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Mechanics and materials in the design of a buckling diaphragm wave energy converter

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ABSTRACT

The design of a flexible wave energy device with a spine shape diaphragm proposed by Sea Energy Associates Ltd. was analysed. The operation of the device involves reversible buckling of a diaphragm in both longitudinal and transverse directions. The design constraints of the diaphragm were identified and Cambridge Engineering Selection software was applied to select candidate materials for the diaphragm structure. Best candidates of materials were identified for both laboratory scale and industrial scale. The initial curvature of the diaphragm was analysed using the minimum energy principle. The theoretical predictions of transverse deflection and longitudinal radius of curvature were in good agreement with measurements taken on a 1/10th scale-model of the diaphragm structure.

1. Introduction

The need to explore and develop new renewable energy sources is well understood. Globally, we need to reduce our dependence of fossil fuels and to reduce our carbon emissions. The reduction of CO_2 emissions is not only driven by the desire to combat climate change but now forms part of UK legislation. The UK requires approximately 350 TW h/year of electricity, and with up to 840 TW h/year available in UK and Irish waters through wave action [1], meeting a significant proportion of the UK's electricity needs should be technically and economically viable. For the UK, wave and tidal marine renewable energy is seen as having the potential to provide 15–20% of current electricity demand within the timeframe of 2050, and is likely to have a similar impact globally [2]. The UK holds a leading position [3,4] in the new wave and tidal industry and it has the potential to become a major export sector for the UK [5].

However, many of the marine energy devices being developed are demonstration or prototype deployments, with only ten full-scale, grid-connected devices deployed by the end of 2011 [3]. Unlike in other sectors (marine current, tidal, wind) there is a lack of convergence of technology in the wave energy converter sector that can be ascribed to the different natures of wave resources around the world [6]. This diversity in technology means that there are fewer developers trying to solve the same problems than in other industries.

There also remain considerable risks associated with the industry, both from financial and technological points of view [1]. Some of the reasons for the slow start to the industry are attributed to high costs of deployment and operating offshore; lack of investment due to the current economic climate; high level of risk and survivability of device and components; long planning and consenting stages and uncertainty of the full cost of energy [1,2,7].

The economic viability of each wave energy converter (WEC) is determined by the amount of money that can be made once the capital and operations costs have been taken into account. This is usually expressed as LCOE (levelised cost of energy). The UK's Carbon Trust estimates that by 2050, the LCOE of ocean energy could be 15 pence/kW h. For comparison the LCOE for natural gas is approximately 8 pence/kW h [8,9]. Leijon et al. [10] note that the costs of development are driven by the highest energy sea states, the income derived from WECs is related to the commonest sea state.

Wave energy devices show little convergence of technology [1,2] and it is thought that continued innovation may allow costs to fall faster than for tidal technology, for which there is more convergence [2]. Based on this, the Carbon Trust suggests that there is potential for a step-change in wave energy technology [2]. Drew et al. [11] give a good review of wave energy converter types, noting that there are three broad categories (attenuators, point absorbers and terminators), with numerous operating principles. The European Marine Energy Centre [12] elaborates on the categorisation of the currently available WECs to include nine different types, which can be sorted

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Nomenclature

α	factor of end conditions in 3-point bending, 1 for simply supported, 4 for double clamped	B_1	initial width of the diaphragm
Δ	interval of measurement along the length	B_2	width of the spine
ΔL	longitudinal displacement of spine	C	deformation constant of structure
ΔP	contact pressure (or the air pressure it can seal)	E_1	elastic modulus of diaphragm
ε_1	maximum bending strain of diaphragm	E_2	elastic modulus of spine
ε_2	maximum bending strain of spine	I_1	second moment of bending
κ	curvature of spine	L_0	initial length of the diaphragm
e_1	elastic energy of diaphragm section	R_1	radius of curvature of diaphragm in transverse direction
e_2	elastic energy of spine	R_2	radius of curvature of spine in longitudinal direction
e_t	total elastic energy of the structure	P_1	load exerted by the spine onto the centre of the diaphragm section
h	deflection of diaphragm section	T	traction in the membrane
h_1	transverse deflection of diaphragm edge	T'	in-plane compression in diaphragm per unit length
h_2	transverse deflection of spine	V_2	volume of the spine
t_1	thickness of single diaphragm sheet	W	width of each diaphragm section
t_2	thickness of spine		

into three categories: shore-line, bottom-mounted and floating devices. More recently, Babarit et al. [13] undertook a numerical study of eight different wave energy device types to benchmark their performance in a variety of sea states.

