A feasibility study on Elastomeric-based WECs (ELASTO)

WES Structural Materials and Manufacturing Processes Stage 1 Public Report

The University of Edinburgh

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1. Project Introduction

This project has considered a compressible self-rectifying point absorber (SQ1) WEC. This is an axisymmetric heaving buoy with a completely flexible elastomeric bag as the deformable body connected to a rigid ballast container. The flexible bag is in the form of a fabric (reinforced elastomer) encased within an array of meridional tendons. When the bag is inflated, the fabric forms lobes between the tendons. This effectively keeps the tension in the fabric to a minimum, and the tendons become the major load-bearing members.

The project included four major activities: 1) Modelling of the device, 2) materials and manufacturing of samples and components, 3) testing of materials, manufactured samples and components, and 4) techno-economic analysis and roadmap for technology development.

The project's success is dependent on the following key measures: 1) Modelling of the flexible device to provide the required materials properties and load conditions to inform the materials and component testing parameters; 2) identification of promising materials and manufacturing samples and critical components; 3) static and fatigue testing of materials and manufactured components at relevant loads and conditions; 4) development of state-of-the-art techno-economic models and tools to assess the technology and provide a business case and commercialization strategy for the proposed technology.

2. Description of Project Technology

A frequency-domain model, developed by Kurniawan et al. (2017), was used to model the SQ1 wave energy device. The SQ1 device is a flexible air-filled bag connected to a rigid ballast that deforms under wave action and pumps air between flexible and rigid chambers across an air turbine. The performance of the device and tension in the tendons was investigated under a range of wave conditions. These simulations provided the load conditions under which the candidate materials and components were tested.

We have considered flexible structures manufactured with rubber-based materials which already have a track-record of long-term operation in sea water in fatigue-inducing conditions. We tested materials and components related to both the flexible membrane and load carrying tendons (natural rubber, nylon reinforced natural rubber membrane, Vectran rope and assembled Vectran rope and membrane components) by employing an extensive testing program both in terms of overall strength and fatigue resistance (guided by the simulation results). The usage of alternative materials (i.e. different from steel) in WECs could lead to potential significant reductions in structural cost, and hence have an impact in the overall LCOE. In this case, flexible structures manufactured with rubber-based materials were explored.

3. Scope of Work

The existing frequency-domain model was extended to include elasticity effects and was used to model the SQ1 device and provide data on the anticipated power outputs and loads at full scale. The modelling provided valuable information regarding the required material properties along with assisting in determining the LCOE for the device. This was necessary to evaluate the effect of material elasticity on device performance and loads. The predicted power output was compared with that of a rigid device which has equivalent mean geometry but produces power through heaving motion relative to the seabed, rather than through inflation and deflation.

We provided the conceptual designs of critical parts of the flexible assembly based on predicted loads in addition to initial estimates of safety factors and cost estimates for full-scale bags. The full-scale trial sections of flexible fabrication based on conceptual designs were manufactured. We performed static testing of two different membrane material types (Natural rubber and nylon reinforced natural rubber). The static testing of the reinforced membrane material was carried out in multiple orientations in order to identify the anisotropy of the material. Fatigue testing of reinforced membrane material coupons was completed and results were used for the LCOE. Testing included membrane materials immersed in salt water. We designed and built fibre rope testing fixtures and performed static and fatigue testing of Vectran rope coupons in addition to static testing of the bond between an assembled tendon and the membrane material. Dynamic mechanical thermal analysis of reinforced membrane material was used to investigate any material property changes within the operating conditions of the materials.

An LCOE tool was assembled and adapted to the present project. Generic cost data were gathered from various devices for real-world cost comparisons. A techno-economic assessment was performed through the computation of the Levelised Cost of Energy and alternative metrics. Furthermore, we carried out a scalability and sensitivity analysis and developed the technology roadmap and commercialisation strategy, focused on achieving the greatest deployment of rubber-based material on SQ1-like type of WEC devices.

4. *Project Achievements*

The frequency domain modelling showed that the resonant frequency of the SQ1 device could be lower than that of the equivalent rigid device. This would be beneficial as the length scale of the SQ1 device can be less than the rigid equivalent to achieve the same target wave frequency. This will save on materials and make it easier to transport, thus reducing cost. The frequency domain modelling also showed that the tendons should be constructed out of relatively inextensible material since there was a reduction in the performance of the device for more elastic materials.

