Optimisation of Wave Power Devices Towards Economic Wave Power Systems

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Abstract

This paper presents a thought provoking discussion of the design of economic wave power converters and is intended to stimulate debate and challenge developers to critically assess their own devices. As the primary optimisation criterion is cost of energy production rather than maximum utilisation of the resource, the best commercial device is not necessarily the most efficient wave energy converter. It is argued that the precise shape and method of primary power conversion from the waves is relatively unimportant provided it meets certain criteria. It is proposed that the main design criteria are survivability, serviceability and practical installation whilst limiting expensive working hours at sea. The maximum interface with the waves must be achieved with minimum materials to reduce both cost and the energy embodied in the structure. It is observed that nearshore sites with a water depth of between 10 and 20m have primarily been considered for fixed structures such as oscillating water columns. After applying the design criteria proposed, it is concluded that moving structures such as sea bed hinged flaps located in the near-shore zone are potentially attractive from a cost and productivity viewpoint and require further investigation.

Introduction

The first recorded patent on wave power conversion was granted to Monsieur Girard in France in 1799, and up until the early 1970’s a further 300 patents had been filled. However, since then there has been significant activity through out the World and several prototypes have been built with a further batch either under construction or planned. The European Marine Energy Test Centre (EMEC) on Orkney has been set up to enable developers to test their systems and have their performance certified. Six mooring locations in 50m water depth are available and the first of these is being utilised by Ocean Power Delivery for their Pelamis system (Yemm et al. 2003). It is planned to develop 6 nearshore sites in the 15 to 10 m water depth range. Several of the sites are already booked for a wide variety of device types.

To date the majority of the devices built have been shoreline oscillating water column (OWC) systems. Mostly these have been built to demonstrate the technology and test the power conversion systems from wave to electrical production. In general these machines have been over-engineered, due to the early stage of wave power development, and consequently are a long way from reaching the economics of developed renewables such as wind. Most of wave-power research has concentrated on hydrodynamic and power chain efficiency rather than cost effective construction to enable economic power production. The problem is that systems must be designed to survive the 1 in 50 year storms which typically produce loadings two or more orders of magnitude higher than the average values. Thus expensive structure lies redundant for most of the year and does not contribute to energy production.

The research group at Queen’s University Belfast (QUB) has been actively involved in wave power R&D since the mid 1970’s. Most importantly they have co-ordinated the design, construction and operation of two full-scale prototype shoreline OWC devices on the Isle of Islay. The first of these was a 75kW machine (Whittaker et al. 1997) completed in 1990 and operated for research purposes until 1999 when it was decommissioned. The second device, LIMPET (Whittaker et al. 2003), has a 500kW installed capacity and is currently owned and operated by Wavegen.

Consequently, the group at QUB in association with their industrial associates is one of a small number of teams in the World who have taken designs from the conceptual phase through to power production at sea. This experience has resulted in an understanding of the design challenges facing wave power developers which goes beyond simple hydrodynamic and power chain efficiency. If there is to be wide scale commercial development of wave power systems then they must deliver energy at a competitive price. However, a simple design objective such as minimising the cost of energy is not particularly useful on its own as the cost of energy is a consequence of the interaction between a wide range of variables. It is much more useful to use a set of design criteria which influences the magnitude of the variables. As a result, a set of characteristics for the idealised potentially cost effective wave power converter have been developed and are presented in this paper. These are then applied to a particular type of system by way of illustration. However, it is recognised that there are several generic concepts which could meet the idealised criteria.

Ideal characteristics of a wave energy converter

To understand the source of the ideal characteristics of a wave energy converter it is important to first identify the major cost centres and influences on productivity. For a wave energy converter the major cost centres are typically foundations/moorings, structure, M&E plant and operation & maintenance, with their indicative contributions to the cost of electricity shown in **Figure 1**. There is clearly a trade-off between maintenance and capital costs. This figure illustrates the significant contribution of operation & maintenance, which includes maintenance tasks, insurance, unscheduled repairs and periodic refits, to the total costs and is based on an annual cost £56/kW installed, from a study commissioned by the Royal Academy of Engineering (The Royal Academy of Engineering 2004). The cost of the M&E plant is likely to be closely related to the installed plant capacity, with £400/kW chosen as a typical cost for M&E plant, which amortises to approximately 1.25p/kWh assuming a capacity factor of 35%. The structure and foundations/mooring costs are very device dependent and will depend on the quantity of material required to provide sufficient strength during operation and survival, the ease of manufacture, assembly and installation on site. The productivity of a wave-power plant will depend on the useable wave energy resource, the conversion efficiency from wave to wire, averaged over the lifetime of the plant's deployment, and the plant availability, which is coupled to the plant's reliability and maintenance programme.

