WAVE ENERGY: A BRITISH WAY FORWARD WITH THE CIRCULAR SEA CLAM

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INTRODUCTION

Since 1975 the SEA-Lanchester energy systems group has been part of the United Kingdom wave energy programme. The principal objective of the national programme was to investigate the feasibility and likely costs of wave energy schemes capable of a major contribution to the U.K. national grid system. Thus a 2 GW wave power station, situated off the Outer Hebrides, was designated as the reference design.

In 1982, after a detailed assessment of the likely electricity costs from 10 proposed wave energy device designs, the United Kingdom wave energy research and development programme was virtually closed down. At this time the predicted unit electricty costs for the most promising device, the 300 m long, straight spine, floating SEA-Clam, was 6-10 p/kWh, described in reference 1.

Since then very little further work has been carried out in the U.K., although both Japan and Norway have tested prototype devices with the costs for the Norwegian cliff mounted, oscillating water column being about 4 p/kWh.

However, with support from our industrial sponsors, RMC and Redlands, and some funding from the Department of Energy, the SEA-Lanchester Energy Systems Group has further developed and tested the design of the SEA-Clam. Initially the development was aimed at the design and model testing of smaller straight spine SEA-Clam units, rated at about 1 MW, and the predicted cost of power generation from small groups of such devices was about 6 p/kWh. With this predicted cost in 1985, the prevailing energy climate and the U.K. commitment to nuclear power made it unlikely that funding could be found for a 1 MW prototype construction and test programme. Thus, in an attempt to improve the device energy capture efficiency and the structural strength to weight ratio, the SEA-Lanchester group reconfigured the basic airbag - Wells turbine system from its straight spine form to a circular spaceframe configuration. This development combined with the use of membrane air-bags has achieved remarkable improvements in energy absorption efficiencies, and hence has brought the power costs down into the range of 3.3 - 5.6 p/kWh. In the light of this progress the group are proposing a programme for the detailed design optimisation, construction and performance testing of a 60 m diameter Circular SEA-Clam prototype wave energy device.

CIRCULAR SEA-CLAM

Development

The principle of operation of the straight SEA-Clam is to use the wave induced displacement of air, to and from a series of flexible bags to drive self-rectifying, "Wells", air turbines situated in the ducting between each bag outlet and the spine. The long, hollow, floating spine acts as the main structural element and provides a stable frame of reference for the attachment of the air bags as well as a suitable passage for the exchange of air between bags. This straight configuration has been extensively tested at lengths representing at full scale 60 to 300 m and although proving to be of a simple and efficient structural design it is relatively inefficient in terms of energy capture due to a number of basic limitations.

Although designed as a terminator, the finite volume of the of the closed air system means that common mode operation, where the wave crests are long and parallel to the spine, can only be utilised by compression of the system air. Thus to avoid most of the energy being reflected the spine has to be angled at about 45-55 degrees to the principle wave direction to ensure optimum phased operation of the air-bags.

The tear-drop shaped flexible air-bags, used with the straight spine because of basic stability requirements, have high hydro-geometric spring rates which results in a severe mismatch of energy transfer from wave to air with a consequent loss of efficiency. The total displacement of the air-bags also limits the power capture capability of the device and, with the limited pitch stability of the straight spine, increasing the air content of the tear-drop bags increases the spine pitch angle and decreases the effective capture depth of the bag.

These major performance limitations have been overcome by re-configuring the main elements of the system onto a circular structure. The Circular SEA-Clam, Bellamy and Peatfield (2), consists of a circular spine in the form of a space frame annulus which supports 12 identical membrane faced airboxes on its outer surface. Each membrane-airbox is connected to a continuous air duct running all the way round the spine and with Wells air turbines located in the entry to each air bag, to give parallel connection, or between airboxes giving series connection. This design maintains efficient structural strength and brings major energy capture efficiency improvements over the straight version due to its greatly increased stability, from both the increased waterline area and its wave spanning ability, which allows the use of low spring rate, membrane type airboxes. These airboxes not only give an increased swept volume but also a much lower hydrogeometric spring rate with a consequent closer match of energy transfer from wave to air. The circular form with a continuous air duct also ensures energy capture from all wave directions and avoids the common mode bag operation which reduced the operational efficiency of the straight device.

Model Testing

A fully instrumented 1/15th. scale model of a 60 m diameter circular clam was extensively tested at the SEA-Lanchester Loch Ness test site to determine the capture efficiency, structural loadings and mooring forces for the device in a wide range of sea states.

The model sections were constructed in steel and each air box front was fitted with a cross-corded latex rubber membrane. The 12 sections were joined together in a 4 m diameter ring with the membrane covered outward faces of the air boxes being set at an inward angle of about 15 degrees to the vertical. The air connections between the boxes were made into a 0.15 m diameter pipe which formed a complete ring round the internal circumference of the device near the top level of the air box sections, thus allowing air interchange in either direction round the device. Figures 1 and 2 show the 1/15th scale model, ready for launch and under test at the Loch Ness site.

