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The Circular Sea Clam Wave Energy Converter

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Summary

The SEA Clam Wave Energy Generator has been developed to a prototype design suitable for supplying electricity to island communities and coastal communities. It consists of a 120 m long floating spine supporting six air bags breathing through self-rectifying Wells turbines into a common air duct. An alternative configuration of the SEA Clam has been model tested at Loch Ness and has achieved a dramatic improvement in efficiency. This paper describes the structural configuration of the Circular SEA Clam and explains the features which led to a breakthrough in performance. Predictions are made of the cost of power produced by a 60 m diameter full scale unit deployed in the North Atlantic.

Introduction

After eight years of research and development the current design of the SEA Clam wave energy device has reached a stage where further improvements would be difficult to achieve. The large 10 MW unit designed for a 2 GW scheme off the Hebrides was declared in 1982 to be the leading wave energy device arising out of the UK national wave energy programme and having the most potential for further development. Recent development has been towards smaller units aimed at the world wide market of supplying electrical power for small islands and coastal communities. Detailed design has now been completed for a 1 MW rated prototype for testing off the UK Atlantic coast. Unfortunately, with the current energy climate it is unlikely that a prototype SEA Clam will be built when the predicted cost of power generated is around 7½p/kWh.

Sea Energy Associates Limited and Coventry (Lanchester) Polytechnic have been involved in the UK national wave energy wave absorbing face.

The design of the 1 MW SEA Clam, illustrated in Figure 1, utilises the displacement of air to extract energy from sea waves. Flexible air bags attached to the face of a floating spine breathe in response to wave forces. This causes air to be forced through self-rectifying turbines in and out of the hollow spine, allowing interchange of air between Clam bags. The randomness of sea wave patterns allows phased operation of the Clam elements enabling the spine to act as a stable reference body. For small scale wave energy deployment 1 MW units would feature six Clam elements on a 120 m long spine whereas larger 10 MW units, 290 m long, would be appropriate for 2 GW schemes.

Fig.1. Artists Impression of a 1 MW SEA Clam

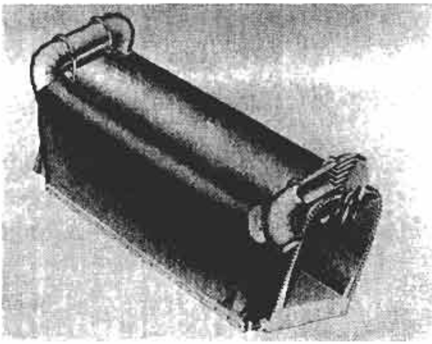

Fig.2. Cutaway View Showing Spine, Air Bag and Turbo-Generator

Figure 2 shows a cutaway section of the post-tensioned concrete spine with a flexible bag and its associated turbo-generator module. The air exchange between bag and spine is through ducting attached to one corner of the bag and the top of the spine. The turbo-generator module is contained in the top of the spine and can be sealed off by a butterfly valve in the ducting in the event of failure of the bag. The air turbines are of the self-rectifying "Wells" design with a single stage 6-bladed rotor directly coupled to an induction generator or alternator. The mooring is a self-aligning single point system

3. The closed circuit air system of the SEA Clam has a finite air volume which impedes the common mode operation of the air bags. Any component of a wave which is parallel to the spine cannot be absorbed because the air has nowhere to go. The partial solution to the problem has been to align the spine at about 45° to the principal wave direction which gives a compromise between improving wave phase distribution and the loss of capture width. An alternative solution of providing a compensator to enable the air bags to effectively breathe to atmosphere has run into engineering problems.

These three fundamental limitations have impeded the further development of the SEA Clam. What is required is a new configuration of the device having efficient air bags of high capacity without incurring instability problems. The Circular SEA Clam appears to satisfy these requirements.

