists of a paddle suspended from a hinge located above the water surface so that it can rotate about an axis approximately parallel to the wave crests, together with an angled back-wall behind this paddle. This is shown in Figure 1. Enhancements to this basic concept of the OWSC could include the paddle oscillating about a non-vertical position and more complex profiles of the back-wall. These and other possible enhancements will be investigated when a more thorough understanding of the OWSC hydrodynamics and dynamics has been developed.

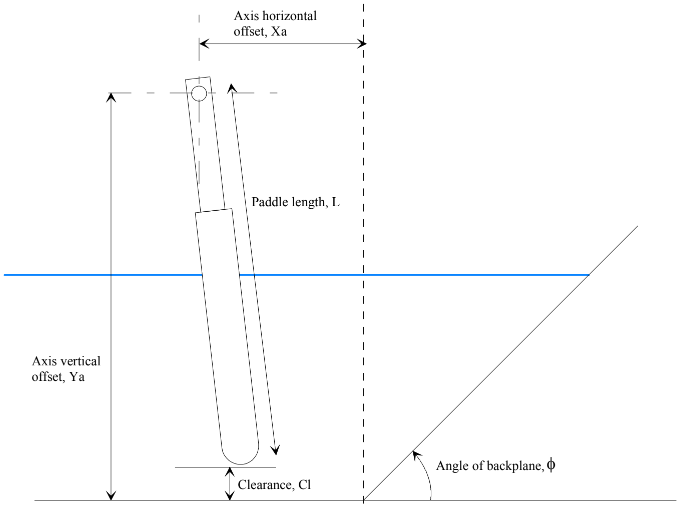

Figure 1: Schematic diagram of an OWSC

The concept of the OWSC evolved from the analysis of shoreline OWC's. Fundamentally, an OWC consists of a box with an underwater opening so that a water column in the box rises and falls in response to waves. This movement of the water surface causes air to be driven through an air-turbine. Because a water surface must remain approximately horizontal, to change the air volume in the box the water surface must move orthogonally to this, i.e. vertically. However, in the absence of any bodies, water particles in a wave move in an approximately elliptical orbit, thus for an OWC to work effectively, the horizontal motion of the water particles needs to be converted into vertical motion. This was achieved in LIMPET by inclining the water column at an angle of 40 degrees to the horizontal, which aided the transition from horizontal to vertical water particle motion. Unfortunately, this inclination of the water column has two additional unwanted effects; namely, diverting an amount of the water up the outside of the front wall of LIMPET and inducing transverse oscillations in the water column, which do not cause a change in the air volume. As the water depth decreases, the motion of the water particles become more horizontal and although it would be technically possible to design OWC's to minimise these side-effects, it does not appear to be possible to do this economically in 'shallow' water. The exact definition of 'shallow' is intentionally vague, since it depends on the hydrodynamics and economics of the OWC. With LIMPET however, a dramatic reduction in performance was observed as the water depth at the device reduced from 10 metres to 6 metres.

The larger horizontal water particle motions in 'shallow' water, suggest that the working surface of the wave energy converter should also move in an approximately horizontal plane, and to minimise the required volume of displacement, this suggests a relatively thin paddle. To achieve the largely horizontal motion of the paddle, the paddle can be hinged at the top or bottom, utilise a multi-hinged "straight line" mechanism, or move on horizontally aligned slides. The horizontally-aligned slides and "straight-line" mechanisms are likely to be costly and difficult to maintain, so that the choice is between hinging the paddle at the top or bottom.

It is generally considered that hinging the paddle at the bottom would better match the motion of the water particles due to the exponential decay in water particle motion with its depth of submergence (Scher 1985). However, in "shallow" water the horizontal water particle motion is still significant at the sea-bed, whilst the horizontal motion of the paddle at the hinge would be zero. Alternatively, if the hinge was placed some distance above the water surface then it could be possible to match better the average horizontal water particle motion. Hinging the paddle above the water surface also provides two additional benefits. Firstly, the bearings and power-take-off would be significantly more accessible when compared to a bottom hinged paddle. Secondly, the top hinged paddle suffers no "end-stop" problems and could feasibly swing through a full 360 degrees.

