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AN ALTERNATIVE DESIGN OF THE SEA CLAM WAVE ENERGY CONVERTER

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ABSTRACT

The SEA Clam wave energy converter is a floating device to extract the energy from sea waves and convert it to electricity for transmission to land. The design of the SEA Clam is well established and is seen as the leading device arising out of the UK wave energy programme and having the most potential for further development. Present development effort is towards smaller 1 MW units suitable for the small scale requirements of islands and coastal communities.

This paper describes an alternative design of the SEA Clam which utilises the same component parts in a different configuration. The Circular SEA Clam, as it is called, is described in detail and its features discussed. Results of experimental work carried out in Loch Ness to determine performance and structural loading are given. Finally, improvements in design are suggested which should lead to a more viable and cost-effective device.

NOTATION

- D - Spine diameter
- d - Depth of spine
- w - Width of spine
- H - Wave height
- ε - Damping coefficient
- ρ - Density of sea water
- g - Gravitational constant
- F_s - Force in surge (horizontal)
- F_h - Force in heave (vertical)
- C_{fs} - Surge force coefficient (= 0.35)
- C_{fh} - Heave force coefficient (= 0.27)
- λ - Wavelength
- T - Tension in one spoke

INTRODUCTION

After seven years of research and development the current design of the SEA Clam wave energy device has stabilised and is ready for exploitation. It arose out of the U.K. national wave energy programme which in its final assessment in 1982 confirmed the SEA Clam as the leading device 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. Detail design is now in progress and plans are being made to build a demonstration prototype for testing off the U.K. coast.

Sea Energy Associates Limited and Coventry (Lanchester) Polytechnic have been involved in the UK national wave energy programme funded by the Department of Energy since its inception in 1975. Extensive design studies and sea trials have been carried out to evaluate structural designs, mooring configurations and power conversion systems which has resulted in an experienced team capable of pursuing all aspects of wave energy technology. By following the two basic themes of simplicity and overall cost effectiveness the SEA-Lanchester group have put together the most attractive concepts in wave energy to produce a successful device.

Although the current design of the SEA Clam was frozen in July 1981 a number of design variations have been explored and either rejected or shelved for further consideration in the future. The search has been for new ideas which would improve the productivity, reliability and cost-effectiveness of the total system without adding complexity or unproved technology. It appears that the present device configuration is a natural solution to the problem and that any further improvement in performance will come from the optimisation of the structural dimensions and the parameters of the power conversion system. However, there are alternative configurations of the SEA Clam which deserve investigation. This paper deals with an alternative spine structure and power conversion arrangement which, for obvious reasons, is named the Circular SEA Clam.

THE SEA CLAM WAVE ENERGY GENERATOR

The current design of the SEA Clam [1] can be classified as a spine-based pneumatic terminator. Devices utilising spines, that is long narrow structures, have been shown to be structurally efficient and, as such, have featured in the more cost effective devices in the U.K. national development programme. The use of air as a conversion fluid has many desirable properties including the ability to convert slow moving but large wave forces into high speed turbine driven electrical generation. Terminator is the name given to devices which face, or nearly face, the wave front and extract energy by terminating the wave in a matched load. Therefore, one can argue that a practical wave energy converter can be conceived as a floating spine terminator with a pneumatic wave absorbing face.

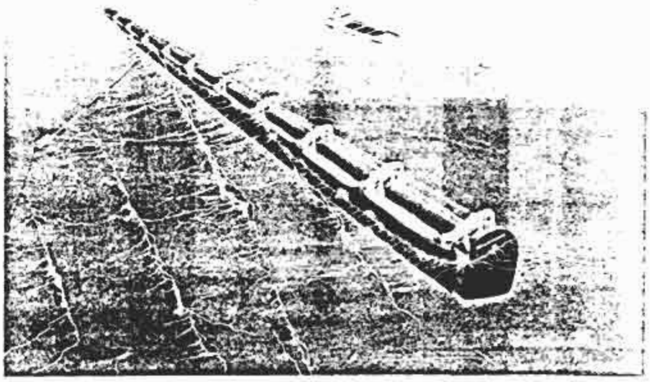

FIG. 1 ARTISTS IMPRESSION OF A SEA-CLAM WAVE ENERGY STATION

The SEA Clam, illustrated in Figure 1, is a device which 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 large scale wave energy stations 10 MW units would feature ten Clam elements on a 290 m long spine [1] whereas smaller 1.2 MW units, 120 m long, would be suitable for local supplies to island and coastal communities [2].