The Circular SEA Clam

By re-structuring the components, spine, air bag and turbo-generator modules, an alternative configuration of the SEA Clam can be evolved. The circular spine structure shown in Figure 3 is in the form of a rigid annulus 4 m in diameter, comprising of 12 identical sections. The separate sections of the model spine are held together by one compression joint and two tension links arranged in such a manner as to facilitate the measurement of wave-induced surge and heave bending in the ring. A continuous air duct around the inner top surface of the circular structure provides the common air connection between the 12 Clam elements. Each section has its own sealed buoyancy tanks for good sea-keeping and is fitted with membrane-type air bags (Figure 4) breathing through rotating vane air dampers (Figure 5) having the same characteristics as a Wells turbine. To activate the device the air system is pressurised to inflate the bags to a mean displacement in still water and during operation the air bags interchange air through the air dampers dissipating power in response to phased random waves.

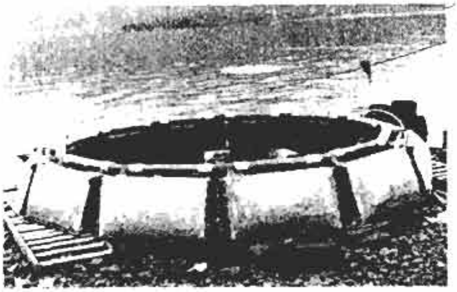

Fig.3. Circular SEA Clam Model Ready for Launching

Fig.4. Profile of Membrane Bag

The key features of the Circular SEA Clam are:-

1. The circular frame of reference provides excellent stability due to its wave bridging properties in both the wave and crest directions. Pitch and roll motions are also minimised which helps to stabilise bag operation. A floating circular configuration has inherent stability which does not depend on the properties of section such as the centres of gravity and buoyancy.
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 half a 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 resonant with the hydrodynamic added mass to give a relatively low Q response. This results in a very efficient and nearly flat frequency response of the 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 corresponding effect of direct wave forces on the frame of reference is unclear at this time.
7. Inflation of the air bags on the pitch-stable circular spine raises the whole structure vertically rather than increasing the pitch angle as in the straight spine. Therefore, bag displacement is a function of water line area rather than restoring moment. This important difference in the bag inflation mechanism leads to a high ratio of air bag capacity to total device displacement which should improve performance and reduce costs.
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 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 sea keeping. 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 power 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 restore power capacity progressively.

11. Being omni-directional, the energy capture is independent of device alignment and hence unaffected by currents and mooring resonances. The device is efficient in dealing with multi-directional seas.
12. Arguments within the wave energy community as to the relative merits of terminators, attenuators and point absorbers have continued for many years. This device can be classified as all three.

The provisional specification of a full scale Circular SEA Clam design for small scale applications in North Atlantic sea states would be:

Spine diameter	60 m
Spine depth	7 m
No. of sections and air bags	12
No. of turbines	8
Displacement	4000 tonnes
Capture air power (annual average)	1200 kW
Turbo-generator efficiency	65%
Transmission efficiency	95%
Availability	80%
Power landed (annual average)	593 kW
Annual energy output	5.2 GWh

Performance of the Circular SEA Clam

The capture efficiency of the Circular SEA Clam has been determined experimentally by testing a fully instrumented 1/15t scale model in Loch Ness (Figure 6). The model was fabricated from steel sheet and fitted with corded latex membrane air bags. Each section was numbered clockwise from 1 to 12 with th single point mooring attached between 12 and 1 o'clock.

Measurements were made of the pressure drop across each calibrated air damper during 6 minute test periods in order to compute the air power dissipated for each sea state.

Fig.5. Rotating Vane Air Dampers

Fig.6. Circular SEA Clam Tests on Loch Ness

Structurally bending moments and mooring forces were also recorded, but these will be reported in a later paper. Sea states were computed from the output of capacitance type wave gauge mounted on a mast near to the test area.

Two parameters were varied during the tests in order to seek optimum performance. First, the volume of air in the system was varied which, in effect, varied the mean operating profile of the air bags and hence their mean spring rate. Secondly, the speed of the rotating vane dampers was varied between 4000 and 10000 rev/min to give damping factors of 3636 to 9090 Nsm^{-5} for the linear pressure-flow characteristics. The model was tested in a range of sea states up to a significant wave height, H_S, of 0.5 m and energy periods, T_E, of 3 s. All results were processed by on-line computer and scaled to full scale.

