24

Paper 30

Reinforced rubber membranes for the 'Clam' wave energy device

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SYNOPSIS

The Sea Energy Associates 'Clam' wave energy device was initially designed as a long, straight, concrete spine carrying a number of double-sided air bags along one face. Tests at one-tenth scale were very encouraging. In its most recent, circular, version the spine is toroidal shaped and has 12 air cells around the outer circumference. A rubber membrane seals the air in each of these cells. Waves acting on the membranes compress the enclosed air and force it through air turbines and hence drive electrical generators. This structure is inherently more stable as a frame of reference than the straight-spine and model tests at one-fifthteenth scale together with structural and costing exercises suggest that the cost of the electrical output of a 60 m diameter full-scale device should be approx. 6 p/kWh. In the North Atlantic environment this device would be capable of providing a mean output of 600 kW, sufficient for a small community on a remote island.

The lifetime of the rubber membranes dominates the operational cost of the device. A 5 year life is regarded as the minimum acceptable and we are confident that this can be achieved by careful control of the elastic and strength properties of the membrane. This should lead to the membrane executing extreme volume changes without developing severe kinks. The reinforcing cords in the rubber membranes can be incorporated in a suitable manner to satisfy these requirements. The performance of the device strongly depends upon the matching of spring rate and turbine damping; the superior stability of the circular device permits the use of air cells with a controllable spring rate and hence allows optimum tuning of the device to the average wave climate.

INTRODUCTION

At the end of the United Kingdom national wave energy research and development programme in 1982, the straight 'Sea-Clam' emerged as the most promising device with predicted unit electricity costs in the range 6–9 p/kWh. The air bags for this device were described at the previous meeting of this conference[1].

This floating 'Sea-Clam', in common with the various oscillating water column (OWC) wave energy devices, uses the concept of water–air power conversion and the utilization of the 'Wells' self-rectifying air turbine. However, unlike the OWCs, the Sea-Clam uses rubber membrane bags to separate the water–air interface and produce a finite volume, closed air system with considerably increased band width of its response to the waves. This approach allows the use of a floating device without the necessity of the massive support structure required for open-air systems.

Since 1982, the Coventry Energy Systems Group, with support from our industrial sponsors, Sea Energy Associates, and some funding from the Department of Energy, have further developed the 'Clam' concept, moving from the straight, floating spine system to a circular, space frame torus which supports a number of inter-connected, membrane-faced air boxes on its outer surface.

The move to a circular Sea-Clam system has greatly increased the energy absorption efficiency, and productivity figures obtained from testing 1:15 scale models at the Loch Ness test site, combined with estimates of construction, installation and transmission costs, show the expected unit power cost to be in the range of 3.3–5.6 p/kWh for a small 10 MW station[2]. This cost reduction by a factor of 2 from the best straight spine designs compares well with the 4–5 p/kWh predicted from the Norwegian cliff-mounted OWC prototype now under trial.

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A major factor in the nearly 4-fold improvement in efficiency for the circular device is the increased stability which enables the use of low spring rate membrane-faced air cells rather than the high spring rate tear-drop bags used in the straight structure. This optimization of spring rate greatly improves the matching of energy transfer from wave to air.

The process of design, construction and testing of the rubber membrane material has been taking place in conjunction with Avon Rubber plc over a period of about 8 years.

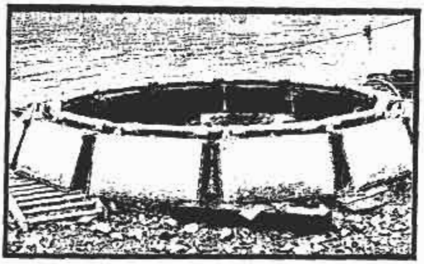

Fig. 1. A 1:15 scale model of the circular Clam ready for launching at Loch Ness
The model is 4 m in diameter and carries 12 air cells, each covered by a latex membrane around its circumference.

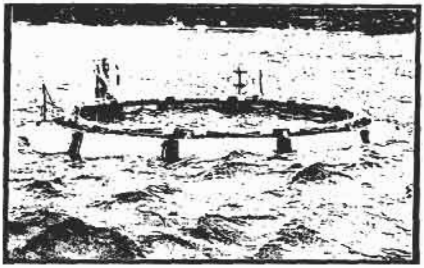

Fig. 2. The model deployed in the water in a typical inflation position
The instrumentation cables can be seen which convey signals from the various transducers back to the shore-based data logging computer.

