

Performance comparison of the floating and fully submerged quasi-point absorber wave energy converters



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ABSTRACT

Axisymmetric point absorbers are mostly designed as floating buoys that extract power from heave motion. Power absorption limits of such wave energy converters (WECs) are governed by the displaced volume of the buoy and its ability to radiate waves. In the case of fully submerged WECs, the power performance becomes a function of additional variables including the proximity to the mean surface level of the water, body shape and the maximum stroke length of the power take-off system. Placing the body below the water surface increases its survivability in storm conditions but changes the hydrodynamic properties of the WEC including maximum absorbed power. This paper investigates the differences between floating and fully submerged point absorber converters from the number of perspectives including energy extraction, bandwidth, and optimal size for a particular wave climate. The results show that when compared with floating converters, fully submerged buoys: (i) generally absorb less power at longer wavelengths, (ii) have narrower bandwidth, (iii) cannot be replaced by smaller units of the same total volume without a significant loss of power, and (iv) have a significant advantage as they can effectively utilise several modes of motion (e.g. surge and heave) in order to increase power generation.

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1. Introduction

Intensive research on extraction energy from ocean waves started in the 1970s [1]. Initially, attention was paid to the terminator-type converters which were studied as two-dimensional devices with an infinitely long body extension perpendicular to the wave front (e.g. Salter's duck [2]). However, due to the sensitivity of such prototypes to the direction of wave propagation, researchers focussed on the concept of a point-absorbing wave energy converter (WEC) [3] whose performance does not depend on the angle of wave incidence. Thereafter, point absorbers (PA) have become one of the most studied WECs, making up a large part of existing full-scale prototypes.

Generally, PAs are designed to operate on or just below the water surface, extracting wave power from the heaving motion. As opposed to submerged buoys, floating converters require less installation and maintenance work under water. However, there could be several very important reasons to keep the WEC fully submerged (see Fig. 1):

- (i) to increase the survivability of the converter during storms with large wave conditions;
- (ii) when there is an unconditional requirement from the public authorities to minimise visual impact of the wave power generator, e.g. the buoy must not be visible from the shore.

Based on the fundamental equations of maximum power absorption for axisymmetric bodies, floating and submerged WECs are able to extract the same amount of wave power provided unconstrained motion amplitudes [3,4]. Thus, under this condition the maximum capture width of the oscillating body does not depend on its size, shape or submergence depth, but is governed by the mode of motion [5,6]. According to these findings, the body that moves in surge and heave simultaneously can absorb three times more power than a heaving buoy.

In practice, WEC motion should be constrained during large waves, hence power absorption becomes dependent on the maximum allowed oscillation amplitude and the wave excitation force exerted on the converter [7,8]. As the latter is determined by the shape, size and submergence depth of the WEC, it becomes apparent that identical fully submerged and floating buoys cannot capture the same amount of wave energy. It has been observed [1] that submerged converters are poorer wave absorbers as compared

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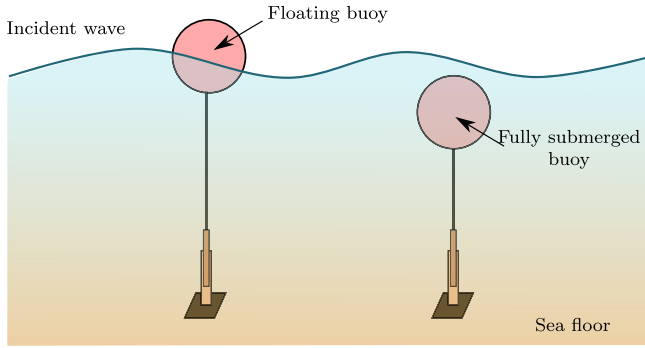


Fig. 1. Schematic representation of the floating and fully submerged WECs that extract energy from oscillations in heave.

to the floating heaving buoys because their upper and lower portions of the swept volume have different polarities during the oscillatory motion. In addition, floating and fully submerged WECs have distinctive low-frequency limits of the heave excitation forces. As the wave frequency tends to zero, the amplitude of the heave force on the floating body is limited by the hydrostatic stiffness coefficient, whereas for the fully submerged converter the excitation force approaches zero due to the diminishing water plane area [5]. Subsequently, based on these findings and also taking into account the swept volume of the body, Budal [9] was able to formulate power absorption bounds for floating WECs that oscillate in heave. This approach has been extended to the fully submerged buoys where the expressions of the power limits for several basic geometries are derived [10]. However, it may be concluded that in the case of point-absorbing WECs, the main research focus has been drawn to the floating buoys, while some features of submerged converters still remain unclear or have not been sufficiently explored.