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 an air port in the top of the spine. The turbo-generator module is contained in the ducting which can be closed by a butterfly valve in the event of failure of the bag. The air turbines are of the self-rectifying "Wells" design [3] with a single stage 8 bladed rotor directly coupled to an alternator or induction generator. Power collection is by parallel connection of the generators to the local grid via a sea bed transmission cable. The mooring is a self-aligning single point system with a V-yoke connection to the spine. Extensive testing of SEA-Clam models both in an indoor wide tank and in the natural waves of Loch

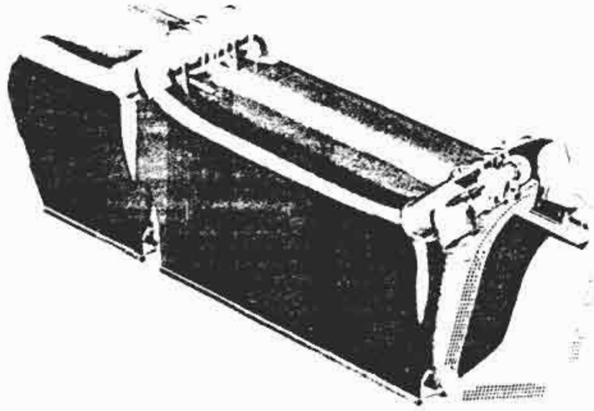

FIG. 2 CUTAWAY VIEW SHOWING SPINE STRUCTURE, FLEXIBLE AIR BAG AND TURBO-GENERATOR

Ness, Scotland has defined the structural behaviour and annual performance in the various sea states of possible wave energy sites. From this data, full scale designs have been produced, plant operation predicted and cost estimates made.

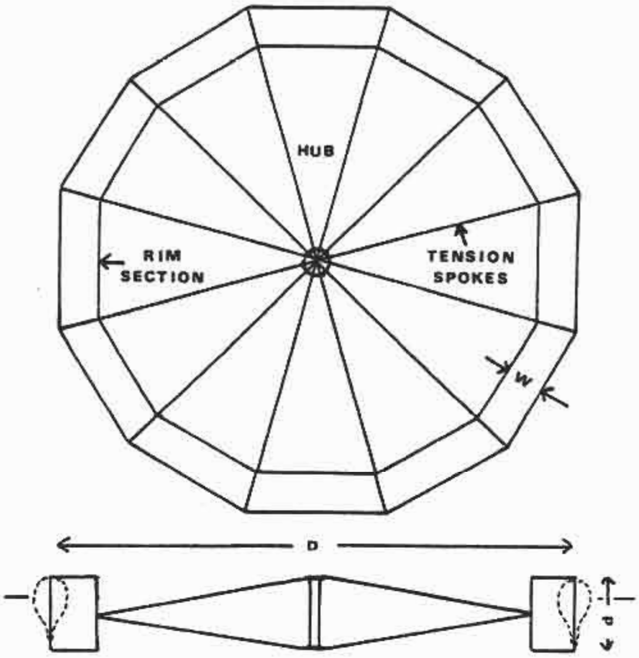

FIG. 3 CONFIGURATION OF CIRCULAR SEA CLAM

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 spoked wheel and comprises a number of rim sections held in compression by spokes from a central hub. Rigidity of the structure is provided by the rim modulus aided by the spoke frame in the horizontal plane and by the spoke triangulation in the vertical plane. A flexible air bag is fitted to the outer surface of each rim section and connected in series to its neighbours by a turbo-generator module to form a continuous air flow system around the spine. To activate the device the air system is pressurised to inflate the bags to a mean displacement in still water. During operation the bags interchange air through the turbines and develop power in response to the phased random waves.