Extensive performance tests were carried out for distinctly different airbox to turbine air configurations :- (a) The parallel air connections first tested consisted of turbines situated between the air exit from each membrane box and the entrance into the air ring pipe where it could then have undamped access to all other turbines (b) The series air configuration, subsequently tested, consisted of turbines situated in the air ring pipe between the air exits from adjacent membrane boxes, thus any air travelling from a front box to a rear box would have to pass through a number of turbines in series.

Figure 3 shows a plot of air power capture efficiency, based on a nominal wave frontage equal to the device diameter, against the energy period of the particular sea state for the series air connection case. The spread of the results represents the fact that many of the results are not at optimum conditions for damping and/or for device air displacement. The results are presented as scaled to 60 m diameter, 7 m deep, full scale circular clam device conditions.

The measured efficiencies for the parallel configuration, not illustrated here, show no significant difference from the series results presented in fig. 3. However when compared with the capture efficiency results for the straight, 120 m long SEA clam the circular device shows an improved efficiency, in both parallel and series cases, of about a factor of four.

The major improvement in power absorption efficiency for the circular clam arrangement can be attributed to a number of factors. Due to its wave spanning properties in both wave length and crest length directions, the configuration of a floating circular structure provides a highly stable frame of reference and can thus be used to mount the single-sided, low spring rate, membrane airboxes which, when matched to the Wells turbine, have a much more efficient energy transfer characteristic than the double-sided 'tear-drop' bags which had to be used on the straight spine clam devices.

Unlike the straight spine system, no common mode operation of the bags can occur in the circular configuration, which allows bi-directional movement of air and enables the device to extract energy from all components of a sea state, irrespective of their direction of approach.

FULL SCALE PRODUCTIVITY AND COSTINGS

A proposed 60 m diameter device design, based on a circular space frame structure supporting 12 rubber membrane covered air boxes, each 7 m deep, has been designed to be capable of withstanding the maximum bending moments and mooring forces predicted from the Loch Ness model tests.

Productivity

Using the curves of air power efficiency against sea state energy period produced from the Loch Ness tests, suitably combined with the turbo-generator performance characteristics, it is possible to predict the likely device productivity at any site whose yearly sea state distribution is known. This has been carried out for the typical scatter diagram for the North Atlantic, off the Outer Hebrides, and off the South-west coast of the Shetlands, where the annual electrical energy output, assuming an 85% device availability, would be about 5.5 GWh.

Costings

The proposed 60 m diameter circular Sea-Clam device has been costed, including mooring, transmission and integration costs, as part of a production run and operating in a five device wave energy station situated off SW Shetland or Western Lewis. Estimated costs/kWh are presented for both the broad parametric costing method proposed by ETSU and based on 1986 cost ranges provided by them and also using a more detailed breakdown of device component costs based where possible on prices quoted for the closely similar components used in the 120m long linear Sea-Clam or on a quantities cost approach.

Parametric Costing

The parametric technique applicable to the circular Sea-Clam device uses cost ranges derived from the actual costs for completed ships and offshore structures apportioned into a small number of different categories by material weight, purpose or power rating and is deemed to be all inclusive of the costs of such factors as design, provision of construction facility, manufacture, installation and condition monitoring of machinery and the installation and mooring of device on site.

The appropriate cost heads and ranges are :-
Assembly, installation and mooring of steel structure : £1500-2500/tonne
Providing and installing ballast : £40-60/tonne
Manufacture and installation of on-board machinery : £8000-12000/tonne
Provision of transmission facilities : £100-200/kW

Costs :- in £1000s

	Low	High
Steel structure, 660tonnes	990	1650
Ballast, 400tonnes	16	24
On-board machinery, 40tonnes	320	480
Transmission, 2MW/device	200	400
Totals	1526	2554

Annual charges (capital 7.1% operating 5%)	184	309
Electrical output/year	5.52GWh	
Cost/kWh (1986 prices)	3.33p	5.60p

Component costing

The component costs have been based where possible on prices quoted by suppliers for the closely similar components used in the detailed costing of the 120m long linear Sea-Clam or on a quantities cost approach. Item costs were collected under 12 major cost centres, only the total cost (in £1000s) is presented here.

Total production cost/device	1650
Annual charges (7.1% capital and 5% operating)	200
Electrical output	5.52 GWh /year
Cost/kWh (1986 prices)	3.62p

The resultant predicted cost /kWh for electricity delivered to the grid at such a site lies in the range 3.3 - 5.6 p/kWh. This compares well with the 4 p/kWh achieved from the now proven, Norwegian prototype, cliff mounted oscillating water column, and the availablility of suitable sites is much greater for a floating device.

Even with the present reduction in oil prices, diesel generating cost for many island and coastal communities are from 5 - 18 p/kWh and thus small groups of circular clam devices, each with yearly average outputs up to 1 MW, could be very cost effective in many parts of the world. Furthermore predicted wave energy costs now appear to be close to those for future nuclear and coal generation where the demand for more safety and anti-pollution measures is only likely to increase.

