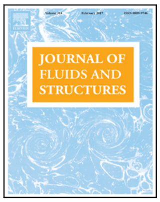
ARTICLE IN PRESS

Journal of Fluids and Structures ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs



A linear numerical model for analysing the hydroelastic response of a flexible electroactive wave energy converter

Aurélien Babarit [a,*], Jitendra Singh [a,1], Cécile Mélis [b], Ambroise Wattez [b], Philippe Jean [b]

[a] Ecole Centrale de Nantes - CNRS, 1 rue de la Noe, 44300 Nantes, France
[b] SBM Offshore, 24 avenue de Fontvieille, MC98007, Monaco

ARTICLE INFO

Article history:
Received 30 August 2016
Received in revised form 22 May 2017
Accepted 7 June 2017
Available online xxxx

Keywords:
Wave energy converter
Numerical modelling
Flexible tube
Electroactive polymer

ABSTRACT

In this paper, a linear mathematical and numerical model for analysing the dynamic response of a flexible electroactive wave energy converter is described. The Wave Energy Converter (WEC) is a floating elastic tube filled with slightly pressurised sea water. It is made of Electroactive Polymers (EAPs). Under simplifying assumptions, a set of governing equations is formulated for the flow inside the tube, the flow outside the tube and the behaviour of the tube wall. By combining them, the evolution of the flow velocity in the tube can be written as a wave equation. The corresponding eigenmodes of vibration are calculated. Then, using spectral decomposition, the equation of motion for the response of the tube in waves is derived. Experiments were carried out on a scale model of the wave energy converter in the wave tank of Ecole Centrale de Nantes in 2011. Numerical results are compared with experimental results in regular waves, showing rather good agreement, which validates the model and the initial modelling assumptions. Finally, estimates are made for the energy performance of a possible prototype.

1. Introduction

Over the four last decades, several hundred projects for ocean wave energy conversion have been initiated globally. A useful classification and explanation of the different working principles of Wave Energy Converters (WECs) can be found in Falcao (2009). In most cases, wave energy converters rely on one or several interconnected rigid bodies which serve as the primary wave absorbers. Since these bodies are rigid, they experience very large forces and stress concentrations in extreme seas. As a result, their structures and mooring systems are expensive, and hence also the cost of the energy they yield.

Recently, flexible or deformable WECs have been proposed, such as the Anaconda WEC (Farley and Rainey, 2011) or the SBM S3 WEC (Pollack and Jean, 2012). These devices consist of water-filled horizontal elastic tubes floating just beneath the sea surface. They are expected to have to cope with significantly smaller structural loads and mooring forces in extreme conditions in contrast with rigid WECs. Thus, it is expected that the cost of energy will be significantly smaller for these devices.

When ocean waves travel above a device like the Anaconda WEC or the SBM S3 WEC, see Fig. 1, they apply a time-varying pressure on the tube wall which induces local changes in diameter. This effect creates bulge waves in the tube. The work

---

[*] Corresponding author.
E-mail addresses: aurelien.babarit@ec-nantes.fr (A. Babarit), vishist.jiten@gmail.com (J. Singh), cecile.melis@sbmoffshore.com (C. Mélis), ambroise.wattez@sbmoffshore.com (A. Wattez), philippe.jean@sbmoffshore.com (P. Jean).

[1] Now with IBM.

http://dx.doi.org/10.1016/j.jfluidstructs.2017.06.003
0889-9746/

Please cite this article in press as: Babarit, A., et al., A linear numerical model for analysing the hydroelastic response of a flexible electroactive wave energy converter. Journal of Fluids and Structures (2017), http://dx.doi.org/10.1016/j.jfluidstructs.2017.06.003.

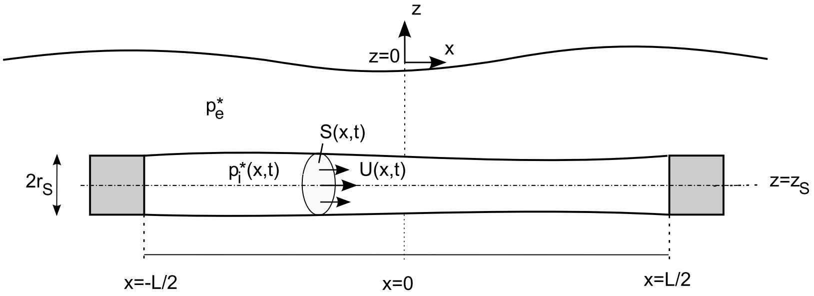


Fig. 1. Submerged elastic tube in waves.