Bottom-mounted devices such as Aquamarine's Oyster (surge converter) [14] incur high construction, installation and maintenance costs [15] due to the requirement for seabed anchoring and inefficient pumping systems. A principal advantage of pumping a working fluid, as with the Oyster, is that the power take-off mechanism can be separated and even placed onshore to reduce some of the maintenance costs. Semi-submerged attenuators such as Pelamis have advantages in ease of maintenance, since they can be towed to calmer waters to be repaired, but they may still incur high construction costs. Shore line devices, such as breakwater-mounted oscillating water columns present the cheapest option for maintenance and can be very robust but their response can be narrow banded if not actively controlled. Semi flexible floating bags containing compressed air to drive a turbine are called 'clams' [16]. These devices have low construction costs but are always mounted on some supporting structure. The all-fabric conical free-floating clam [17] uses a new principle that it shrinks as it sinks. This lengthens the resonance period, so that it can be tuned to long waves. The efficiency is yet to be proved.

Sea Energy Associates Ltd. (SEA Ltd.) is a device developer hoping to progress its design to the point of scale sea trials. Its device – the SeaWave – has been designed to obtain a more favourable cost of power. The SeaWave is intended to combine the advantage of semi-submerged attenuators, the separation of capture device and power take-off (PTO), as in the surge converters, and the low materials costs of the clam-type devices. By being a semi-submerged device, installation and maintenance costs should be lower than for a bottom-mounted device and its operating principle, which is a combination of attenuator and pump, relies on the wave celerity (phase velocity), which is faster than wave orbital velocity.

It is noted that the design and material selection are vital to the survivability and durability of all WECs [18,19]. To select the desirable materials requires full understanding of the mechanism, the design constraints and the operation environment. Therefore an introduction to the structure is provided in the following section.

2. SeaWave device

The SeaWave wave energy converter consists of a long flexible hose with a central diaphragm [20]. The structure takes the form of the skeleton of reptiles but it curves by stretching the spine instead of contracting the hose. It is a type of deployable structure. The diaphragm at the centre of the hose is pre-stressed by a central spine so that it buckles and forms a wave shape. The stiffness of the structure is tailored so that it can be coupled with a water wave, Fig. 1. By coupling to the surface, the crest of the diaphragm will be displaced along the device at the wave celerity. This motion of the diaphragm crests will move pockets of air along the hose to the end section where compression can occur by controlling the output flow rate. The pressurised air can then be used to run an air turbine to generate electricity. Compared to many other devices, this is a lightweight semi-submerged structure which will reduce deployment and maintenance costs. It has the potential to improve energy conversion efficiency due to the ability to adapt to the frequencies of the wave. The energy output relies on the volume of compressed air generated rather than the pressure. That means a thinner diaphragm and hose can be used so that less expensive materials can be used. Therefore the manufacturing cost of the device is expected to be cheaper than other wave energy devices.

The diaphragm will determine the performance and the service life of the structure in a large part. The basic structure of the diaphragm is made up of a series of diaphragm sections linked by a longitudinal spine at the centre and two strings or stiffeners on the edges to restrain the extension of the edges. When the central spine is pushed in, the diaphragm sections will bend in transverse while the spine buckles into a waveform. Several experimental models have been developed using various materials and designs by trial and error. A 1/10th laboratory scale model produced using plastics for both the diaphragm and spine with a PVC hose has been tested in the wave tank. Fracture of the spine has been a problem because it is a long structure. Another issue identified is the sealing between the diaphragm and the hose. To prevent air from flowing backward, a seal between the crest of the spine and the hose is required. The energy capture efficiency is directly proportional to the output air pressure achieved. Therefore sufficient in-plane stiffness is required of the diaphragm. On the other hand, this will increase the longitudinal bending stiffness of the device and hinder the coupling with the wave. A systematic analysis of the structure is needed to resolve the contradiction and to optimise the design before the device can be operated successfully.

During operation, the buckling of the diaphragm is reversed under the action of waves so that the bending of both the diaphragm and the spine is reversed. Therefore the structure is subjected to completely reversed stress. At WaveHub (a grid-connected facility in the UK where sea-trials can be undertaken), the most likely wave