The results of efficiency against energy period for the Circular SEA Clam model are plotted in Figure 7. The curve through the experimental points is the mean result of the 6 minute records taken with various air volumes and damping factors and represents an improvement by a factor of 4 over the efficiency of the straight 120 m long SEA Clam. When displacement of the devices is taken into account, this improvement in efficiency is equivalent to an improvement in power to weight ratio of 3 which

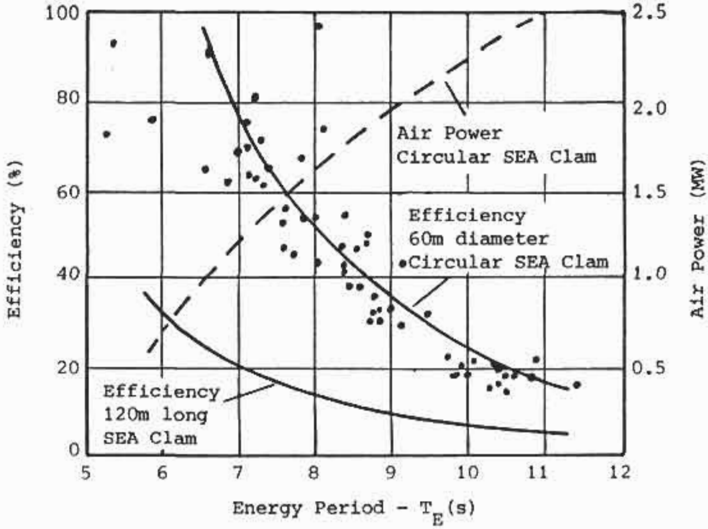

Fig.7. Scaled Air Power Results for 60 m Diameter Circular SEA Clam

should be reflected in the cost of power produced. Also shown on the graph is the air power curve for the Circular SEA Clam which has been derived from the efficiency curve.

Figure 8 shows samples of the distribution of air power dissipated by each damper numbered around the clock. As would be expected in a locally wind generated uni-directional sea like Loch Ness the distribution of power is reasonably symmetrical about the mooring line which is a check on the validity of the results. The major proportion of the total air power, P_T, is generated in the 8 front air bags and suggests the power captured by the 4 rear bags is not worth having.

Conclusions

As a result of investigating the hydrodynamic and structural limitations of the SEA Clam, a new device configuration has been tested which has produced a remarkable improvement in efficiency. After a series of model tests of the Circular SEA

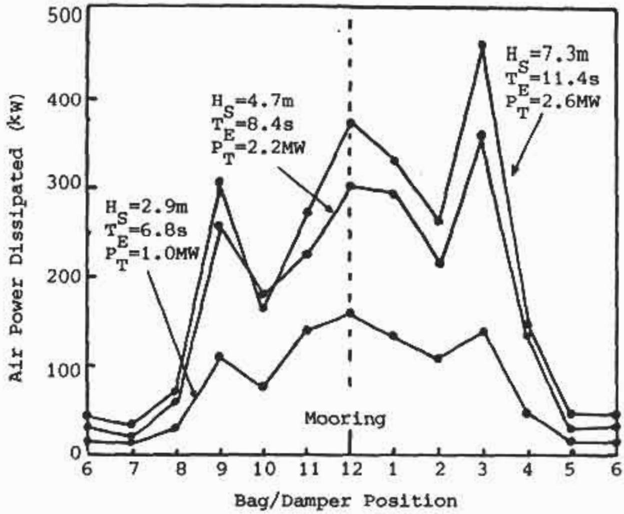

Fig.8. Scaled Air Power Distribution Around Circular SEA Clam

Clam in Loch Ness an improvement in productivity by a factor of 3 has been confirmed for the same structural displacement. This coupled with an improvement in the engineering features of the device is predicted to give a significant reduction in the cost of power generated from wave energy.

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