done by the pressure differential applied on the radial moving tube surface is the energy harvested from the ocean waves. A major problem is how to convert the harvested power to useful output power. For the Anaconda WEC, it was proposed to use power take-off (PTO) systems composed of hydraulic valves, hydraulic accumulators and turbines. The power take-off can be located at the stern of the tube or distributed along the tube (Farley et al., 2012). In the SBM S3 WEC, the PTO consists of rings of electroactive polymers (EAP) distributed along the tube (Jean et al., 2012). Energy harvesting is achieved through the deformation of the tube, thanks to the electroactive properties of the EAP rings. One can note that the use of electroactive material in the context of wave energy conversion had previously been proposed by Chiba et al. (2008), but with a different implementation.

Theoretical one-dimensional models for the dynamic response of the Anaconda WEC have been proposed in Farley et al. (2012) and in Chaplin et al. (2012). In Farley et al. (2012), the theoretical model predicts that the bulge wave amplitude grows linearly along the tube. Comparisons of numerical predictions with experimental results show fair agreement provided that losses in the tube wall and in the radiated wave field are taken into account. Distensibility and losses were calibrated against the experiments. In Chaplin et al. (2012), the proposed model is more comprehensive. It takes into account the boundary conditions and the power take-off. At the bow, the condition is a no-flow condition. At the stern, the condition is a relationship between the flow and the pressure which depends on the impedance of the power take-off system. A general solution for bulge wave propagation is given which includes forward and backward propagative terms (whereas there is only a forward propagative term in the solution of Farley et al., 2012). Experiments with a flexible tube are described. Comparisons of theoretical and experimental results show good agreement for absorbed power performance (after calibration of the losses). For wave components, despite strong similarities between experimental and predicted data, quantitative agreement is not very good.

In the present study, the focus is on the SBM S3 WEC. For this particular wave energy converter, the models that were derived for the Anaconda WEC are not suitable for several reasons. Firstly, the boundary conditions are different. Indeed, the condition at the stern is a no-flow condition in case of the SBM S3 WEC. The tube is also allowed to move horizontally whereas the models developed for the Anaconda WEC assumes that the device is fixed. Secondly, the longitudinal tension is not taken into account in the models of the Anaconda WEC. In Chaplin et al. (2012), it is neglected because it was found that it has a small effect on the distensibility. For the SBM S3 WEC, we found that it is critical for matching the boundary conditions for the tube section (no deformations at both ends of the tube) and for achieving good agreement between experimental and predicted eigenperiods. Thirdly, the models for the Anaconda WEC require calibration of the distensibility and losses using experimental data. Thus the model is not suitable for prediction of the power performance of a full scale device. Finally, quantitative agreement for the wave components is not very good in Chaplin et al. (2012). This is an issue for the SBM S3 WEC because power absorption occurs at the EAP rings which are distributed along the tubes. Errors on the amplitudes of the wave components would transfer directly to errors of the same order of magnitude in power absorption performance.

Therefore, to assess and optimise the performance of the SBM S3 device, one needs a model that rectifies the deficiencies of the models of Farley et al. (2012) or Chaplin et al. (2012), which is the primary aim of this study. The proposed mathematical and numerical model is described in Sections 2 and 3. The model is validated against experimental results in Section 5 which are described in Section 4. Using the numerical model, preliminary estimates of power absorption potential are made and provided in Section 6.

2. Governing equations

In this section, governing equations are derived for all the aspects that need to be taken into account in the numerical model of the device. Thus, sub-models are derived for describing the behaviour of the fluid inside the tube (inner flow problem), outside the tube (outer flow problem) and the motion of the tube and its wall (structural problem).

The modelling problem central to this study has clear similarities with the modelling of blood flow in arteries (Formaggia et al., 2003). However, there are significant differences, namely the coupling with the outer flow, the boundary conditions (in this study the tube is closed at both ends whereas there are flow conditions for blood flow in arteries) and the considerably greater time and length scales.

Please cite this article in press as: Babarit, A., et al., A linear numerical model for analysing the hydroelastic response of a flexible electroactive wave energy converter. Journal of Fluids and Structures (2017), http://dx.doi.org/10.1016/j.jfluidstructs.2017.06.003.