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HIGH EFFICIENCY, LOW COST, WAVE ENERGY CONVERSION SYSTEM

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ABSTRACT

The SEA Clam wave energy converter is the outcome of a 18 year programme of wave energy research carried out by an experienced team at Coventry University. The objective has been to develop a high-efficiency, low-cost, wave energy conversion system that could commercially exploit this attractive resource. This paper describes the SEA Clam and its component parts together with its key features of operation. Structural designs in steel and concrete are presented in detail with supporting illustrations. Comparisons with the OWC are mentioned and the reasons for the Clams superior performance highlighted. Independently assessed productivity and costs are tabled which show the performance advantages of the latest version of the SEA Clam.

1. INTRODUCTION

The Energy Systems Group at Coventry University has been researching wave energy and developing wave energy devices since 1975. With the help of Sea Energy Associates Limited and the U.K. Department of Energy the straight SEA Clam device was developed and tested in 1979 [1] followed by the re-configured version, the circular SEA Clam, in 1984 [2]. A series of model scale design was refined in 1991 with the help of a major consultancy company, Rendel Palmer and Tritton.

The U.K. Department of Energy carried out an in-depth review of wave energy and reported its findings in December 1992 [3]. Five major designs were included plus reference to three more recent concepts. The report summarised its findings by comparing the major devices regarding their state of development and the predicted electricity generating costs. It concluded that wave energy is at a relatively immature stage of development and that the shoreline gully-type Oscillating Water Column (OWC) had the lowest generating costs followed closely by the offshore SEA Clam. This cost comparison has to be seen in the light of the potential resource exploitable by offshore devices as against onshore units.

2. THE CIRCULAR SEA CLAM

The SEA Clam is a simple device that uses the displacement of air to extract energy from sea waves. Twelve air chambers, the outer surfaces of which are formed by flexible rubber membranes, are placed around a floating ringed structure. Differential wave action moves the membrane in and out forcing air to be interchanged between chambers. Wells turbines placed in the manifolds between the air chambers extract power from the air flow. The rigid torus structure, 60m diameter or more, acts as a stable reference body and is moored a few kilometres off shore. Typically a 25 MW scheme, shown in figure 1, deployed off

Figure 1 Deployment of SEA Clam Units

the West coast of Scotland would feature 10 SEA Clam units and produce over 50 GWh per year of electricity.

The concept of the circular SEA Clam was proved and tested on Loch Ness, Scotland in 1984 with a fully instrumented 1/15th scale model. Figure 2 shows the final model under test in a medium sea state. The air power delivered by the flexible air bags was dissipated in rotating vane dampers which represented the linear characteristic of a Wells turbine. Structural and mooring forces were measured over a range of sea states during the experiments.

The use of flexible membrane [4] as a pumping interface between active sea water and internal air is the innovative feature that facilitates high energy capture efficiency. The membrane is the key moving part of the Clam and has to be strong enough to survive the forces acting upon it whilst accommodating the cyclic shape changes. The design solution is similar to that used in radial tyres and involves a two-ply nylon or kevlar reinforced rubber membrane with plies aligned at a narrow angle. This alignment allows a flat membrane to stretch in one direction and takes tension in a direction at right angles thereby distorting to the desired shape required by wave interaction. The behaviour of a large membrane has already been tested in similar operating conditions as part of a novel low head hydroelectric scheme [5]. Support for the membrane is provided by a steel frame that can be clamped to the main structure during assembly or, if necessary, at sea. The

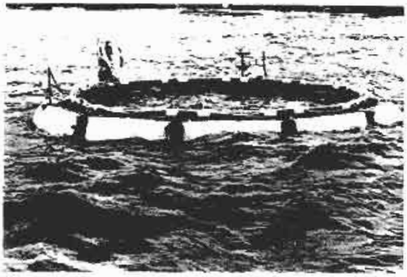

Figure 2 Model Tests on Loch Ness

chosen inclination of the membrane support frame maximises capture efficiency by minimising added mass and spring rate. Capture efficiencies on a 60m diameter Clam can peak at over 100% for 7 second waves falling to around 20% for 11 second waves. Predicted annual capture efficiencies for the characteristic sea states off South Uist, Scotland, were calculated as 33% in the wave energy review.

