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Three-float broad-band resonant line absorber with surge for wave energy conversion

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ABSTRACT

A line absorber consisting of three cylindrical floats is shown to have high crest capture widths for wave energy conversion across a broad band of frequencies. The bow, mid and stern floats are small, medium and large respectively; the floats are spaced about half a wavelength apart so that forces and motion of adjacent floats are substantially in anti-phase. The bow and mid float are rigidly connected by a beam and a beam from the stern float is connected to a hinge above the mid float for power take off. The draft of the stern float enables heave resonance at a prominent wave frequency and the smaller draft of the mid float provides resonance at a somewhat lower frequency. Experimental results at about 1:8 scale show capture widths greater than 25% of a wavelength in regular waves and greater than 20% of a wavelength in irregular waves across a broad range of wave periods. A time-stepping model for regular waves with coefficients from linear diffraction theory showed similar power prediction with a generic drag coefficient of 1.8. The model shows the importance of surge forcing and heave resonance. The model also shows that reducing drag coefficient will increase capture width.

1. Introduction

Many devices have been developed for wave energy extraction and principles are well described in Ref. [4] and more recently in Ref. [2]. Here we give a brief review to provide some context for this study. Point absorbers are single devices moving in heave, pitch or surge or some combination. Resonance amplifies power generation such that the theoretical maxima in terms of capture width (of a wave crest) are $1/2\pi$, $1/\pi$ and $1/\pi$ wavelengths respectively. Examples of heaving point absorbers are Wavebob [23], WaveStar [24], Archimedes Wave Swing [15], CETO [17], Buldra [22], Manchester Bobber [10]; examples of surging and pitching devices are PS Frog [6], Oyster [14] and Langlee [19]. Response to resonance is generally narrow band although this may be broadened through latching control, e.g. Ref. [1]. To be effective most devices are designed for deployment within arrays, either separately tethered to the bed or from a fixed platform. In another form of point absorption wave motion is transmitted to an air column, driving oscillatory air motion through a turbine, usually a Wells turbine rotating in one direction, e.g. Mighty Whale [16], Ocean Energy [20].

Another concept is based on line absorption with Pelamis [21] the most notable example. The device consists of a number of longitudinal cylindrical segments, aligned with the wave direction, connected by hinges at which power is taken off. A segment is typically half a wavelength long so the pitching motion is maximised. The device is floating with a mooring and is usually about two wavelengths long. This has the potential to exceed the capture widths of single point absorber. A different form of line absorber known as Anaconda [18] has the form of a flexible submerged tube designed so that a bulge of water in the tube forms due to the wave pressure and travels at the wave speed, effectively in resonance.

Some basic principles become apparent. Single devices are of limited value for large scale generation. Resonance is desirable to optimise power generation but this is a narrow band process for a single mode and geometry. In terms of engineering practicality floating moored systems are relatively easy to deploy and maintain relative to systems with fixed supporting structures. Power take off systems may take various forms with hydraulic systems quite mature, although accessibility above water level is desirable for maintenance. In this study we consider how a line absorber may accommodate various modes of motion with a range of resonance

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frequencies spanning predominant values of waves. To enable this three floats are used acting predominantly in anti-phase to maximise relative motion between floats and hence power output.

2. Design principles

We are here concerned with offshore wave energy conversion rather than nearshore where the resource is less; typically water depths would be at least 20 m. A moored floating system is required as fixed platforms would be prohibitively expensive in these depths. One question is: what is the greatest power which may be generated from a floating system unlimited by size or mass given that forcing frequency is determined by waves and power may only be maximised through large float mass. It is realised that power conversion is enhanced by resonance and, while this is straightforward for a single wave frequency, effective wave energy conversion requires resonance enhancement across the range of predominant wave frequencies of the chosen area, typically peak periods of 6–8 s for wind driven waves and 9–12 s for swell waves. Different modes of motion may be excited; here we are concerned with heave, pitch and surge and these may have different resonant frequencies for each float and the excitation of different modes may be superimposed further enhancing power generation. It is recognised that surge will not resonate without hydrodynamic stiffness (due to hydrostatic pressure restoring force) but forcing could enhance power output. The converter should be effective in irregular (random), directional seas and this is consistent with the requirement of resonant response with different modes over a range of regular wave frequencies, at least on the basis of linear superposition.

In order for a large floating mass to generate power it must be connected to another float or to the sea bed with power resulting from the relative motion. Here we are concerned with a floating, moored system for ease of deployment so the motion must be relative to another float and this is maximised if the motions are in anti-phase. The spacing between two floats should thus be about half the predominant wavelength. It will be shown that pitch excitation on a single float is small relative to heave and surge. In order to optimise geometry for power two floats moving only in heave in anti-phase were initially considered. Subsequently a system comprising three floats excited in heave, pitch and surge was analysed. A linear analysis with diffraction coefficients from WAMIT [13] is described in the Appendix, giving an analytical solution for power and response for two floats in heave.