The back-wall of the OWSC is required to perform a number of functions. Primarily, the back-wall and paddle form a virtual water column, which influences the tuning of the device. It is necessary to shape this water column so that it is optimally tuned for the incident wave climate. The back-wall must also be shaped to minimise the generation of turbulence that reduces device performance, with the horizontal water particle motions being efficiently converted into elevation of the water column surface. Finally, the sloped back-wall can help to stabilise the OWSC when it is constructed using a caisson; the water running up the back wall tending to push the caisson into the sea-bed.

The OWSC has clear similarities to Pendulor (Watabe 2000, Watabe and Kondo 1990), which consists of a caisson with a top hinged paddle at the mouth of a water chamber. The length of the water chamber is ¼ of a wavelength to produce harbour resonance and so that all of the water particle motion at the paddle is horizontal. Unfortunately, typical wave periods where wave energy converters are likely to be sited, would result in un-economically long water chambers. The OWSC differs from Pendulor in that tuning is achieved using a water column; the water particle motions are already largely horizontal due to the "shallow" water effect.

EXPERIMENTAL SET-UP

Experiments were carried out in the narrow (0.35 metres wide) wave flume at QUB. Six different seas were used to test the performance of the OWSC; a summary of their characteristics are shown in Table 1.

Table 1: Summary of sea–states used for testing the OWSC

	Energy period (secs)	Incident wave power (kW/m)	North Atlantic weighting
Sea-state 1	7.4	10.2	0.3
Sea-state 2	7.3	20.5	0.15
Sea-state 3	10.1	11.2	0.3
Sea-state 4	10.2	22.4	0.15
Sea-state 5	10.1	45.0	0.05
Sea-state 6	12.9	44.8	0.05

The seas were generated using a Bretschneider spectrum with a random phase between the wave components. To enable the use of linear wave theory for calculating wave power, the seas were defined at the 17 metre contour at full scale (FS). Thus the calculated capture factors include losses associated with the wave breaking and energy dissipation shoreward of the 17m depth contour. The wave flume seabed profile is shown in Figure 2, which is typical for a site on the west coast of Scotland.

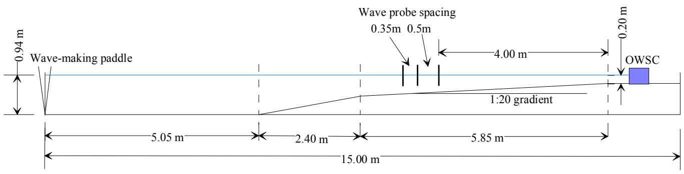

Figure 2: QUB wave flume set-up

The OWSC model tested is 1/40th scale model, manufactured primarily from Perspex. For ease of adjustment the paddle is supported from rails above the wave flume and whose axis can be moved forwards and backwards as well as up and down. The rotation of the axis is measured using a potentiometer and the torque on the shaft measured using a torque transducer. The motion of the paddle is damped using a coulomb friction brake on the shaft. The force applied to the shaft via the friction brake can be adjusted to adjust the level of applied damping. The friction brake provides a near constant torque opposing the rotation of the paddle and is thus has a similar characteristic to a constant pressure pump. The backplane of the model can be adjusted to provide angles of inclination from 35 to 90˚. The backplane completely blocks the flume, although a small amount of leakage past the backplane occurs where the backplane meets the seabed due the side walls of the wave-flume diverging by approximately 0.25˚. The amount of leakage is not expected to influence performance significantly. By simply making the angle of the backplane 90˚ and moving the paddle to the ¼ wavelength position this model can also be used to determine the performance of a Pendulor.

