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Interaction of surface waves with an actuated submerged flexible plate: Optimization for wave energy extraction

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ABSTRACT

We investigate the interaction of linear surface waves with a submerged wave energy converter which consists of a submerged flexible plate actuated by one (or more) units of power take off (PTO), each modeled as a combination of a linear spring and a linear damper. We develop a wave-flexible structure interaction model through modal decomposition of the structure deformations, and use Boundary Element Method to find hydrodynamic coefficients of each deformation mode of the structure. We validate our methodology with existing analytical results of hydro-elasticity. We then perform a case study and obtain the maximum efficiency (or Capture Width Ratio (CWR)) of our wave energy converter when excited by monochromatic waves through a comprehensive parametric study of the device parameters (e.g. rigidity of the plate, and location and characteristics of the PTO units). In the absence of viscous effects, the device can reach an efficiency as high as 80%. We find that the efficiency is more sensitive to the location of the PTOs than to their damping coefficients. For a range of plate length to wavelength ratios (close to unity) and with a single PTO unit, the optimal PTO location is past the middle of the plate (along the incident wave direction). This location is nearly independent of the rigidity of the plate although the resulting CWR depends on the rigidity. When two PTO units are used the optimal configuration of PTOs depends on the plate's aspect ratio and its placement with respect to the incident wave: the two PTOs may need to be at the same location, lined up along the direction of wave propagation, or placed side-by-side perpendicular to the direction of the wave propagation.

1. Introduction

Ocean waves arriving at a shoreline constitute simultaneously a threat of degradation of coastal infrastructures and an opportunity for energy harnessing. The use of flexible membranes as wave barriers for the shore protection has been extensively addressed in previous studies. Early work in attempting to reflect waves mainly dealt with inextensible and vertical flexible membrane, possibly attached to a buoy at its top and hinged to the seafloor (Lee and Chen, 1990; Thompson, 1991; Cho and Kim, 1998; Ul-Hassan et al., 2009; Chakraborty and Mandal, 2014). These studies essentially use the two-dimensional linear hydro-elastic theory to formulate the problem. Analytical methods are mainly based on eigenfunction expansion while numerical simulations use Boundary Element Method or Finite Element Method. Supported by experiments, the aforementioned studies showed that a flexible vertical membrane can be an effective passive breakwater due to its

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ability to resonate and reflect waves at different frequencies corresponding to its natural modes. Later designs of wave barriers feature porosity on the structures. Therefore, the flexible membrane cannot only scatter and reflect the incoming wave, but also dissipate part of the otherwise transmitted wave energy (Cho and Kim, 2000; Chan and Lee, 2001). While these studies deal with a single structure, the case of multiple vertical flexible membranes moored to the seafloor has also been investigated in the quest for a higher wave blocking efficiency. It was found that dual membrane breakwaters perform significantly (more than twice) better at reflecting waves than a single membrane, for both normal and oblique incident waves (Cho et al., 1998). While this remarkable result was obtained in the asymmetric configuration, i.e when each membrane has a different in-plane tension, the reflection performance is reduced in the symmetric case.

Despite their efficiency, such vertical structures in the near shore region of oceans can potentially prevent the circulation of currents in addition to causing animal entanglement, thus influencing the ecosystem. For these reasons, other configurations have been tested and proved to be remarkable wave barriers as well. For instance, through the method of eigenfunction matching, it was shown properly tuned horizontal membranes can generate motion-induced waves that cancel the otherwise transmitted waves (Cho and Kim, 1998). Depending on the membrane parameters, a total reflection configuration can be reached for some incident wave frequencies. Later studies show that adding structural porosity helps reduce waves transmission as well as plate deflection and hydrodynamic loads on the membrane by increasing viscous dissipation (Cho and Kim, 2000; Behera and Sahoo, 2015; Koley and Sahoo, 2016).