Recently, a novel, 150 kW hydro-electric device using a similar water–air power conversion system via a cross-corded rubber membrane has been built by the Energy Systems Group. Experience now being gained from this use of a membrane interface of much the same size, strength and usage as is proposed for the Sea-Clam, is expected to verify the design concepts and predicted material life span.

THE CIRCULAR SEA-CLAM OPERATIONAL CONCEPT

The Sea-Clam is a moored, floating pneumatic wave energy device that uses the exchange of air, in a closed circuit dry air system between a series of flexible bags, to extract energy from sea waves. 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 air turbine-driven electrical generation.

The torus-shaped spine consists of 12 identical box sections, each with the front face covered by a cross-corded rubber membrane, joined together in a ring. This is illustrated by the photographs of a 1:15 scale model in Figs. 1 and 2. Each air cell is connected into a continuous air duct which forms a complete ring round the internal circumference of the device near the top level of the cell sections, thus allowing air interchange in either direction round the device.

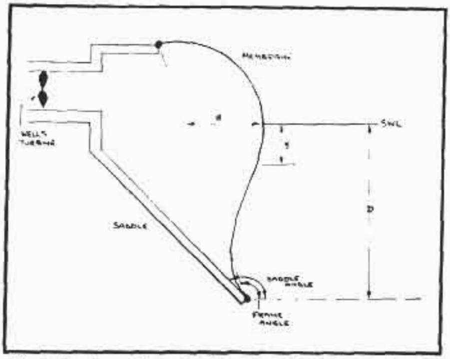

Fig. 3. A schematic vertical cross-section of one air cell for the Clam
The membrane is the curved line joining the two solid circles and has a prescribed fabric length. It is also constrained to roll up on the saddle of the cell. SWL = the still waterline. *D* and *y* are the depth of immersion and depth beneath SWL respectively. *B* is the beam at the SWL. Air expelled from the cell passes through the Wells turbine.

A single-stage Wells self-rectifying air turbine is located in the ducting from each cell and so extracts energy from the air flow whether it be from or to that particular cell. There is no requirement for the rectifying valves demanded by a conventional air turbine. With its 'linear air flow to pressure drop' characteristic, which allows close matching to both the small and large waves in any wave grouping, the Wells unit enables a high primary absorption efficiency to be achieved. It is particularly suitable for pressure drops of the order of a few metres of water.

Membrane requirements

Fig. 3 shows schematically one air membrane for the 'Clam'. The membranes are to be fabricated from rubber reinforced with cords of polyaramid fibre. The air chamber is a box with its front face covered by the membrane. Since the membranes are partially submerged, operation of the device is only possible if the system is slightly pressurized, when the membrane adopts a cross-sectional shape dictated by the air and water pressure regimes. Incident waves cause the water level to change and the membrane responds by rolling inwards (and outwards) on the 'saddle'.

The primary considerations in the specification of the membrane are those of strength, durability and spring rate. In practice the first two are mutually specified because of the need to maintain a buckle-free shape. Although we have only described the vertical plane here the membrane actually executes very large three-dimensional deflections.

For durability, the cords should not be loaded to any significant fraction of their ultimate strength for long cumulative periods, nor should they be permitted to bend through small radii, as would occur when the fabric buckles or kinks. Thus the membrane must adopt buckle-free shapes throughout an operational cycle of extreme air volume changes.

Ideally, then, we should have stretch in the longitudinal

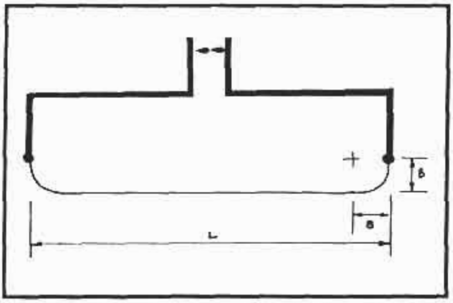

Fig. 4. A horizontal cross-section of a cell at the still water line
B is the beam calculated from the computer program. *L* is the horizontal length of the cell, taken as 15 m in this case.

direction of the membrane (parallel to the lower edge) to accommodate shape changes but in the vertical plane the fabric must be rather inelastic to avoid volumetric losses during operation and in effect support the vertical buoyancy forces. This anisotropy can be achieved by employing corded material fabricated with the cores laid at angles near to the vertical, as will be described later. Fig. 4 shows a horizontal cross-section of the cell at the still water line.