A similar circular configuration called a ring-buoy was suggested but not pursued by Masuda [4] in 1974. The structure was 8-sided with 40 chambers used as oscillating water columns to extract wave energy.

The main features of this circular configuration and associated series power conversion system are:

1. The spoked wheel is a well known structural configuration noted for its minimum weight and cost effectiveness.
2. 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 excellent stability which does not rely on the properties of the section such as the centres of gravity and buoyancy.
3. The modular structure is amenable to low cost production techniques and eases transportation problems.
4. The rim structure is under compression and hence concrete is the natural choice of material. Spokes would be steel tendons with protective sleeving.
5. The series air bag connection separates the 'buoyancy' air from the 'power' air and allows the structure to be partitioned for good sea-keeping. Buoyancy air is the term used to describe the air which is only used to keep the structure afloat whereas power air describes the air used to transmit the power from the bag to the turbine.
6. 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 leads to a high ratio of air bag capacity to total device displacement which should improve performance and reduce costs.
7. The stability of the structure can be enhanced by making its diameter about half the 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.
8. Being omni-directional, the energy capture is independent of device alignment and hence unaffected by currents and mooring resonances. The structure is efficient in dealing with multi-directional seas.
9. 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 specification of a full scale Circular SEA Clam design for small scale applications would be:

Spine diameter	60 m
Spine depth	6 m
Spine width	2.4 m
No. of sections	12
Section length	15 m
No. of spokes	24
Displacement	2500 tonnes

The device as specified would use very similar air bags, turbo-generators and mooring system as in the SEA Clam and have the same power collection and transmission systems. Capital costs may be less than the equivalent SEA-Clam due to the lower dead weight displacement and a simplified air duct system. Maintenance costs may be higher because of the problem of access to power modules near the water line and the difficulties in closing off sections of the air system to isolate faults.

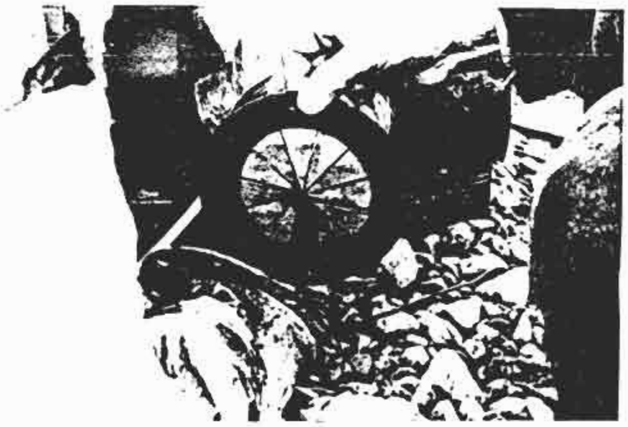

FIG. 4 STAR-CUT LINEAR AIR DAMPER

PERFORMANCE OF THE CIRCULAR SEA CLAM.

The capture efficiency of the Circular SEA Clam has been determined experimentally by testing instrumented air models, with representative linear damping characteristics, at 1/10th and 1/12th scale in Loch Ness. Two models of different construction were tested each having 12 flexible air bags interconnected by 12 air dampers. Measurement of the pressure drop across each calibrated damper during a 6 minute test period enabled the air power dissipated to be computed for each sea state.

The air dampers were fabricated from steel or beryllium copper shim, 0.003 in thick, by cutting a 12 point star as shown in Figure 4. The deflection of these star-cut dampers during operation results in a linear pressure-flow characteristic representative of a Wells turbine. Sea states were computed from the output of a capacitance type wave gauge mounted on a mast near to the test area.