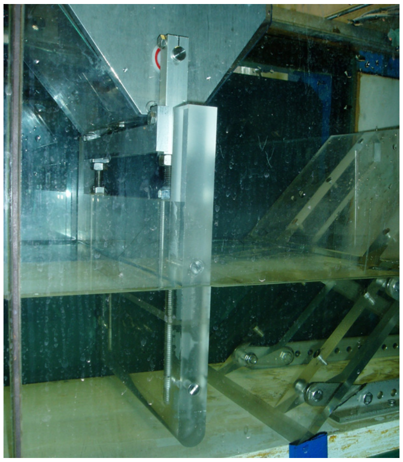

Figure 3: Photograph of the OWSC model in the 2D wave flume

Clearance between the paddle and side-walls of the wave flume is 5mm, equivalent to 0.2 metres at full scale. This is considered the minimum clearance that avoids excessive costs associated with manufacturing to a tight tolerance. The paddle thickness is the equivalent of 1.0 metres at full scale.

The three wave probes were used to calculate the incident and reflected wave powers using a linear reflection analysis. This information together with the calculated power extracted by the coulomb friction brake enables a rudimentary audit of the incident wave power to be carried out.

PERFORMANCE OF THE OSCILLATING WAVE SURGE CONVERTER

The performance of the OWSC has been determined for the six sea-states detailed above and for a limited number of configurations. For each sea-state and configuration the optimum damping has been determined by testing at a range of braking loads. The maximum capture factor is then determined by plotting the root mean square (RMS) of the braking torque against the capture factor. A typical plot is shown in Figure 4, showing a peak capture factor of approximately 0.45 at an RMS torque of 0.7 Nm. The amounts of power reflected or radiated from the OWSC and power lost due to viscosity/turbulence are also shown.

This variation of the power capture with damping load is typical for a wave power station. Power capture is the product of damping torque and rotational velocity of the paddle. At zero torque and zero velocity (due to high damping torque) there clearly can be no power capture with the optimum torque occurring somewhere between these two extremes. The optimum torque occurs when the sum of the reflected/radiated wave power and the power lost to viscosity/turbulence is a minimum.

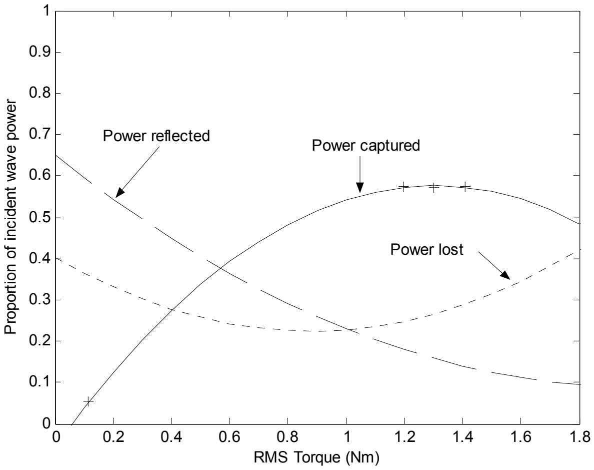

Figure 4: Effect of damping torque on power

Figure 5 shows the power audit for the six sea-states for the OWSC configuration tested. By applying weightings to each sea-state appropriate for the North Atlantic wave climate the average capture factor for the OWSC was calculated as 0.46. Note that this capture factor includes any losses in wave energy due to wave breaking or otherwise shoreward of the 17 metre depth contour.