Therefore, the bulk of studies concerning hydroelastic interaction of deformable structures with waves have regard with shore protection. However, as mentioned earlier, incoming waves also represent a large and reliable source of energy (Cornett, 2008; Mork et al., 2010) that could be harnessed and converted into useful electricity rather than dissipated by perforated structures. To this end, the past decade has witnessed the development of several wave energy converters (WEC) with various operating principles. Despite many WECs made of rigid elements interacting with the incoming waves (Falnes, 2007; Falcao, 2010), the use of flexible bodies for wave energy conversion is not new (Newman, 1979; Farley, 1982). From the start, the motivation for deformable structures was to enhance the performance of WECs by overcoming some intrinsic deficiencies of conventional systems (a single resonance frequency for instance). One of such devices is the "Wave Carpet" (Alam, 2012b), a WEC design inspired by the visco-elastic behavior of muddy seafloors which dissipate the energy of waves arriving a shoreline (Sheremet and Stone, 2003). The "Wave Carpet" device consists in a long submerged flexible and elastic plate equipped with equally spaced power take-off (PTO) units, comprising springs and dampers, to harvest energy. This plate can bend under the action of the wave-induced pressure difference above and below its surface.

There are several advantages for this novel design. First, it can be tuned and designed to perform well either for shore protection (wave reflection) or for energy conversion of the transmitted waves. Secondly, in terms of the operational frequency range, flexible systems normally are more appropriate for wider range of frequencies since they contain multiple resonance frequencies. This device can thus be more fitting for ocean waves which are usually polychromatic. Note that other WECs with this particular feature have also been recently developed (Choplain, 2012; Chaplain et al., 2012; Mei, 2014; Babarit et al., 2015). Third, since the Wave Carpet is placed under the water surface, it is more survivable under the action strong waves and during storms. Moreover, the scalability of a concept being another crucial factor in ocean energy devices, the Wave Carpet is modular. Last, in term of visual appearance, it is also unarguably better than the WECs operating at the surface. However, note that in previous analytical studies (Alam, 2012b, a), the carpet was directly mounted on the seafloor and the fluid–solid hydrodynamic interaction was solved for a continuous viscoelastic boundary at the bottom of the sea. In those studies, the carpet flexural stiffness as well as its inertia has been ignored and the WEC is assumed to have an infinite width. Using a finite size Wave Carpet and finite number of localized PTOs in a laboratory wave tank (Börner and Alam, 2015), a real-time hybrid simulation has been performed in order to optimize the power conversion from incoming monochromatic waves. In that work, the design parameters being varied in the optimization procedure were the PTOs damping coefficient and their location along the carpet length. While that study provided optimization parameters for a given setup, it would be very costly if one were to apply such real-time hybrid simulation systematically to various configurations and sea states.

The present study aims at providing a reliable wave-structure model that can be systematically used for the optimization of the Wave Carpet in the limit of linear waves. Specifically, we here extend the aforementioned studies on hydro-elastic interaction of the case where the horizontal flexible structure is modified by application of a finite number of localized PTO units. To this end, we work in the frequency domain and make use of the so-called normal mode approach which is widely known in vibration problems and can be extended to study the interaction between waves and deformable bodies (Newman, 1994). Here, we formulate the problem in three-dimension in order to investigate the effects of non-zero angles of the incident waves on the device optimal parameters. The methodology described in this paper can be straightforwardly extended to irregular waves since real seas are known to be well described as superposition of linear monochromatic waves (Falnes, 2004).

This paper is organized as follows. We first describe the wave-structure theoretical model and its numerical implementation. In the latter section, we particularly take care of comparing and validating preliminary results with other approaches. Next, we present the results of the modal analysis of the wave-plate system (which acts as a global oscillator at the frequency of the incoming wave) and analyze the influence of the free parameters, being the angle of the incident wave, the number of PTO units, their locations, their damping coefficient, the plate bending modulus, the plate length and aspect ratio, and the in-plane tension on the structure, on the performance of the system.