The Clam, in common with many other devices, utilises the Wells turbine for air power conversion. The Energy Systems Group has recently had the experience of testing a 1.08m diameter, 3000 rpm Wells turbine driving a 150 KW induction generator [6], shown in figure 3, as part of the previously mentioned low-head hydroelectric

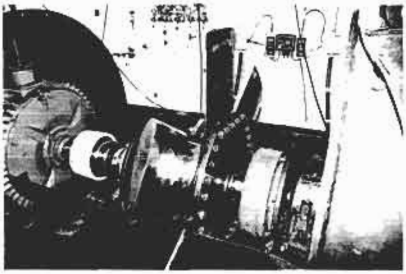

Figure 3 150 kW Wells Turbine

scheme. This turbine was built of stainless steel at very low cost using a novel blade fabrication technique. Larger turbines based on this design give predicted annual air power to shaft power efficiencies of 70% within the Clam power configuration. The proposed turbines, 10 off per unit, would have 2m blade tip diameters with design air powers of 480 kW and would directly drive 1500 rpm induction generators with nameplate ratings of 250 kW at 3.3 kV. This nameplate rating classifies each device unit at 2.5 MW.

3. OPERATIONAL DESIGN FEATURES

The SEA Clam was the outcome of 10 years of research and development by an experienced team. The objective had been to develop a technically viable wave energy converter to deliver the maximum amount of the available resource to the electrical grid at an economic cost. Concepts requiring complex solutions to technical problems or expensive structural costs were discounted. This left the various configurations of OWC as the favoured solutions although the structural costs of offshore units were regarded as excessive. Onshore OWCs were seen as technically and economically feasible but were unattractive because of their severely limited resource potential. The SEA Clam can be regarded as a form of OWC in which the oscillating interface is vertical rather than horizontal. This configuration both enhances the energy capture bandwidth and reduces the structural mass requirements. Being an offshore modular unit it maximises the resource available and can be deployed in small, medium or large scale schemes.

The key features of circular SEA Clam are:-

1. The circular frame of reference provides excellent stability due to its wave bridging properties in both wave and crest directions. Pitch and roll motions are also minimised which helps to stabilise bag operation.
2. The rigid annulus is well known for its inherent structural strength. In this application the heave, surge and torsional moments are roughly uniformly applied around the spine and hence the structural strength is efficiently used.
3. The stability of the structure can be enhanced by making its diameter about a half wavelength of the predominant waves. This has the effect of making the device a resonant absorber at the chosen wavelength and hence extending its bandwidth.
4. The modular structure of post-tensioned concrete sections or fabricated steel units is amenable to low cost production techniques and eases transportation problems.
5. The vertically inclined flexible membrane bag is considered to be the most ideal and efficient transformer of wave to air power discovered to date. Both experimental work and hydrodynamic analysis confirm this view. The properties of an inclined bag are such that the controllable spring rate can be chosen to resonate with the hydrodynamic added mass to give a relatively wide bandwidth response. This results in a very efficient and nearly flat frequency response of the

incident wave to air energy transfer provided the air turbine acts as a linear matched load. The Wells turbine running at constant speed is an ideal load for this system.

6. The circular spine with its stable hydrostatic characteristic can be designed to just compensate for the unstable buoyancy of the air system associated with low spring rate air bags. The resulting buoyancy forces on the nearly unstable combined bag-spine system are, therefore, reduced and hence the disturbance of the frame of reference by the buoyancy component of the waves is minimised. The effects of increasing wave forces on the frame of reference bring about set-down effects, which reduces the free board, and eventually load shedding motion; both of which limit induced structural stress.
7. Inflation of the air bags on the pitch-stable circular spine raises the whole structure and provides a means of controlling and optimising the capture power.
8. The circular configuration of the device can extract energy from all components of a wave whatever angle they impinge on the device. Common-mode waves cannot occur as with a straight spine structure and hence the air has always somewhere to go in spite of the closed circuit finite volume air system.
9. A separate power air system from the buoyancy air system is used which allows the structure to be partitioned for good seakeeping. Buoyancy air is the term used to describe the air which is only to keep the structure afloat and power air describes the air used to transmit the air from bag to turbine.
10. It is essential for a wave energy device to be closed down, irrespective of wave conditions, for such reasons as operational requirements, maintenance, failure of the device or transmission system, or the lack of consumer demand. Complete deflation of the air bags puts the circular SEA Clam into a fail-safe mode where the flexible membrane bags are held inactive and under partial tension on the profiled spine surface. Inflation of the air system will progressively restore power capacity.
11. Being omni-directional, the energy capture is independent of device alignment and hence unaffected by currents and mooring resonance. The device is efficient in dealing with multi-directional seas.
12. The SEA Clam can be classified as a combined terminator, attenuator and point absorber and exhibits the relative merits of all three.