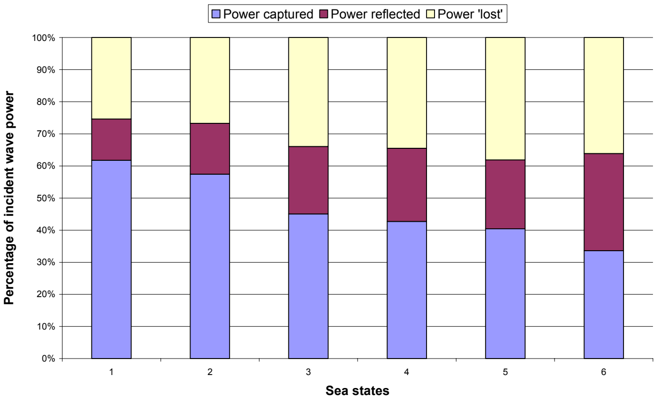

Figure 5: Power audit for the OWSC

Figure 5 also shows that a significant amount of power is lost in the OWSC due to viscosity/turbulence. A potential explanation of this can be derived from observation of the motions of the water column surface, which contains many short waves, suggesting that the coupling between the water column and paddle is weak. Reducing the size of the water column, or the clearance underneath the paddle, may help to improve the behaviour of the water column and consequently the power capture of the OWSC. The amount of reflected/radiated wave power increases as the energy period of the incident wave climate increases. This may imply that the OWSC is tuned to shorter period waves. It is possible that a change in the 'water column' shape could improve performance, however currently insufficient data is available to make a measured intervention.

COMPARISON OF OWSC PERFORMANCE WITH A SHORELINE OWC AND PENDULOR

The commercial potential of the OWSC is fundamentally dependent on its relative performance when compared to devices that could be deployed in similar locations. Unless the OWSC can be shown to be an improvement over current technology, either in performance or cost of construction/operation, its development is purely academic. Currently, the two devices that can be deployed in shallow water locations to the OWSC are a shoreline OWC and Pendulor.

Table 3 shows the maximum capture factors for the OWSC, a typical shoreline OWC and Pendulor for the six sea-states used in testing. The performance of Pendulor has been obtained using the same sea-states and with a harbour length appropriate for a wave with a 10 second period. The performance of the shoreline OWC has been derived from previous tests using the same wave-tank configuration, but with a slightly different set of sea-states. Calculating the average capture factors by weighting each sea-state for a North Atlantic coastline gives capture factors of 0.46, 0.29 and 0.42 for the OWSC, a shoreline OWC and Pendulor respectively. It is clear from this that even without optimisation the OWSC has a higher capture factor than both a shoreline OWC and Pendulor.

In comparison to a shoreline OWC the OWSC has the additional advantage of having a higher capture factor in the smaller, but more common, sea-states (sea-states 1 and 3), and a lower capture in the larger, more energetic sea-states (sea-states 5 and 6). Because the power capture is the product of capture factor and incident wave power this means that there is smaller range in the power captured. Thus, the ratio between the average power capture and optimum power plant rating can be increased. The benefit of this characteristic is that the power plant will typically be operating with a higher part-load, with associated higher conversion efficiency. Moreover, the power plant would be smaller and consequently cheaper for the same annual energy production as a shoreline OWC.

Table 3: Maximum capture factors of the OWSC, a shoreline OWC and Pendulor

	OWSC	Shoreline OWC	Pendulor
Sea-state 1	0.61	0.19	0.50
Sea-state 2	0.56	0.17	0.46
Sea-state 3	0.42	0.38	0.43
Sea-state 4	0.41	0.35	0.41
Sea-state 5	0.38	0.30	0.38
Sea-state 6	0.31	0.36	0.33

POSSIBLE EMBODIMENTS OF THE OWSC

A number of distinct embodiments of the OWSC can be envisaged. These different embodiments all exploit the beneficial hydrodynamics of the paddle and 'water column', but differ in how this is achieved and consequently in their construction and performance. Three promising embodiments identified are the single shoreline OWSC, the single near-shore OWSC and the near-shore OWSC terminator array.

The single shoreline OWSC

The water chamber for a shoreline OWSC can be created by blasting and excavating an appropriately shaped gully out of a cliff. This technology was used to create the gully for LIMPET and can produce a relatively accurate profile, although some finishing work may be required. Following the blasting at least one winter would be required for wave action to remove rubble from the gully and surrounding area. This scouring action may need to be supplemented or augmented, depending upon the presence of appropriate ocean currents required to carry debris away, although this may in some circumstances not be possible due to environmental constraints.

Having created the gully, foundations for bearings and machinery would be laid, before installing the necessary fixed plant. The final part of the installation would involve mounting the paddle onto the bearings and then lowering it into the water.