The first model, 6m in diameter, was manufacture in plywood with PVC bags and had relatively soft dampers (ε = 8066 Ns m^{-5}). A more refined steel model, 5 m in diameter, with representative corded latex bags and stiffer dampers (ε = 8726 Ns m^{-5}), taking scale into account, was used for a second series of tests. Figures 5 and 6 show this model prior to launch and during testing.

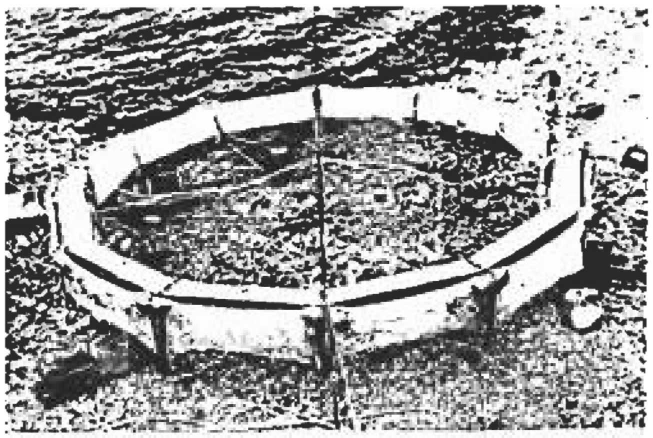

FIG. 5 CIRCULAR SEA CLAM READY FOR LAUNCHING

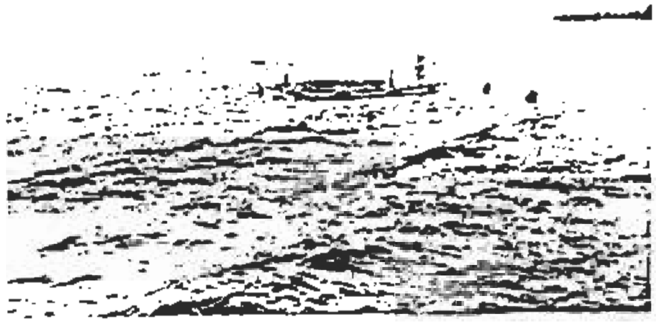

FIG. 6 CIRCULAR SEA CLAM TESTS ON LOCH NESS

Figures 7 and 8 show samples of the distribution of air power dissipated by each damper numbered around the clock. The single mooring rode was attached to the 12 o'clock position. 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. Power distribution appears to be independent of significant wave height but is very different for the two models. The relatively soft dampers of the 6 m model appears to encourage air flow towards the rear of the device whereas the stiffer dampers of the 5 m model concentrates the dissipation of air power at the front. This effect could be used to advantage in a full scale device for controlling power distribution in order to maximise output in high sea states or minimise plant operating in low sea states.

