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Modelling of the buckling of a diaphragm–spine structure for a wave energy converter

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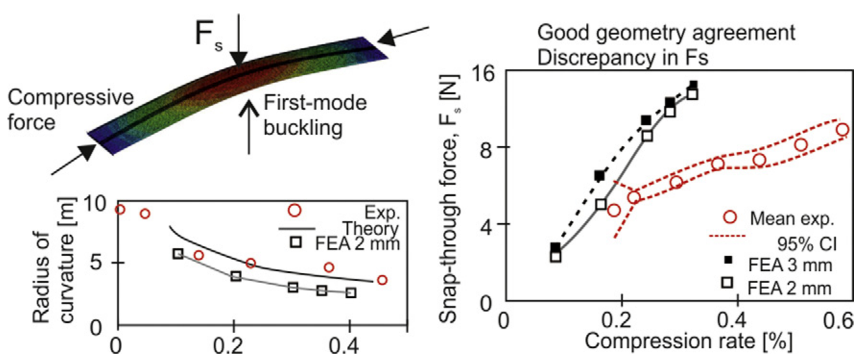
HIGHLIGHTS

- Snap-through force of 3D anisotropic layered buckled model wave energy converter can be computed with FEA
- Stiffer longitudinal components can result in more energy being stored in the structure (inferred from geometry)
- 0.5 J/m of device stored at a compression rate of 0.1%, equal to 25 kW for a full-scale device of 1m diameter, 1000 m length

GRAPHICAL ABSTRACT



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ABSTRACT

A wide range of wave energy converter (WEC) designs exists, and the SeaWave WEC uses an unstable buckled spine mode of operation. The SeaWave consists of a hose and buckled spine-diaphragm, which pumps air along the device under wave action. A physical model and finite element analysis (FEA) is compared to a previous theoretical model in this paper. The FE model was developed in ABAQUS 6.14 using shell, solid and contact elements and the analysis was done with a quasi-static approach to reduce the computational costs. The physical model was a scale version of the novel arrangement of the spine and diaphragm made from steel, polycarbonate and latex rubber. Geometry of the deformed device was investigated results showed an increase in transverse and longitudinal curvature as the compression rate increased. The FEA tended to overestimate the bending stiffness of the model, and hence the transverse curvature, because certain behaviours of the physical model were not captured. The force required to switch from one buckled state to another was measured both in the physical and FEA models and the potential energy storage was estimated to be 0.5 J/m of device at a compression rate of 0.1%.

1. Introduction

The wave energy industry lags behind the tidal energy industry in terms of technology convergence and readiness [1] and there are many different devices currently being developed. Wave energy converters (WECs) may be categorised by their operating principle, typically an oscillating body WEC will comprise parts moving relative to one another. The moving parts will translate the wave motion to the device machinery and either use such a motion to mechanically drive an on-board power take-off or use the motion to do work on a fluid, which can then be dealt with on shore. A comprehensive description of the

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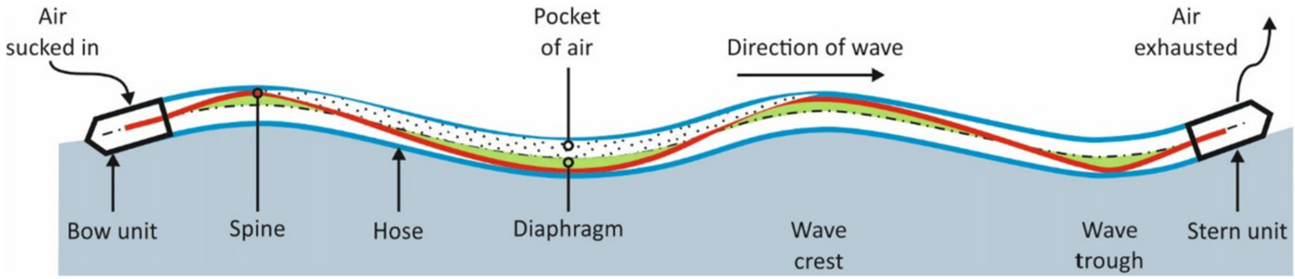

Fig. 1. Working principle of the SeaWave device under wave action [4].

different types of WEC is found on the EMEC website[1] and a review of the many different types of WEC and their necessary power equipment has been carried out by [2]. One of the difficulties facing the WEC industry is the number of concepts in development; the lack of design convergence has led to a large range of devices spanning concept designs to working prototypes. With no clear market leader in WEC technology, new designs are constantly being developed.

