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Application of an adaptive bistable power capture mechanism to a point absorber wave energy converter

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HIGHLIGHTS

- The adaptive bistable mechanism greatly improves efficiency of point absorbers.
- The adaptive bistable device performs better than linear and bistable converters.
- The adaptive bistable mechanism dramatically broadens the frequency bandwidth.

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ABSTRACT

This work proposes a novel adaptive bistable power capture mechanism, which is applied to a point absorber wave energy converter in regular waves. The adaptive bistable mechanism is realized by two symmetrically oblique main springs (responsible for the bistable characteristics) together with two auxiliary springs (making the bistable system adaptive) and it can adjust the potential function automatically to lower the potential barrier near the unstable equilibrium position. The "adaptive" feature helps solve the low-energy-absorption problem of a conventional bistable wave energy device (whose potential function is invariable in time) caused by the intrawell oscillation in low-amplitude excitation. With a suitable choice of physical and geometric parameters, an adaptive bistable wave energy converter outperforms its linear counterpart while a conventional bistable wave energy device has a poorer performance in low amplitude waves. Even for relatively large waves, an adaptive bistable wave energy converter has a comparable power capture capacity with its conventional bistable counterpart, both of which perform better than a linear wave energy converter especially in the low wave frequency region.

1. Introduction

Due to the high power density and considerable level of available energy, ocean waves have been promising energy resources to power offshore operational bases or to supplement other supplies on a continental electrical grid [1]. Although the average power in ocean waves is remarkably higher than in solar and wind energy, its development is much less mature than the other two types of energy technologies. Various types of wave energy converter (WEC) concepts have been proposed in order to capture energy from ocean waves, such as point absorbers [2,3], oscillating water columns [4,5], overtopping devices [6,7] and interconnected multi-module WECs [8,9]. Among these different wave energy devices, point absorber WEC (whose horizontal dimensions are much smaller than the wavelength) is a promising solution for wave energy absorption in offshore regions (typically more than 40 m water depth) due to its insensitivity to wave directions and relatively low average cost associated with the construction and installation of the device [10].

There are two main types of point absorber WECs, i.e. a single-body buoy reacting against a fixed frame of reference (a bottom-fixed base or the sea bottom) [11] and two-body systems oscillating differently [12]. The motion of a floating body (for a single-body point absorber) or the relative motion between two oscillating bodies (for a two-body system) excited by ocean waves is converted into electricity by the power-take-off (PTO) systems [13]. One type of PTO is the high-pressure oil system in which the body motion is first converted into hydraulic energy by hydraulic cylinders and the hydraulic energy is then converted into electricity through hydraulic motors driving conventional electrical generators [14]. Another type of PTO is a linear electrical generator which converts the motion into electricity directly [15]. For simplicity,

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a point absorber WEC with a PTO system is usually simplified as a mass-spring-damper model which can be analyzed using the frequency domain method [16]. The (constant) equivalent PTO damping is calculated following the principle of energy equivalence. According to the frequency-domain analysis, a (linear) point absorber WEC achieves its maximum power at the resonant state, i.e. incident wave frequency is equal to the natural frequency of the WEC with PTO damping taken as the radiation damping of the oscillating body [17].

One of the main problems in wave energy utilization is the survivability of point absorbers (as well as other types of WECs) in harsh sea environment [18]. The survivability reflects the ability of a wave energy device to avoid damage, during sea states that are outside of intended operating conditions, that leads to unplanned downtime and the need for service. Point absorbers that lack of sufficient survivability may fail in extreme waves for a number of reasons. For example, the excessive wave loads may cause the failure of mooring systems including mooring lines, anchors and connection points or the over-excitation of components within the power conversion chain may lead to both mechanical and electrical failures. Therefore, it is of practical importance to evaluate the performance of a WEC device in extreme waves, as well as develop an accurate model to predict the dynamic response. Yu and Li [19,20] investigated numerically the dynamic response of a floating point absorber with and without PTO systems under normal and extreme waves by using a Computational Fluid Dynamics (CFD) approach. Their study highlighted the significance of nonlinear effects including viscous damping and wave overtopping, especially in larger waves. In [21], effects of wave overtopping (under extreme waves) on peak forces on a point absorber WEC with a linear generator in relation to the event when the translator hits the upper end stop have been studied with a numerical wave tank (NWT) model. The verified NWT model was used by the same authors to further evaluate the survivability of a point absorber WEC with realistic system parameters in extreme waves and for a tsunami wave event [22]. Orszaghova et al. [23] performed experimental tests of the dynamic response of a submerged buoy WEC under extreme wave conditions, with a focus on the PTO extension (which corresponds to the piston stroke within the hydraulic cylinder of the prototype PTO system). In [24], a design wave (or a focused wave group) was identified across several long-duration experiments in extreme random seas for the extreme response (i.e. the maximum PTO extension) of a point absorber WEC. Hann et al. [25] carried out experimental measurements of the interaction of a taut moored point absorber with extreme waves and found that snatch loading occurred for the mooring system due to excessive extension of the mooring line. Chen et al. [26] applied a CFD method to study the hydrodynamics and structural dynamics of a floating point absorber WEC with a stroke control system in irregular and extreme waves. Their numerical results highlighted the significant effect of wave height on structure displacements and connection rope extension.