The air system spring rate is defined as the rate of change of air pressure with volume. The bags for the linear Clam design are double-sided and adopt an inflated shape which is dominated by hydrostatic forces producing spring rates of the order of 3 kPa/m^2 per metre of membrane length. It is not possible to modify the spring rate of these bags. This relatively high spring rate helps to maintain the stability of the device or reference frame but leads to rather restricted volume changes in response to incident waves.

On the circular spine, however, the inherent stability of the reference frame is greater and is not so readily compromised by the changing buoyancies of the operating membranes. It becomes possible then to use a smaller spine cross-section and membranes with a lower spring rate leading to a better capture efficiency.

The hydrodynamic efficiency is a product of the tuning efficiency and a function of device geometry. The tuning efficiency, E, is given by:

$$E = \frac{4 D_a D_t w^2}{\left[(SR - w^2 M)^2\right] + (2w D)^2}$$

where D is the sum of turbine (D_t) and added (D_a) damping, SR is the membrane spring rate, M is the sum of structural and added masses and w is the angular wave frequency.

Clearly, at any particular frequency (w) the tuning efficiency can be maximized by arranging for SR to equal $w^2 \cdot M$. Typically, a spring rate of 1 kPa/m^2 is required for the current reference design and we shall show that this can be achieved by using single-sided membranes and substantially controlling the spring rate by appropriate choice of frame and saddle angles.

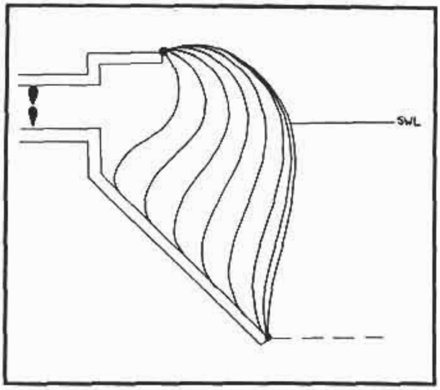

Fig. 5. A series of membrane profiles obtained by computing the shapes for a range of gauge pressures
All other parameters such as frame and saddle angles, depth of immersion, length of fabric are held constant.

COMPUTATIONAL METHOD TO PREDICT FABRIC TENSION AND SPRING RATE

A simple analytical method of determining the shapes shown in Fig. 3 is not possible and so we have computed the vertical cross-sectional shapes numerically using an iterative 'shooting' method. Calculations give contained air volume, vertical fabric tension and spring rate, etc.

Above the water line the radius of curvature is fixed by:

$$r = T/P \qquad (1)$$

where T is the vertical fabric tension and P is the air system gauge pressure. At any depth, y, below the water line the gauge pressure is reduced by the head of water, ypg, and so eqn. 1 becomes:

$$r = T / (P - ypg) \qquad (2)$$

The radius of curvature is thus continuously increasing as we descend from the water line until it becomes infinite at $P = ypg$ and subsequently becomes negative. By taking a fixed length of fabric in this cross-section (specifically 9.375 m and P = 18.75 kPa), and guessing the value of T and the initial orientation of the fabric, we have stepped along the length of the fabric, starting from the upper attachment, at each position computing the radius using eqns. 1 or 2, and hence calculating the co-ordinates for the next step. If the sequence fails to end at the lower attachment then a new value of T is chosen and the process repeated. The membrane is constrained to be on or above the saddle. In this way we have been able to establish the vertical cross-sectional shape for a range of combinations of P and immersion depth, and from them determine the corresponding fabric tension, contained air volume, freeboard, spring rate, beam at water line, etc.