4. STRUCTURAL DESIGN OF THE CLAM

A number of design concepts were considered for the toroidal structure of the Clam in order to meet the functional, fatigue and seakeeping requirements. The early tubular steel framework was rejected in favour of closed hull designs in steel or concrete. Certain design constraints were imposed to ensure the size of the units matched the theoretical and experimental work carried out to date. It was expected that the steel design would be more economical than concrete and more appropriate to prototype and early production units. This proved to be marginally true for the 60m diameter units but the concrete structure could be stretched to 80m diameter with only a linear increase in cost but with a significantly greater increase in productivity. Therefore concrete structures are favoured for major deployment of larger diameter production units.

The steel hull design, shown in figure

4, is 8m deep and 4m wide and is made up of 12 modules separated by watertight

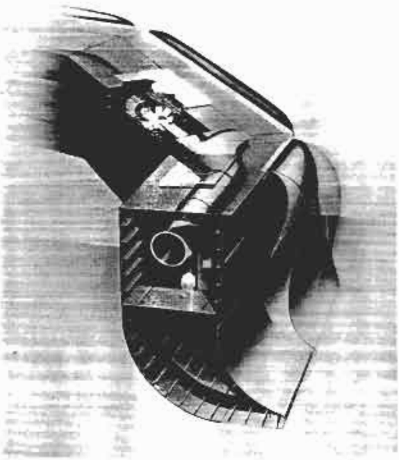

Figure 4 Structural Design in Steel

bulkheads, each module forming one side of the 12 sided structure. Each module supports one flexible membrane bag and contains one turbine cell to which access is gained via a hatch in the deck. The turbine cell occupies the upper section of the central third of each module and is isolated from the rest of the module by watertight bulkheads and a floor. The turbine cell is designed to contain the turbine pod, the switchgear, oil coolers and other ancillaries. The rest of the hull in each module forms a single cell that will be fully ballasted with inert water when the device is operational. A continuous power duct passes through all bulkheads with branches off to each air bag. The reverse curved front of module forms a recess designed to suit the membrane energy capture unit. The rim of this recess is shaped to accept a steel attachment frame for the air bag membrane.

The design allows hull construction to follow normal shipbuilding practice as closely as possible and to make use of a yard's existing panel lines, jigs, etc. An assessment at one shipyard showed that the device could be constructed under cover in two halves, the two halves being joined outside. Such a procedure would allow all mechanical and electrical fitting out, ductwork painting and testing to be carried out under cover in a controlled environment.

Each device as constructed, is relatively light at 922 tonnes and has a draught of only 1.5m. Provided at least this depth of water is available at the quayside it can be launched down a slipway of adequate width and then ballasted at sea with inert water to give a displacement of 4500 tonnes. Ballast adjustments can be made using portable pumps powered from a maintenance vessel. Such adjustments allow part of the hull to be raised clear of the water so that inspection and painting can be carried out in-situ, provide the weather is calm.

Access for a limited amount of internal maintenance is provided via a manhole in each power compartment. The turbine generator power pod and other large ancillary components can, if necessary, be removed via a specially designed hatch for maintenance ashore.

Costings have been based on quotations from the UK, Germany and the Netherlands. The range of tender costs for the steel hull is expected to be around £1.5M at 1991 prices.