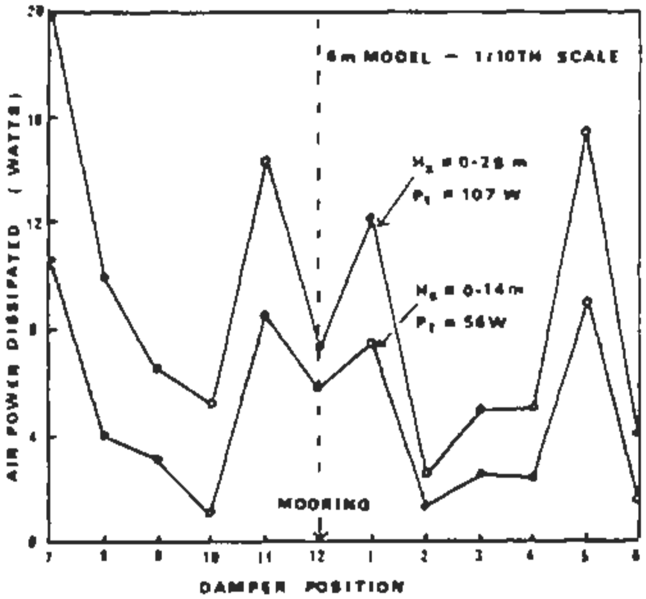

FIG. 7 AIR POWER DISTRIBUTION FOR 6 m MODEL OF CIRCULAR SEA CLAM

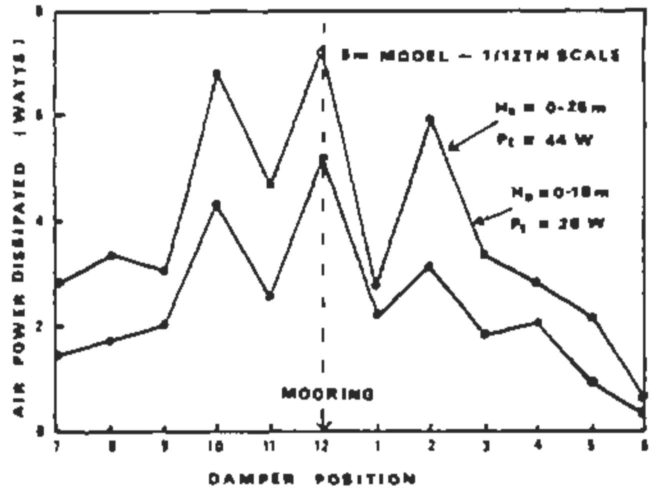

FIG. 8 AIR POWER DISTRIBUTION FOR 5 m MODEL OF CIRCULAR SEA CLAM

For practical reasons both models were only performance tested in a limited range of sea states and hence the maximum power capacity of the device was not determined. Some of the results obtained are given in Figure 9 which shows the total air power plotted against significant wave height after scaling up to a 60 m diameter full scale device. The curve is very similar to the results shown which are predicted by model testing for 100 m long straight SEA-Clams which have a maximum power capacity of around 1 MW. This suggests a similar air power rating for the Circular SEA Clam giving an annual average power delivered to land of 350 KW in North Atlantic seas.

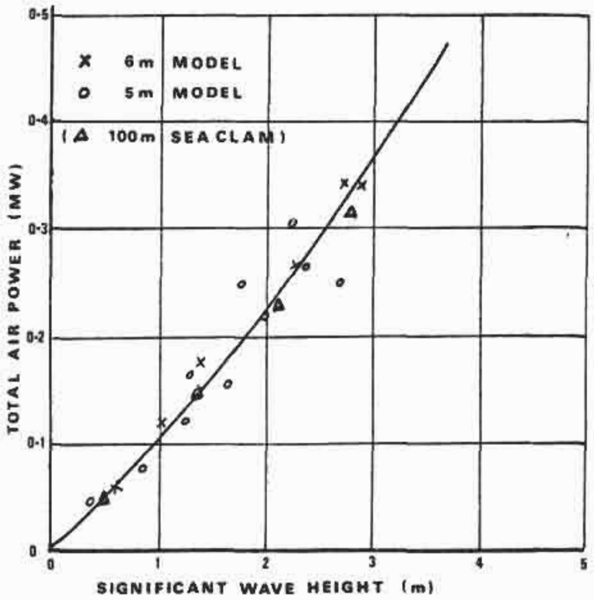

FIG. 9 SCALED AIR POWER RESULTS FOR 60 m DIAMETER CIRCULAR SEA CLAM

STRUCTURAL LOADING

Extensive testing of straight spine models in Loch Ness led to the development of a quasi-static analysis method [5] to determine wave induced bending moments. The underlying principles of this analysis can be applied to evaluate the wave loading on a circular spine in order to estimate the maximum spoke tensions and compressive stress in the rim structure. The basis of this analysis is a simple formula for deriving surge and heave forces:

$$F_s = \rho g\, C_{fs}\, d\, H \qquad \text{where } d = D/10$$
$$F_h = \rho g\, C_{fh}\, w\, H \qquad \text{Where } w = D/25$$