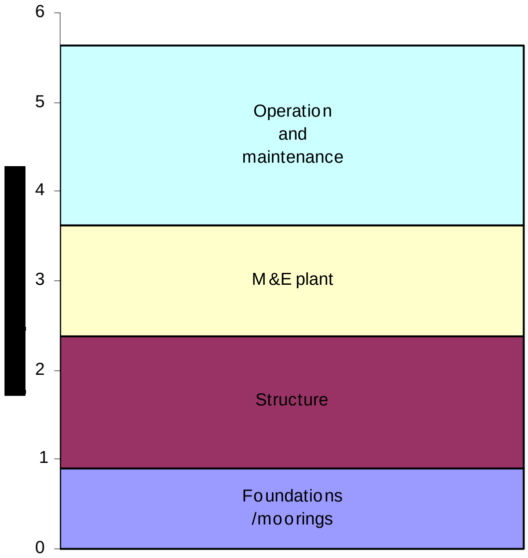

Figure 1: Typical cost breakdown for a wave energy converter

It has been found useful to couple these observations with experience from prototype plant and an understanding of wave energy converter hydrodynamics to convert them into a set of ideal characteristics that embody all of this. The following list is not exhaustive, nor is it meant to be definitive, but is intended to represent the main characteristics identified so far by the group at QUB.

(I) The primary wave-body interface is a good wave-maker

It is important that there is a strong coupling between the fluid motion in the near field boundary around the device and the far field fluid motion which is associated with wave action in the most commonly occurring seas. This results in an efficient wave power extractor as there is a reciprocal relationship between wave generation and absorption. However, as the motion of the body becomes greater it should progressively reduce its ability to generate waves. This means that as the seas get larger the moving body progressively decouples from the wave induced fluid particle motion thus limiting the amount of power that has to be converted.

(II) The device can avoid extreme loading in storms

Apart from progressive decoupling as the sea state increases the device needs to be able to move to a 'fail safe' condition in which it completely avoids the extremes of wave loading in storms. This is a 'last resort' scenario as ideally it is desirable for a device to continue production in storms due to substantial decoupling from the waves. It is not economic to provide structure to withstand extreme loads as it is only required for a very small percentage of time and mainly lies redundant.

(III) The device has an appropriate broad bandwidth response

The device should have a good power capture over the range of most commonly occurring incident wave frequencies it is subjected to. In a physical system, reactive energy is stored as kinetic and potential energy, whilst the active power is related to power capture and radiated power. At a system's natural frequency the variation in reactive energy is zero, as the incident wave force and the velocity of the working surface are in phase. Thus for a broad bandwidth response the device dynamics must ensure that this is largely achieved over a range of frequencies and there is a variety of means to do this. For example, by having two or more natural frequencies within the wave frequency range the responses from them can merge to give a broad bandwidth. This can be achieved with 'harbours' in front of oscillating water columns (Count & Evans 1984). Alternatively 'slow tuning' can be adopted where the stored kinetic or potential energy is adjusted with sea-state so that even with a narrow bandwidth the natural frequency of response is centred on the incident wave frequency to maximise performance. Finally so called 'phase control' or 'complex-conjugate control' can be used in which the kinetic or potential energy is manipulated on a wave-by-wave basis to maximise performance (Budal & Falnes 1980; Salter et al. 2002).

(IV) The system has its highest efficiency in the least energetic seas

This reduces the variation in power production between moderate and high seas, as power produced is the product of efficiency and incident wave power. More consistent power production increases the load factor on the generating equipment which minimises under utilisation of expensive equipment improving economics. It also leads to high average conversion efficiencies as the influence of poor part-load efficiency of the generating plant is minimised. The efficiency of the system is not very important in highly energetic seas because it is likely that in these circumstances the generator would be running at full load even with a low efficiency.