Another critical issue related to the development of wave energy technologies is the power efficiency of wave energy converters. One of the main drawbacks of traditional linear point absorber WEC is its less powerful performance with wave periods off resonance. The off-resonance condition may occur because realistic ocean waves typically come in a spectrum of frequencies and the dominant frequency may change from time to time. In order to enhance the efficiency of a WEC, many researchers devoted themselves in optimizing the geometrical and physical properties of the WEC or developing control strategies. For the former, the optimization may be targeted at the geometric shape of floating bodies [27], the inertia of floats [28] and a combination of different aspects [29]. For the latter, various approaches have been proposed so far, such as latching control [30,31], declutching control [32,33], model predictive control [34] and some other novel control algorithms [35–37]. Based on numerical or experimental results, these control algorithms seem to enhance the power capture performance of oscillating-body WECs. However, most of the control strategies require the overall information of incident waves as a prerequisite [38]. If the prediction deviation of incident wave profile (or wave force) is considered, the control performance of these strategies may be less powerful [39]. Moreover, extra sensor, actuator and processor elements and the corresponding maintenance cost which are accompanied with the implementation of control strategies are still challenges in engineering practice.

Another possible solution to the power efficiency problem of point absorbers is the application of nonlinear power capture mechanism. One of the main advantages of such nonlinear systems is the potential capability of energy harvesting in a broad-band random excitation [40]. Among different nonlinear mechanisms, bistable power capture mechanism (snap through mechanism; negative stiffness) has been highlighted and widely investigated in the realm of vibration energy harvesting [41,42]. A bistable system has two stable equilibrium positions and one unstable equilibrium position (which forms two potential wells separated by a potential barrier) and it may experience intrawell and interwell oscillations under different excitations. It has been proved by many researchers in the realm of vibration energy harvesting that a bistable system which is capable of overcoming the potential barrier and thus experiencing interwell oscillations has a better energy harvesting performance than its linear counterpart [42–45].

Although it has been a research focus in the realm of vibration energy harvesting, the bistable mechanism is studied limitedly by researchers and experts in the field of wave energy utilization. Zhang et al. [46] made the first attempt to apply this nonlinear mechanism (composed of two symmetrical oblique springs) to a point absorber WEC in regular waves. Frequency domain approach was adopted to roughly estimate the power performance of the WEC. Their results indicated that such a nonlinear WEC captures more power than its linear counterpart for incident waves of relatively low frequencies. This bistable power capture mechanism was further investigated, respectively, by Zhang et al. [47] and Zhang and Yang [48] using the time domain method in regular and irregular random waves. TodalShaug et al. [49] designed a passive pneumatic machinery component as a negative stiffness module (which was referred to as 'WaveSpring') and performed experimental investigation of the power capture performance of a point absorber WEC in irregular waves. Their experimental results showed that the device with the 'WaveSpring' component can absorb three times more power in realistic sea conditions than without it. The 'WaveSpring' technology has been applied to a compact high-efficiency point absorber WEC- the CorPower wave energy converter developed by CorPower Ocean [50]. Younesian and Alam [51] realized both bistable and tristable power capture mechanism for a heaving buoy in waves by using two symmetrical springs but with a different arrangement from what was adopted by Zhang et al. [46]. Through a quantitative analysis, they showed that the nonlinear multi-stable system enhanced the absorption efficiency, as well as broadened the frequency bandwidth and the bandwidth of PTO damping. Wu et al. [52] numerically investigated the power capture capacity of a point absorber WEC with a negative stiffness unit (which is similar to those in [46–48]) and found that the nonlinear stiffness system increased the captured power, pushed up the natural period and broadened the resonance range of the WEC. Apart from symmetrical springs and pneumatic machinery components, there exists other means to accomplish the same (bistable or multi-stable) effect, such as using a system of magnets [53,54].

The above-mentioned bistable mechanism is referred to as 'conventional' bistable mechanism as the nonlinear system has an invariable (in time) potential function as well as an invariable potential barrier. Under low-amplitude excitation, the conventional bistable system may be trapped in one well and hardly cross the potential barrier which will lead to worse power capture performance [42,55]. Therefore, it will be desirable to design a bistable system with a time-varying potential barrier which can be adjusted automatically to enable interwell oscillations even under low-strength excitations.

In this paper, an adaptive bistable power capture mechanism is

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