Thus the SEA-Lanchester Energy Systems Group is putting forward proposals for a design, construction and testing programme of a 60 m diameter, circular SEA-Clam to the U.K. Department of Energy.

PROTOTYPE DEVELOPMENT PROGRAMME

The proposed development programme for a 60 m diameter, 7.5m deep, 2 MW rated prototype, would be for a six year period overall, with the following three main phases :-

(1) Performance optimisation and detailed design; comprising a model test programme and the detailed finalisation of prototype design.

The device productivity so far predicted has been based upon results from a single series of model tests with very little performance optimisation being carried out. However indications from some of the later tests imply that an optimisation of design flotation levels and subsequent control of air system content for changing sea states can considerably improve the energy absorption efficiency. Equally the proposed structural, mooring and power generation design used for costing purposes was simply a first attempt and although structurally and mechanically sound, was not in any way optimised in terms of structural cost efficiency.

Thus it would be reasonable to assume that a cost/kWh reduction of 10-20% might be achieved by such a design optimisation programme.

Time period :- 2 years. Cost :- £ 1 Million

(2) Prototype construction and test site preparation, including moorings, transmission cables and electrical shore station. The test site would probably be off Barvas bay on the Isle of Lewis.

Time period :- 1 year. Cost :- £ 4 Million

(3) Device instrumentation, installation and operational test programme.

Time period :- 3 years. Cost :- £ 2 Million

Total cost : £ 7 Million.

CONCLUSION

The predicted costs for electricity generation using the Circular SEA-Clam show a two to one improvement over the best costs predicted by the 1982 U.K. Wave Energy assessment report. Having achieved such a cost breakthrough, borne out by proven Norwegian prototype experience, it is apparent that the long term development of wave energy in the U.K. and the rest of the world should be re-examined.

The future surely holds more than the use of a few local schemes for isolated island and coastal communities. There is now a real possibility that wave energy can provide a considerable contribution to a post Chernobyl world energy scene, where renewable alternatives to nuclear and fossil fuel dominated generation will play an increasing part.

If the U.K., whose ideas and enthusiasm powered the initial research, is to be a part of this future development then it is important that we follow the example of Norway and Japan and proceed to a prototype design, construction and testing programme. For, as with the wind programme, such a step is essential if wave energy is to be properly evaluated and eventually to provide a meaningful contribution to the U.K. and world renewable energy development programme.

The Circular SEA-Clam, as a floating device, has the advantages of greater structural economy and site availability over sea-bed mounted systems and offers the most promising British way forward towards a cost effective utilisation of a large and as yet untapped source of renewable energy.

REFERENCES

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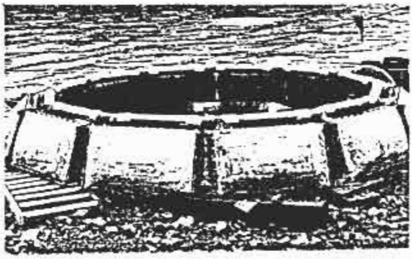

Figure 1 Model ready for launching

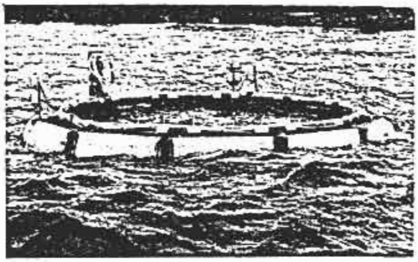

Figure 2 Model under test at Loch Ness

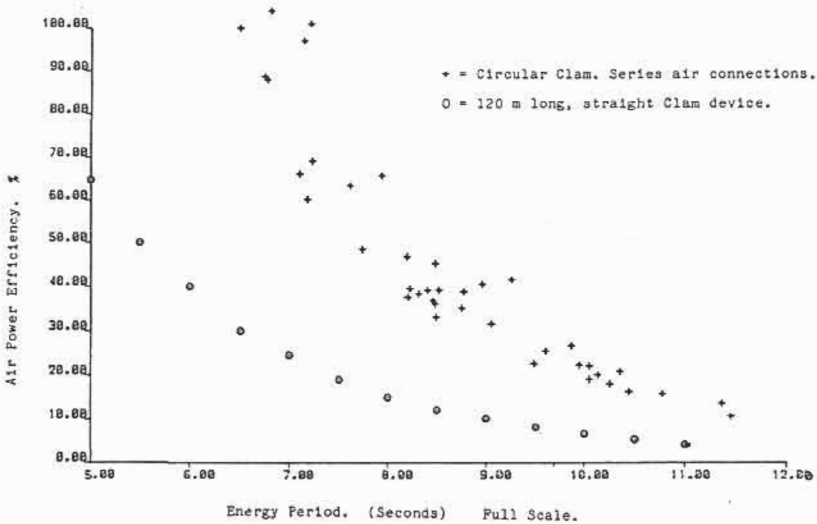

Figure 3 Model test efficiency results (Scaled to prototype size)