(V) The device is not site specific and can be mass produced

These factors minimise production and design costs. From experience of the two prototype wave energy converters on Islay the amounts of expenditure required to design and certify bespoke components are substantial, making site-specific adaptations extremely undesirable. The use of mass production techniques has the potential for dramatic reductions in cost, particularly in the power take-off components. This implies that other device elements should be modified so that they are sized suitably for a mass-produced module. Reliability of the components will also increase with mass-production because of the increased effort in design and experience gained in their use.

(VI) The device has short direct load paths

The use of short, direct load paths is a well known design principle and is clearly of relevance to the design of wave energy converters where large forces have to be transmitted. This influences the size and cost of structural elements in the device. For wave energy converters the loading scenario is complicated because of the inherently oscillatory and distributed character of the incident wave force.

(VII) Either the whole device or the serviceable components are easily removed

Working at sea is fundamentally more expensive and more hazardous than working ashore. Moreover, the sea-state may severely limit the times that the device is accessible for servicing thus reducing availability. With sea bed mounted devices it is desirable that all the components which are likely to require attention are demountable for servicing back at base. This implies a static non-serviceable part of the device remains at site. This is likely to have the additional benefit of making installation an easier operation. Floating devices should be easy to uncouple from the moorings and power take-off connection and be towed into dock.

Merits and Characteristics of near-shore wave energy converters

Before presenting a concept design which fulfils the criteria specified, it is useful to explore the influence location has on wave power converters. Devices can be located on the shoreline, in the near-shore zone or offshore. The depth classification of offshore and near-shore is somewhat arbitrary. It is suggested by the authors that sea bed mounted devices are considered to be near-shore and would normally be placed in water depths of less than 20m. Floating devices are generally considered to be offshore as normally they require water depths in excess of 50m to provide sufficient compliance in the moorings. There was a considerable amount of development work on offshore wave power devices as part of the UK wave energy programme prior to 1984. Interest in offshore devices is again growing and Pelamis (Yemm et al. 2003) is a good example of the latest stage of development. The primary argument for offshore wave energy is that the average wave resource is much greater than near-shore or shoreline and consequently larger stations can be built which make more use of the resource available; also that the higher sea power should be beneficial to the economics. It can be argued that there are a number of flaws in this argument. Firstly, a higher power capture will not necessarily translate into a lower cost per unit of energy delivered. Secondly, although the average wave energy resource in the near-shore may be only 40% of the offshore resource off the Western Isles of Scotland for example, much of this reduction is due to wave breaking in the more energetic seas. Numerical modelling of the UK's shoreline and near-shore wave resource (The Department of Energy 1992) showed that offshore there could be a factor of 60 between the peak and average sea power and yet in the near-shore this was less than 10. In comparison in very shallow water with a depth of 5m the ratio was as low as 3 due to wave breaking in modest seas and above. Another interesting feature of the near-shore resource is that refraction reduces the directional spread and creates 'hot spots' which can be exploited. When the cost effectiveness of the installed capacity and its utilisation is taken into account a much higher proportion of the near-shore wave resource can be converted compared to offshore. Consequently the attractiveness of the magnitude of the offshore resource compared to near-shore might not be as attractive as it might seem. This leads to the conclusion that a near-shore wave power plant could be optimised to operate at a higher load factor thus meeting the requirements of characteristic IV.

In spite of the lower ratio of extreme to average sea power in the near-shore zone, loading due to impact from plunging breakers can still be very high unless the device is designed to avoid the extremes. However, this issue may not be significant because it is expected that any viable device will become transparent during storms, thus avoiding extreme loading, characteristic II. All wave power devices must be designed to accept large as opposed to extreme wave loads during operating sea-states as this is essential to high power conversion.

Any sea bed mounted devices will be in general affected detrimentally by the tidal level variation. The extent of this problem will depend on the size of the tidal range relative to the water depth. There are many sites where the tidal range is typically less than 2.0 metres and it is expected that at these sites the effect on performance will be relatively small. This will of course depend on the actual device design and must be considered in the evaluation of different concepts.