Maximum loading occurs in surge when $\lambda = 2D$ and in heave when $\lambda = D$ as illustrated in Figure 10. Taking $\lambda = 15\,H$ for the steepest wave condition, then

$$F_s = 46.7\, D^2 \text{ N/m}$$
$$F_h = 7.2\, D^2 \text{ N/m}$$

For the purposes of this calculation it can be assumed that the 12 sections are hinge jointed and hence one pair of spokes effectively supports one section, of length D/4, in surge. From the geometry of the structure the maximum wave induced tension is

$$T = \frac{F_s D \cos 15^\circ}{8} = 5.7\, D^3 \text{ N}$$

To maintain a tension in the spokes at all times a pre-tension equal to T has to be applied. Hence the maximum spoke tension will be 2T. Therefore, for the case of a 60 m diameter spine the variation in spoke tension will be ± 122 tonnes about a pre-tension of 122 tonnes. It can also be shown that the rim compression is equal to 3.86 times the spoke tension.

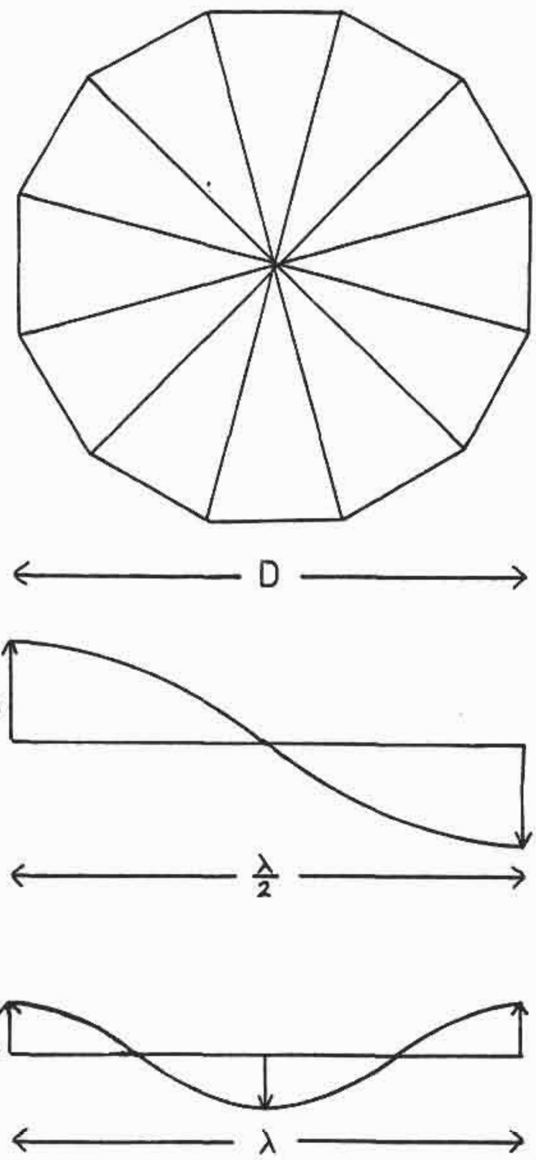

FIG. 10 WAVE PROFILES FOR MAXIMUM SURGE AND HEAVE LOADING

Analysis of the heave loading effects is difficult due to the interaction between the load taken by spoke triangulation and the heave modulus of the structure. In any case, the heave loading is relatively small and out of phase with the surge loading and hence does not contribute significantly to the maximum spoke tension.

To confirm the above analysis experimentally, both the 6 m and 5 m models were instrumented in order to measure spoke tensions in the leading 12 o'clock position and the starboard 3 o'clock position. Recordings were taken of the peak and trough variations about a mean pre-tension in the 4 spokes over 6 minute sample periods. Analysis of the results showed that the maximum excursions of individual spoke tensions in each record occurred in the leading 12 o'clock spokes with the 3 o'clock spoke tensions some 25% less.