One such WEC is the SeaWave, a hose and spine attenuator-type device. The development of any new WEC is a multi-stage process and the aims and objectives of the development step progress with each of the stages. The SeaWave model described in this paper is a width-wise 1:10 scale model in its validation phase [3].

The two main elements of the SeaWave design are the post-buckled spine and the diaphragm-hose enclosure, Fig. 1. When buckled, the spine stores elastic energy that is transferred to the working fluid under wave action and so the mechanical characteristics of the spine are directly linked to the performance of the WEC. The hose entrains the working fluid, allowing it to be pumped along the device as the buckled spine oscillates. As long as the waves have a prevailing direction, the air pumping of the device will be in the up-wave to the down-wave direction. It is envisaged that the air will drive a turbine at the exhaust end of the device to transform the wave energy into electricity; however this is out of the scope of the current work. The device uses the unstable nature of the buckled spine as the mechanism for pumping.

1.1. The SeaWave as a hydrostat

The natural world is full of anisotropy in its structural elements [5] and hydrostats, which take their shape and stiffness from internal fluid pressure, are being investigated as a way to induce controllable anisotropy in composite materials [6]. FEA can also be used to investigate large deformations in anisotropic elastic materials [7]. The current design of the SeaWave has longitudinal and transverse stiffening elements resisting the compression of the buckled spine (see Section 3.1 for more details). If considered as a hydrostatic device, this arrangement allows the SeaWave to resist elongation and shortening but leaves it open to kinking. In contrast hydrostats with helical-crossed stiffening fibres are able to bend smoothly while restricting twisting around the long axis [8,9]. Preliminary experiments with a full sectional model (see for example [10]) revealed that the deformation of the device under wave action was very sensitive to the air pressure inside the model. This can be attributed in part to the longitudinal and transverse stiffening elements present in the design.

1.2. Buckling and bistability

Buckling is the out-of-plane deformation of a structure that has reached an elastic instability thanks to an in-plane compression [11]. Once buckled, a structure may exhibit several stable states, often symmetric, which represent minimum energy geometries.

Energy harvesting using bistable mechanisms has been investigated extensively but only at small scales. The recent trends and advances in buckled beams for smart structures have been discussed and the authors define two main disciplines: energy related and motion related applications [12]. Using the concept map of buckling-induced applications [12], the SeaWave falls into the hybrid form category since it is represents a prototype of a structure designed for bistability.

1.2.1. Buckling forces

In recent years, much research has been carried out on the buckling properties and energy use of beams, however this has been confined to the micro-machine regime. The relationship between the force and displacement is non-linear for buckled and post-buckled beams [13,14,15]. A variety of numerical methods are used to solve for loads and deformed configurations such as shooting methods based on boundary value problems [16,17], incremental displacement methods [14] or non-linear or large deformation FEA [13,18,19,20,21]. Hao and Mullins [21] note that displacement control is necessary in the set-up of the FEA model since the force is no longer a suitable control parameter in the negative stiffness range, which occurs between the critical buckling load and the location of maximum snap through force magnitude.

The maximum force needed to snap from one stable state to another was derived by Vangbo [22] for a clamped-clamped beam and he concluded that by taking into account the contraction of the beam, the maximum snap-through force and the activation energy were both lower. Additionally, snap-through behaviour has been found to be asymmetric if the beams are hinged [13,18]. The location of force application was investigated in relation to snap-through [23] and showed that shifted actuation could decrease or increase the activation energy depending on the geometry considered.

1.2.2. Energy harvesting

Research on the use of elastic instability has increased over the last decade and energy production forms a large part of this research [12] though this also tends to be at the micro-scale. A typical method to harvest energy is using piezo electric components, for which an applied mechanical strain will generate an electric charge in the component and vice versa. It has been noted that a large portion of research into vibration harvesting considers vibrations with a frequency >60 Hz possibly because the conversion to electricity is more efficient [24]. Harvesting of low frequency (<10 Hz) vibrations has been investigated and in many cases [24,25,26] the bistable mechanism is used to induce a mechanical up conversion of the frequency of vibration.

Despite a similarity in input frequencies (gravity and infra-gravity sea waves have frequencies in the range of 0.01 Hz to 1.00 Hz, the working principle of the SeaWave is not to up-convert mechanical vibrations to drive piezoelectric components. Rather, the induced wave motion is used to induce the snap-through as a method of pumping air.

[1] http://www.emec.org.uk/marine-energy/wave-devices/.