The other potential location for a wave energy converter is on the shoreline. However, whilst it may be acceptable to site a number of prototype devices on the shoreline, it is expected that environmental considerations and local opposition will limit the number of opportunities. Moreover, a shoreline site is likely to contravene characteristic V because the design is likely to be strongly site specific.

It can be concluded from the above that there is not a clear cut case which directs the developer to an offshore rather than a near-shore site or visa versa. It largely depends on the type of system being developed. For example there is insufficient water depth in the near-shore zone to provide mooring compliance for floating systems. Fixed oscillating water column systems must be designed to withstand the extreme wave impacts in the near-shore zone which results in excessive redundant structure for most of the year. Under utilisation of expensive structure in this way has a significant influence on the cost of energy production and might lead to the conclusion that OWC's are better suited to shoreline or breakwater locations where much of the structure is provided naturally or as part of a completely different function.

A conceptual design for near-shore locations

Studies at QUB have shown that there is one type of device that can exploit the advantages of the near-shore zone whilst avoiding the disadvantages. The sea bed mounted bottom hinged flap, shown in **Figure 2**, is one of the simplest types of wave power device, yet it has received relatively little attention as a wave power device although it is the most common configuration for wavetank wave generators. An oscillating flap with a fulcrum at a depth 1/3 the wavelength produces fluid particle motion which is a good approximation to that of a deep water wave. In shallower water the match between the induced horizontal fluid motion at the flap and that in the wave is not as good due to the horizontal motion of the fluid particles at the hinge becoming more significant. Yet it still largely meets the requirements of characteristic I. All wave energy devices that extract energy via surging motions have to resist moments induced by to the perpendicular distance between the seabed and the surge wave force. Within this category of devices, a bottom-hinged flap minimises the load path and thus the required structure, characteristic VI. With the hinge at the seabed, it is possible for the flap to lie down parallel to the seabed during storms, making it largely transparent, characteristic II. By the movement of ballast and latching mechanisms it should be possible to make this occur automatically. It may also be possible to allow the flap to move freely during storms and if necessary to utilise the squeeze-film bearing effect to cushion the flap's motion as it nears the seabed where damage could occur. A model of the flap system operating in extreme wave conditions is shown in **Figure 3**. The maximum angular excursion observed was $\pm 50^0$ from the vertical even with the applied damping turned off.