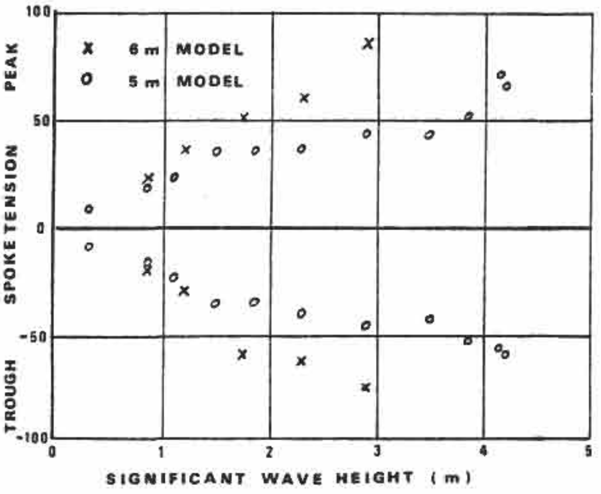

FIG. 11 SCALED SPOKE TENSION RESULTS FOR 60 m DIAMETER CIRCULAR SEA CLAM

Figure 11 shows the maximum peak and maximum trough spoke tensions which occurred during each record plotted against significant wave height. The results are well within the calculated tensions and show a tendency to level out with increasing wave height; a trend observed in bending moment and mooring force characteristics for straight spines. It is, therefore, reasonable to assume that the rather crude analysis given in this section is a useful guide to the wave induced loading in this type of structure.

FURTHER DEVELOPMENT OF THE CIRCULAR SEA CLAM

The experimental work described demonstrated that the new configuration of the SEA Clam performed satisfactorily without any undesirable behavioural features coming to light. This success naturally leads to further ideas on how to improve the performance and cost effectiveness of the device. Two major improvements to the device are now being studied.

The air bag design of both the SEA Clam and Circular SEA Clam is the 'inverted teardrop' which is well proved but a rather inefficient power absorber due to its inherent spring stiffness. For the SEA Clam this stiffness is used to advantage since it helps to give stability to the device by compensating for the unstable buoyancy of the air system. In the case of the Circular SEA Clam, instability of the air system is more than compensated by the stability of the circular structure. This indicates that the more efficient membrane bag with its low and controllable stiffness would significantly improve power output without incurring extra costs.

The drawback of the spoked wheel configuration in a sea environment is the fatigue and corrosion problems associated with the steel tendons used as spokes. Load variations in the spokes are excessive and vibration problems may arise; both of which will reduce the fatigue life of the tendons and end attachments. A simple method to overcome this problem is to use a rigid annulus manufactured in post-tensioned concrete. Simple calculations show that a concrete box section in the form of a circle would be a viable structure up to 100 m diameter. Construction of the structure would be in sections held in compression by post-tensioning cables wound around the perimeter. Life of a floating spine of this type should exceed 25 years without maintenance due to its excellent fatigue properties and corrosion resistance.

CONCLUSIONS

The circular SEA Clam has been shown to be a promising alternative to the established and well researched SEA Clam. There are a number of features of the design which have proved attractive and make the device worthy of further development. Important conclusions are:

1. The floating circular spine structure has been shown to be an extremely stable frame of reference for a wave energy converter. Its modular construction provides good sea-keeping qualities and is amenable to low cost production techniques.
2. The series power conversion system provides an elegant air flow arrangement which minimises the ducting requirements by utilising the air bags themselves.
3. Energy extraction is omni-directional and the device exhibits the properties of a terminator, attenuator and point absorber.
4. Limited performance tests of the device has shown it to be at least as good as the current SEA Clam design of equivalent displacement. Interesting effects have been observed on the distribution of air power absorbed for different damping conditions.
5. The structural loading limits have been predicted by a simple theory and backed up by experimental work. This confirms that a 60 m diameter Circular SEA Clam is a viable structure.
6. Two improvements on the proposed design have been suggested which would significantly improve the performance and structural design.

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