The current paper provides a systematic comparison between floating and submerged PAs by generalising existing knowledge and providing an in-depth analysis. All results are based on the linear wave theory assuming regular and irregular wave conditions and infinite water depth. Background information and power absorption limits of heaving PA systems are presented in Section 2. Key features of different control strategies are discussed in Section 3, followed by the methods of selecting the correct size of the converter in Sections 4–5. Finally, the possibility of extracting power from additional modes of motion is reported in Section 6.

2. Power limits for regular waves

A body placed in water captures wave energy only when it moves in an oscillatory manner and radiates waves in order to counteract the incident wave front. Thus, the maximum amount of power that can be removed from waves is defined by the radiating ability of the body. This limit has been derived in Refs. [3,4,11] and differs for motion modes. A well known equation characterising the maximum absorbed power by an axisymmetric body in monochromatic waves is [5]:

$$P_{\max} = \alpha \frac{J}{k}, \quad (1)$$

where $J = \rho g^2 D(kh) A^2 / (4\omega)$ is the wave-energy transport per unit frontage of the incident wave, α is a coefficient that depends on the motion oscillation mode ($\alpha = 1$ for heave, $\alpha = 2$ for surge or pitch, and $\alpha = 3$ when the body oscillates in heave, surge and pitch simultaneously), k is the wavenumber, A is the wave amplitude, ρ is

water density, ω is the wave frequency and $D(kh)$ is the depth function which is equal to 1 for deep water.

Maximum power in Equation (1) is obtained when the body velocity is [5]:

$$\hat{u}_{j,opt}(\omega) = \frac{\hat{F}_{j,exc}(\omega)}{2B_{jj}(\omega)}, \quad (2)$$

where $\hat{F}_{j,exc}$ is the wave excitation force on the body in mode j , and B_{jj} is the radiation damping coefficient in mode j . However, the amount of power in waves with long period is very high and in order to absorb the absolute maximum, the body should move with large amplitudes at high velocities which is not achievable in practice. Thus, if $|\hat{u}_j| < |\hat{u}_{j,opt}|$, the amount of radiated power (P_r) will be much smaller than the excitation power (P_e) and the absorbed power will be limited by the latter:

$$P = P_e - P_r \leq \frac{1}{2} |\hat{F}_{j,exc} \hat{u}_j|. \quad (3)$$

According to Equation (3), Budal (as cited in Ref. [11]) showed that the power extraction at low frequencies is limited by the swept volume of the body, which is a collective term for the body physical volume and the maximum motion amplitude. Thus, for the floating body, the motion amplitude in heave is constrained by its vertical dimension, such that $|\hat{s}_3| < V/(2S_w)$, where V is the body volume, S_w is the water-plane area of the body, and the subscript $j = 3$ corresponds to the heave motion. Therefore, the maximum velocity in heave cannot be larger than $|\hat{u}_3| < \omega V/(2S_w)$. Furthermore, the heave excitation force is bounded by the integrated pressure force over the water-plane area of the body, which is $|\hat{F}_{3,exc}| < \rho g S_w A$. As a result, the power absorption of the floating heaving buoy has two boundaries:

- (i) a high-frequency limit P_A defined by the body's ability to radiate waves (from Equation (1) assuming deep water conditions $\omega^2 = kg$):

$$P_A = \frac{J}{k} = \frac{\rho g^2 A^2}{4\omega k} = \frac{\rho g^3 (\frac{H}{2})^2}{4\omega^3} = c_\infty T^3 H^2, \quad (4)$$

where $c_\infty = \rho(g/\pi)^3/128$, $H = 2A$ is the wave height, $T = 2\pi/\omega$ is the wave period;

- (ii) a low-frequency limit P_B defined by the maximum swept volume of the body, which applies when the velocity of the converter is smaller than the optimal value due to physical constraints:

$$P_{B,f} = \frac{1}{2} |\hat{F}_{3,exc} \hat{u}_3| = \frac{\rho g \omega V A}{4} = \frac{c_0 V H}{T}, \quad (5)$$

where $c_0 = (\pi/4)\rho g$ and the subscript f corresponds to the floating case.

These boundaries have been derived for floating bodies that move in heave only regardless of shape. In general, the P_A -limit depends only on the mode of motion and has the same expression for submerged and floating bodies. With regard to the P_B curve, the power absorption limit of the fully submerged converter is strongly dependent on shape and should be derived for each case under consideration independently. Thus, for a spherical body with its centre placed d_s below the water surface, the P_B -limit can be expressed as [10]:

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