Fig. 5 shows the computed shapes for a variety of gauge

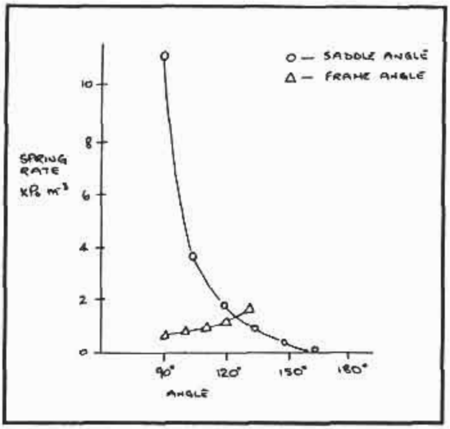

Fig. 6. The influence of saddle and frame angles on the cell spring rate

In both cases only the parameter plotted was varied. All other parameters were fixed as follows: fabric length 9.375 m; frame height 7.5 m; air pressure 18.75 Pa; depth of immersion 4.9 m; frame angle (when plotting saddle angle effect) 110 degrees; saddle angle (when plotting frame angle effect) 135 degrees.

Table 1. Circular Clam bag specification from computer program

In a typical application the following specification may be applied. *L*, horizontal length 15 m, frame height 7.5 m, frame angle 110°, saddle angle 135°, fabric length around vertical cross-section 9.375 m. *P*, internal air pressure 18.75 kPa. All parameters are reported in terms of unit bag length. SWL = still water line.

	Immersion		
	Min.	Mean	Max.
D, depth of immersion (m)	2.9	4.9	6.9
B, beam at SWL (m)	1.0	0.4	−1.8
C, horizontal perimeter (m)	16.1	15.5	17.1
V, air volume (m³)	21.4	13.0	2.0
SR, spring rate (kPa/m³)	7.3	1.2	1.3
T (vert.), fabric tension (kN/m)	39.0	23.0	7.0
T (horz.), fabric tension (kN/m)	18.7	7.5	2.3

pressures with a fixed water line, frame angle, saddle angle, fabric length, etc. Other combinations of theses parameters have revealed that the saddle angle is the most significant factor in determining the spring rate of the system. Fig. 6 illustrates the influence of frame angle and saddle angle on the spring rate.

Horizontal stretch

The horizontal cross-sectional shape of the membrane at the waterline may be imagined as a pair of quarter circles, with a radius equal to that of the beam calculated above (B) joined by a straight line. If the frontal horizontal length of the frame of the air chamber is L, then the perimeter of the membrane around the water line is C, where:

$$C = (L - 2B + \pi B)$$

As the volume or pressure in the membrane is altered the values of B and C will change. A typical set of results is given in Table 1 showing that the maximum change in C amounts to 2.0 m or 13%. In practice the horizontal fabric length may be arranged to be 15.5 m in order to reduce the maximum stretch to 10%.

The fabric tensions are well within the specification of the polyaramid cords and will therefore not compromise the lifetime of the membranes.

Table 1 actually shows the values computed for the system responding to a 4 m wave; when the immersion of the membrane ranges from 2.9 to 6.9 m and the swept air volume of the chamber would be 21.4–2.0 m³/metre. Plotted onto a P–V (pressure versus volume) diagram from more detailed results, this response executes an orbit containing an area equivalent to about 200 kJ/m. Such a wave in the North Atlantic would have an energy period of about 9 s and so the power absorbed would be approx. 200/9 or 22 kJ/m. The power content of waves is given by $H^2T/2$, i.e. our wave contains about 72 kW/m and therefore the device should have an efficiency of approximately 30% in a 9 s sea. This has been borne out by our Loch Ness trials at 1:15 scale and indeed appears to represent the 'swept volume' limitation of the air chambers. At lower energy periods the wave height is reduced and the device efficiency is substantially higher (70% at 7 s, 80–90% at 5–6 s).