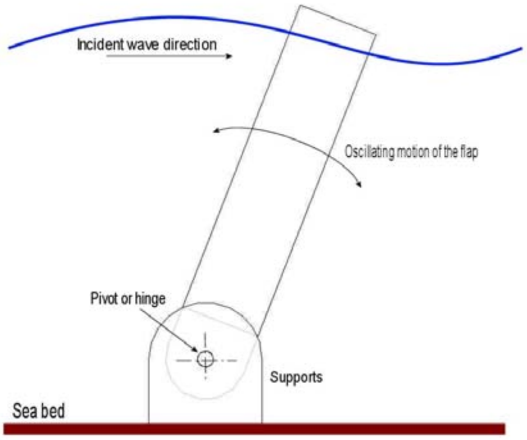

Figure 2: Seabed mounted bottom-hinged flap

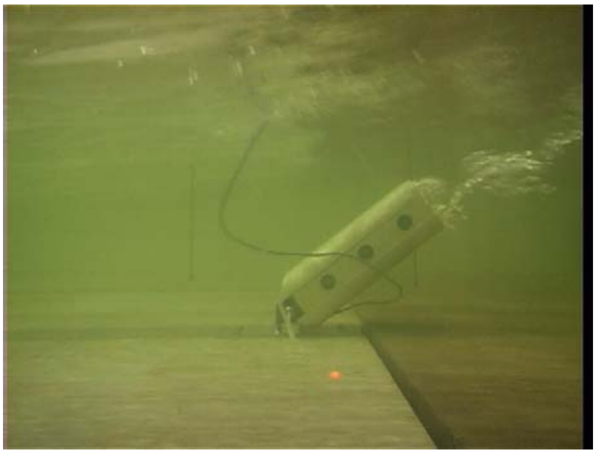

Figure 3: Model flap in extreme wave conditions

Achieving characteristic III, a broad bandwidth response, depends on the natural frequencies of the system. A bottom-hinged flap will only have a single natural frequency, ω_n, dependent on its pitch stiffness, k, and total moment of inertia, I. $\omega_n = \sqrt{k/I}$. Using a CFD tool such as WAMIT, an approximate value for the added moment of inertia of flaps in different water depths can been obtained, whilst the pitch stiffness can be derived from the positions and magnitudes of the centres of mass and buoyancy. The effect of water depth on the natural pitch period for a square flap, with a thickness equal to 20% of the water depth and a specific density of 0.5 is shown in **Figure 4**. For example a 10 metre wide, 2 metre thick flap, in 10 metres of water depth can have a natural pitch frequency similar to the incident wave periods of around 10 seconds. If the natural pitch frequency is at the higher frequency end of the spectrum then performance is likely to be highest in the least energetic sea, characteristic IV. This is enhanced by the wave coupling of a surging flap increasing with the wave frequency. By using the analogy of an inverted pendulum it can be seen that the natural frequency of a bottom-hinged, surface-piercing flap will generally decrease with water depth. It is interesting to note that the tuning of two other bottom-hinged flap-type devices, FROND (Chaplin & Folley 1998) with a proposed water depth of 20-30 metres and MACE (Salter 1992) with a proposed water depth of 60 metres, has proven problematic.

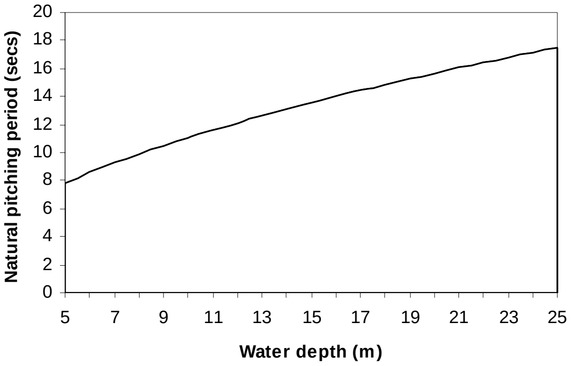

Figure 4: Effect of water depth on natural pitch period of square flap

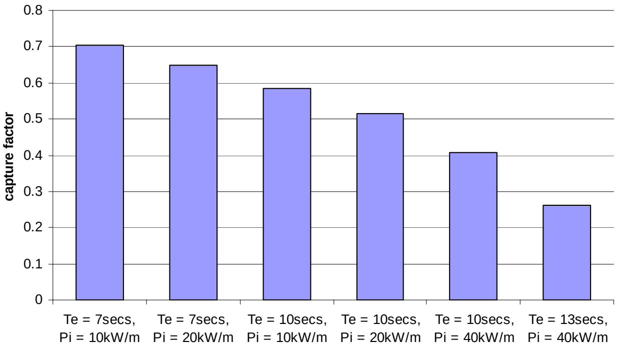

Figure 5: Capture factor for bottom-hinged flap in 6 typical sea states

Figure 5 shows the performance of the flap in different sea states. In this design there is only a factor of two between the average and peak power output. It is evident that as the sea state becomes larger the angular motion of the flap increases and progressively decouples from the wave. At an angle of 45^0 the top of the flap is sufficiently submerged to allow the remaining wave energy to wash over the top, thus satisfying characteristic II.

Finally it is possible to design a system to satisfy characteristic VII. A design comprising a flap hinged to a sub frame pinned to the sea bed with external hydraulic rams and hinges can be serviced by divers in the shallow water depths proposed. The flap can be ballasted on to the sea bed, locked into the base frame and the critical components removed.

Conclusions

In order to design for survival and achieve cost effective energy production the potential loads in extreme seas must be avoided as structure which is redundant for most of the year can not be afforded.

It is proposed that bottom hinged flaps with a sub frame pinned to the sea bed in water depths of between 10 and 15m should be developed as the concept meets the range of desirable characteristics proposed and to date this type of system has received relatively little attention.

The driver for wave power development must be cost of energy and not utilisation of the resource.

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