Figure 5 shows the design of the concrete hull which is basically the same as for the steel hull. Twelve modules separated by watertight bulkheads, each form one side of the twelve-sided device. However, in the concrete design, each module is divided by a horizontal mid-height floor and two intermediate bulkheads into 6 watertight cells. Each module supports one flexible membrane bag connected by a single branch duct to a 1.5m diameter common manifold duct. The turbine pod, switchgear, oil coolers and other ancillaries are located within the central upper cell of each module. The hull width of each module is slightly greater at 4.5m than that for the steel hull design in order to produce sufficient buoyancy to

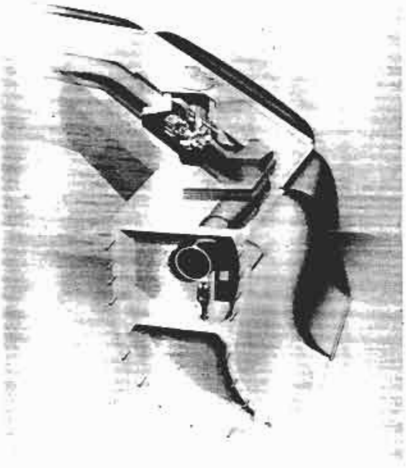

Figure 5 Structural Design in Concrete

support the additional weight. Total displacement at sea is 5240 tonnes including 235 tonnes of water ballast. Wall thickness is a minimum of 300mm with internal high tensile steel wire tendons.
Although large offshore construction basins are capable of handling complete devices, their size and operating cost is such that the construction of a single device in such a location would be uneconomic. A viable alternative is to use a graving dock or slipway. By constructing the device in one quarter or one third segments, the required dock width is reduced. With four segments, for example, the width is reduced to about fourteen metres and several dry docks exist which are now disused and which would accommodate such a method of construction. The device, would however, have to be assembled afloat and would require double bulkheads at the segment ends.

5. PRODUCTIVITY AND COSTS

The SEA Clam has been designed to operate in the energetic seas off the west coast of Scotland where average power levels can reach 70 kW/m and with storm power levels of over 3000 kW/m. The structural design is governed by the fatigue levels induced by these wave climates and the power system design relates to average sea power at a given site. It therefore follows that the design, cost and productivity would vary according to the chosen site of deployment and therefore it would require considerable effort to predict productivity and costs at, say, the Sea of Japan where average power levels are around 13 kW/m.
The productivity and costs of the SEA Clam have been derived using a well-developed methodology as part of the UK wave energy review. This methodology enabled the comparative productivities and costs to be produced for all the major devices. The wave energy resource was well defined by characteristic sea states and the power train from wave to grid was modelled. Costs included capital costs of construction, installation, transmission and project management plus the operating and maintenance costs. Capital equipment was assumed to have a 25 year operating life and electricity costs were calculated for 8% and 15% discount rates.
Table 1 presents the productivity, output and electricity costs of SEA Clam scheme. The figures for the 60m diameter units are from the wave energy review whereas the improved performances of the 80m diameter

units are the result of more recent work.

Location	South-Uist Scotland	
Diameter of Device (m)	60	80
Average Wave Power Level (kW/m)	52	52
Average Capture Efficiency (%)	33	39
Average Turbine Efficiency (%)	70	70
Average Generator Efficiency (%)	92	92
Availability (%)	96	96
Average power per Device (kW)	598	942
Annual Output per Clam Unit (GWh/year)	5.1	8.3
Cost of 5-Unit Clam Scheme (£M at 1991 prices)	16.6	21.4
Electricity Costs at 8% Discount Rate (p/kWh)	8	7

Table 1 Productivity and Costs

6. CONCLUSIONS

The SEA Clam is a floating device concept that can harness offshore wave energy at a high efficiency and hence maximise the utilisation of the available resource. Its configuration and operation have been described with particular reference to the novel membrane-air-turbine power conversion system. Development is at an advanced stage with the structural design complete and the major components tested. Productivity and costs have been determined by an independent party and show the SEA Clam as a leading device in the UK.

Comparisons with its rival, the OWC, have been made and the advantages of the Clam with its wide bandwidth efficiency and low structural weight discussed. Key features of the device have been listed which account for its superior performance and development potential.

Viable structural designs in steel and concrete have been presented which have been fully costed. These designs conform to marine requirements and may be refined to give added benefits. In particular the concrete design can be stretched to larger diameters to give higher efficiency and lower electricity costs.

Finally, productivity and costings are given which show the SEA Clam to be a leading competitor in the international wave energy community.

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