Because the shoreline provides the majority of the structure for this configuration of the OWSC and because the majority of fabrication occurs off-site, the construction costs should be relatively low. In addition, because the plant is accessible directly from the shore, the operating and maintenance costs should be minimised. However, there are potentially two significant problems with the shoreline OWSC. Firstly, construction of a shoreline OWSC requires a suitable site, with relatively tight constraints on water depth at the shore and shoreline profile, in addition to there being a suitable wave climate. Initial studies of the coastline of the UK indicate that there are very few suitable sites. The second problem is that the combination of a large moving paddle on a site that could be relatively easily accessed by the public represents a significant safety risk. Additional structures would be required to restrict access and it is likely that the public liability insurance premiums would be higher, assuming that insurance could be obtained for operation.

The single near-shore OWSC

The single near-shore OWSC consists of a single paddle suspended within a C-shaped caisson, sited in a water depth of 6 – 10 metres. The caisson would be constructed off-site and the paddle fitted prior to transportation to its operating location. The slope of the back wall would help to drive the caisson into the seabed and it may be possible for it to operate without anchor piles. If anchor piles are required their capacity of piles is likely to be reduced from that required when used with a vertical wall (as in a Pendulor). Once in position the OWSC would be connected to the grid using sub-sea cables.

A single near-shore OWSC would be able to take any advantage that exists with respect to the point absorber effect (Evans 1980). Alternatively, it has been shown that power capture can be increased by flaring the entrance to an OWC (Whittaker and Stewart 1993) and it would be reasonable to expect a similar effect would be experienced by an OWSC. Both the point absorber effect and the flared caisson mouth enable the power captured to be greater than incident on the paddle's width, although the extent of these effects depends on particular matching of the incident sea and device dimensions.

The terminator-array near-shore OWSC

The terminator-array near-shore OWSC would consist of a string of paddles aligned at approximately 90 degrees to the direction of wave propagation. Provided the phase between the motions of adjacent paddles is sufficiently small the need for walls between the paddles is removed. These side-walls would be replaced by a single pile between each paddle to support the bearing blocks, with solid side-walls at the ends of the string of paddles only. The effect of this is to reduce the total cost of construction. The back-wall would still be required to create the water column.

The reduction in structure required with the OWSC configured as an array should reduce the plant costs per unit width of paddle. However, the extent of interactions between adjacent paddles and across the array is difficult to estimate. Some additional increase in performance and reduction in cost may be possible be linking the paddles hydraulics together resulting in a larger more efficient motor/generator set.

POSSIBLE CONTROL STRATEGIES FOR THE OWSC

The reported set of tests performed on the OWSC model used coulomb friction to extract energy from the motion of the paddle. This approximates constant pressure hydraulics, where the torque opposing motion is proportional to the difference between the high and low pressure circuits. The control strategy would be to adjust the high pressure circuit to maximise the power capture for any particular sea state. Whilst this is a relatively simple power take-off mechanism using an easily implemented control strategy it is unlikely to be optimal.

Linear theory states that the optimum damping torque is proportional to the paddle's rotational velocity, with the constant of proportionality a function of the wave frequency (Evans 1980). Whilst the hydrodynamics of the OWSC are highly non-linear, a damping torque that in some way increases with rotational velocity is likely to result in a higher average power capture than for the constant damping torque currently utilised. This could be achieved using a variable displacement hydraulic machine (Salter, Taylor and Caldwell 2002) or direct drive electrical generators. The increase in power capture will depend on the quality of the control algorithm, coupled with hardware constraints defined by the power take-off system.

With a purely dissipative control strategy, as described above, the power capture is limited because the phase relationship between the wave force and paddle velocity is not always optimal. Indeed, during testing of the OWSC model it was clear that at times the wave force and paddle velocity were out-of-phase, leading to energy going from the paddle back into the sea. This can occur even with a purely dissipative control mechanism because of the large amount of reactive energy stored in the water column and paddle. Continuous control of the reactive energy, sometimes called complex conjugate control (Salter, Taylor and Caldwell 2002), would ensure that the energy always flows from the waves into the paddle; however this would be very difficult to implement.