For floats to be moving in anti-phase forcing is likely to be effective over a length of up to $L/4$ where L is wavelength. As the maximum diameter will have maximum mass and hence generate maximum force and power the diameter of the stern float was chosen to be approximately $L/4$; the force will be effectively inertial and determined by the wave phase. This simple criterion is not refined further in the present study. Experiments will be described which have been undertaken in a large basin (35 m long × 15.5 m wide and 2.9 m deep) with wave periods varying around 2.4 s, from 2 s to 3.2 s. We thus use these conditions to describe the dimensions of the geometric configurations. The large stern float is given a diameter of 2 m and a draft of 0.95 m giving a heave resonance period of 2.4 s in isolation (using added mass from diffraction theory). We want the floating system to head naturally (passively) into the wave direction and it is desirable for the stern float to be bigger than the bow float hence giving a larger wave drag. At this stage we refer to the bow float as float 2 and the stern as float 3 because a float further upwave, which will be float 1, is introduced later. To cover a range of wave periods we set a target resonance period for the bow float of 2 s which requires a draft of 0.6 m for a range of diameters. With a centre-to-centre spacing of 4 m maximum power is obtained with bow float diameter $D_2 = 1.5$ m approximately for 1 m < D < 2 m. In undertaking these heave optimisations mechanical damping was varied to give maximum power; this occurred when close to the radiation damping of the large float. Both resonant periods are only slightly affected by the proximity of the other float. For $T = 2.4$ s the maximum power was only slightly dependent on draft in the range 0.5 m–0.75 m. A diameter of 1.5 m and draft of 0.6 m were thus chosen. An example of the dependence of peak power on wave period and mechanical damping is shown in Fig. A1 with drag coefficient $C_D = 1.8$ which will be seen later to give good agreement with experiment for the final three body configuration. This configuration was tested at smaller lab scale (1/5 of scale described above) with two horizontal beams with hinges at each end on central vertical columns fixed on each float, the columns and beams effectively forming a parallelogram. The system responded in heave at resonance but off resonance heave motion was replaced by a coupled pitch motion with much reduced relative motion and hence power and the alignment of the two bodies could veer away from the wave direction. This option is clearly not of much practical value. However further advantage may be taken of anti-phase motion by rigidly connecting a further float 1 upwave of float 2 at a spacing also of about half a wavelength; this now becomes the bow float. This float may be relatively small so as not to diffract wave motion from the downwave floats and thus reduce their relative motion. The configuration is shown in Fig. 1. There is a single hinge above the mid float for power take off. In this configuration it is apparent that relative pitch between the two rigidly connected floats 1 and 2 and the stern float 3 will provide rotation in addition to the relative heave motion between the two upwave floats 1 and 2 (bow and mid) and the downwave float 3 (stern). It is further apparent that surge forcing on the mid float 2 and stern float 3 will be in anti-phase further potentially increasing rotation about the hinge (due to their moment about the hinge) although there is no hydrodynamic stiffness in surge to enable resonance.

The three-float system is quite complex. The heave optimisation for the two larger bodies is intended as a useful starting point. The small bow float 1 has a diameter of half the large float 3, of 1 m, and a draft of 0.35 m. This gives a resonant heave period of 1.6 s but this is of little significance. A range of float spacing and diameter was tested at lab scale (1:40) and it was found that reducing spacing of floats 1 and 2 reduced power slightly. Having a slightly smaller bow float diameter of 0.4 D_3 had little effect. A hinge point of 0.95 m above mean water level was near optimum based on laboratory scale tests. These effects were for both regular and irregular waves. It has to be remembered that results are also dependent on mass distribution and the nature of the power take off. At full scale the mass distribution will be determined by naval architecture design methods for floating offshore structures. The power take off here is idealised as a linear damper and this would be optimised hydraulically at full scale, possibly using a form of latching and accumulators for storage. Furthermore the base of the bodies considered here is essentially flat with rounded corners to reduce drag. This is for simplicity of construction and would be practical for deployment. However if drag has a significant effect on power the radius of curvature of the corners could be increased with a hemisphere as the limiting shape.

The intention here is to establish the potential for enhanced power output with forcing due to heave, pitch and surge and heave and pitch resonance. Experiments have been undertaken with the geometric configuration described above. A linear mathematical model has also been developed for regular waves to assess the relative importance of heave, pitch and surge, and also the effect of viscous drag. Comparison with experiment will assess the value of a model with hydrodynamic coefficients from linear diffraction