MATERIAL STRENGTH USING POLYARAMID

Consider, for example one ply of 1 mm diameter polyaramid cords laid at an angle of +15 degrees to the vertical and a second ply at an angle of −15 degrees. Since the individual cords have a nominal ultimate strength of 500 N and there are 1000 cords/m then the strength of a single ply is 500 kN/m. Laid at an angle of 15 degrees to the vertical this gives a vertical strength of 933 kN/m ($= 2 \times 500 \times \cos 15 \times \cos 15$) for a fabric of two plies, when the vertical components of each cord and the number of cords per metre are taken into account. A similar calculation for the longitudinal direction gives 67 kN/m. This simple approach suggests that there is great strength in the vertical plane of the fabric but should leave it sufficiently elastic horizontally to accommodate shape changes. At this stage we have neglected the interaction between the two planes because of its mathematical complexity. Material manufactured in this manner and coated on both sides with 2 mm of a blend of natural and polybutadiene rubber would be strong enough for the anticipated duty.

MEASUREMENTS OF MEMBRANE SHAPE AND FABRIC TENSION

The largest circular 'Clam' membranes so far tested have been on the Loch Ness 1:15 scale model. The corded membranes adopted the expected shapes and executed the anticipated operational cycles, showing no evidence of fatigue due to geometry or strain problems. In order to scale the properties of the fabric[1] a much reduced cord density was employed and coated with liquid latex. Membranes (12) were fitted to the

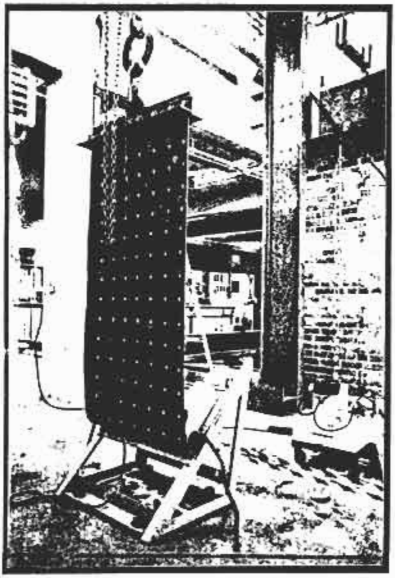

Fig. 7. Material test
A fabric, 0.7 m wide, reinforced with two plies of poly-aramid at ±15 degrees to the vertical. The sample has been subjected to a vertical tension of up to 70 kN/m. The floor fixing also serves as a clamp test.

performance model with excellent results for both shape and energy capture. Subsequent measurement of the spring rate suggests that the membrane was non-optimum. Our understanding of the influence of spring rate came after this trial had been completed and in a future programme we hope to re-test the model with a more carefully established spring rate. We have also tested some small laboratory membranes and obtained reasonable agreement with the computer modelling.

No direct strain gauging of these membranes has been carried out, but the work previously reported[1] on the bags for the straight Clam shows that predicted tensions were accurate and we therefore presume that the current predictions are adequate. Future models will be strain gauged to confirm the fabric tensions.

FULL-SCALE MATERIAL DEVELOPMENT

During the straight 'Clam' programme 1:6 and 1:2 scale bags were manufactured by Avon Rubber plc in nylon-reinforced rubber with cords at ±16 degrees. The smaller one was tested on a 1:6 scale model in Loch Ness and the larger one was statically tested in the laboratory by inverting it and filling it with water. Local strains of as much as 30% were observed. This was due to both the geometrical distortion of the cords (to angles greater than 16 degrees) and also to the stretch of the nylon cords themselves.

Polyaramid is now proposed as the reinforcing element because of its larger modulus and superior strength.

A novel low head hydro-electric device recently installed by the Energy Systems Group shares much of the technology with the 'Clam'. In particular it contains an air system which is separated from water by a membrane which has a similar construction to that required for the 'Clam'. This membrane is 32 m long, 6 m wide and is cross-corded to obtain anisotropic properties. In order to be able to design, manufacture and install this membrane a considerable amount of development of the technology has been accomplished which supports the wave energy application. Fig. 7 shows an edge clamp and material strength test where a sample of the fabric has been tensioned to over 70 kN/m in its 'strong' orientation. This exceeds the maximum tensions anticipated in the wave energy membranes.

CONCLUSION

The life of the corded fabrics in the applications described is not likely to be limited by the cyclical loading imposed on them during as much as 10 years operation. By careful choice of ply angle the membranes can execute full distortion cycles without compromising the cords. Separating water from air using such membranes permits the development of efficient energy extraction processes in wave climates such as those in the North Atlantic. By careful design the 'Clam' can be deployed in other wave climates.

ACKNOWLEDGEMENTS

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