We evolved a viable manufacturing method using hot vulcanising techniques which produced good results. We also found that some existing tyre manufacturing techniques show good promise for incorporation into a bag production method. As a result of tensile tests, it is clear that some details of the joining systems need to be improved. The fatigue testing of the membrane materials showed excellent results with the material being able to survive well beyond the expected lifetime of a WEC device. Static testing of the Vectran rope material showed that a combination of ropes constructed into a load bearing tendon will be capable of withstanding the peak loads generated during WEC operation. Fatigue testing of Vectran rope showed that if the rope suffers wear during loading the design life of the WEC may not be met. It would have been better if a fatigue testing rig for fibre rope could be created which did not introduce wear during the testing. Dynamic mechanical thermal analysis confirmed that it is unlikely to see any significant change in mechanical properties as a result of the range of operating temperatures the device is likely to operate in.

It was observed that the LCOE could reach values close to competitiveness under the optimistic scenarios examined. When assessing alternative metrics such as CWR, energy per unit mass and per unit area, ELASTO's results were found to be potentially competitive with WECs based on traditional materials. Cost reduction could be achieved from materials practices in other sectors, leading to potential commercially viable economic results. The sensitivity analysis showed that the most influential variables in the LCOE calculation were AEP, the cost of the bag and the discount rate. Improvement in the bag and its manufacturing would lead to considerable reductions in the overall LCOE. The uncertainty in the bag duration, which could have initially been depicted as a weakness, was found to be much less influential on the cost of energy. The chosen scale and power rating were found to be in the optimum range from the economic perspective. A roadmap highlighting the main barriers for the technology and the steps to be taken has been outlined.

5. Applicability to WEC Device Types

This work focused on the SQ1 device, which is a floating air bag formed of two volumes with a turbine in between. During a wave period, the device inflates and deflates due to changes in bag pressure forcing exchange of air between the two volumes and, hence, driving the turbine through a “breathing” action. The research may also be relevant to other air filled WEC devices incorporating flexible materials and diaphragms, such as the AWS-III concept, and to flexible dielectric elastomer generator (DEG) devices. The materials testing research may be of use for any WEC which incorporates a flexible material. This would mainly include inflatable bag devices such as the SQ1 and diaphragm devices.

6. Communications and Publicity Activity

- Conference presentation given regarding the frequency domain modelling aspect of the project: “Frequency domain modelling of a compressible wave energy device”, 4th PRIMaRE conference, Southampton, 06/07/2017

- Wave Energy Scotland Annual Conference, Edinburgh, 28 November 2017: Elevator Pitches. “A feasibility study on Elastomeric-based WECs (ELASTO)” Presentation by Prof. Vasileios Koutsos

7. Recommendations for Further Work

There are many parameters which affect the performance of the SQ1 device, but for simplicity some of these were set to a fixed value in this work. For example, the mean pressure in the bag was kept constant throughout this project, but it would be possible to tune this parameter to suit the sea state, and hence increase the performance of the device. Future work would be to develop the numerical model further and validate it at different scales in order to investigate the potential of this type of device in more detail.

Although computationally efficient, the frequency-domain model is a linear model and hence the predictions are only valid for small amplitude waves. To provide a more accurate estimation of device performance, the frequency-domain model was used to derive a time domain model, which allows non-linearities to be introduced. Although, we have progressed well with the time domain model, the calculations were proven to be much more complicated than we had envisaged; we plan to continue working in this direction and publish the results in an academic paper as they could be beneficial to the whole flexible WEC device community. A programme of scale model wave tank testing of the device would also aid further understanding of the nonlinear behaviour.

Larger areas of bag need to be manufactured to optimise joining integrity and the manufacturing process. Both membranes and manufactured sections should be fatigue tested biaxially and while immersed in order to more closely replicate real conditions. A complete (but reduced diameter) inflatable bag should be manufactured to enable inflation tests to be carried out. Further work should concentrate on fatigue testing, specifically focused on the bond between the membrane and the tendons and also the fatigue resistance of the tendon itself. Fatigue testing should be carried out on the components with an inflection point introduced during a fatigue cycle so as to more closely replicate the loading experienced in certain areas of the SQ1 device.

Further cost reductions need to be considered in the areas identified in the sensitivity analysis. The OPEX model could be upgraded with real (rather than estimated) data from the material testing at higher scales. More detailed analysis of the manufacturing, assembly, installation and decommissioning processes is needed. Furthermore, the deployment of the material in other WEC components and other industries and sectors can be considered. We need to reduce the LCOE; a route can be in the direction of increasing AEP and reducing the cost of the bag.

8. Useful References and Additional Data

Original frequency-domain model description is in the following reference: Kurniawan, A., Chaplin, J., Greaves, D., & Hann, M. (2017). Wave energy absorption by a floating air bag. *Journal of Fluid Mechanics, 812*, 294-320. doi:10.1017/jfm.2016.811