Latching has been proposed as a practical implementation for the control of reactive energy (Budal and Falnes 1980). In latching, the body (in this case the paddle) is held for a variable amount of time at the ends of the stroke. It is released at a time where its motion would interact best with the waves. Adopting this control strategy should increase the power capture, although the degree of improvement would depend on the quality of the control algorithm.

CONCLUSIONS AND FURTHER WORK

The Oscillating Wave Surge Converter is a promising shoreline and/or near-shore wave energy converter. Although the tank-testing carried out thus far has not been extensive, it has been sufficient to indicate that the OWSC is more productive than a shoreline OWC and Pendulor. Moreover, the construction costs of the OWSC should be lower than both a shoreline OWC and Pendulor, resulting in a much lower cost per unit of delivered energy, viz. pence/kWh. In addition, a number of alternative embodiments of the OWSC have been identified, all of which have particular strengths and weaknesses.

Further work on the OWSC can be divided into three general areas. Firstly, further work is required on the hydrodynamics/dynamics of the OWSC to increase performance by improving the coupling of the paddle, water column and waves. This will be achieved using further 2D wave tank experiments, utilising PIV and video analysis together with appropriate numerical modelling. Secondly, the effect of different control strategies requires investigation to determine the potential for latching or other sophisticated methods. Thirdly, 3D wave tank experiments are required to measure the performance of the OWSC in realistic circumstances.

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REFERENCES

Budal, K and Falnes, J [1980] Interacting Point Absorbers With Controlled Motion, *Power from sea waves*, Edinburgh, UK, pp 381-98.

Evans, DV [1980] Some Analytic Results for Two and Three Dimensional Wave-energy Absorbers, *Power from Sea Waves*, Edinburgh, UK, pp 213-49.

Folley, M, Curran, R, Boake, C and Whittaker, TJT [2002] Performance investigations of the LIMPET Counter-Rotating Wells Turbine, *2nd Marine Renewable Energy Conference*, Newcastle, UK.

Folley, M and Whittaker, TJT [2002] Identification of non-linear flow characteristics of the LIMPET shoreline OWC, *12th International Offshore and Polar Engineering Conference*, Kyushu, Japan, **Vol 1**, pp 541-6.

Heath, T, Whittaker, TJT and Boake, CB [2000] The Design, Construction and Operation of the LIMPET Wave Energy Converter (Islay, Scotland), *4th European Wave Energy Conference*, Aalborg, Denmark.

Muller, G and Whittaker, TJT [1994] Visualisation of Flow Conditions inside a Shoreline Wave Power-Station, *Ocean Engineering* **22**(6): 629-41.

Salter, SH, Taylor, JRM and Caldwell, NJ [2002] Power conversion mechanisms for wave energy, *Proc Instn Mechn Engrs* **216**: 1-27.

Scher, R [1985] Progress on Flap-Type Wave Absorbing Devices, *Hydrodynamics of Ocean Wave-Energy Utilisation*, Lisbon, Portugal, pp 375-84.

Watabe, T [2000] *Ocean Wave Energy Converter: Pendulor*, Muroran, Japan.

Watabe, T and Kondo, H [1990] Progress on Pendulor-Type Wave energy Converting Device, *International Offshore and Polar Engineering Conference*, Seoul, Korea.

Whittaker, TJT, Beattie, WC, Raghunathan, S, Thompson, A, Stewart, T and Curran, R [1997] The Islay wave power project: an engineering perspective, *Proc Instn Civ Engrs Wat., Marit & Energy* **124**: 189- 201.

Whittaker, TJT and Stewart, TP [1993] An Experimental Study of Nearshore and Shoreline Oscillating Water Columns with Harbours, *European Wave Energy Symposium*, Edinburgh, UK, pp 151-6.