Applied Energy 197 (2017) 292–302

Contents lists available at ScienceDirect

Applied Energy

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

Multi-stable mechanisms for high-efficiency and broadband ocean wave energy harvesting

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HIGHLIGHTS

- Bistable and tristable mechanisms significantly improve efficiency of the point absorbers.
- A multi-stable point absorber has a higher frequency bandwidth.
- Robustness of the multi-stable wave energy device increases with respect to the damping detuning.

ARTICLE INFO

Article history:
Received 20 December 2016
Received in revised form 27 March 2017
Accepted 9 April 2017

Keywords:
Wave energy conversion
Multi-stable system
Point absorber
Nonlinear power take off

ABSTRACT

Here, we show that a nonlinear multi-stable system, composed of a nonlinear restoring mechanism and a linear damper-like generator, can significantly enhance the absorption efficiency of a heaving wave energy converter. This efficiency increase can be as large as few times higher than a wave energy absorber with a classical power take off system composed of a linear spring and a linear generator. Through a quantitative analysis, we also show that a nonlinear multi-stable system broadens the frequency bandwidth of the wave absorber, as well as, the bandwidth of the power take off's damping coefficient. We propose a simple mechanical system that has the required multi-stable response upon which the investigation of this paper is based. Methodology developed and the results obtained here can be readily extended to other types of wave energy converters with one or multi degrees of freedom.

1. Introduction

Interest in ocean wave energy is growing due to the considerable level of available energy as well as the high power density of water waves. Oceanic surface waves carry few Terra-Watt of power [1], which is the order of primary energy demand/consumption in the world. Besides, ocean wave's average power density is remarkably higher than wind (by almost an order of magnitude) and solar (by about two orders of magnitude). All-day availability and predictability of the energy regime based on the geographical location are two other advantages of the ocean wave power with respect to the other renewable energy resources. This significant potential of energy with such advantages has attracted remarkable attention in the community of applied energy so that assessing of availability and variability of the wave energy recourses is nowadays a dynamic context of research. For instance, several researchers [2–5] have recently presented different statistical algorithms to evaluate variability and uncertainty of the wave energy resources. As a byproduct, a wave energy extractor device can also protect shorelines against the destructive momentum of incoming ocean waves.

Several classes of wave energy converters have been proposed and tested so far (see e.g. [6–11]).

High-density wave energy coast lines such as north-west coast of the North America, south coast of Africa, Australia and South America and west coast of Europe are potential regions with maximum power capacity up to 90 kW per meter of the coast line. Because of simplicity in manufacturing and installation, between different types of the wave energy converters, linear point absorbers (i.e. the main frame of this study) have been several times used so far in different test laboratories and also in ocean. The available tested power for a point absorber can reach up to 500 kW for a wave power delivery of 70 kW/m [12]. Power generation cost is also a key factor in wave energy conversion systems. The average cost for the point absorbers is about 12–20 cents per kW which is quite feasible compared to other modes of renewable energies and also other wave energy devices [13]. In spite of aforementioned advantages, similar to the other renewable energy systems, wave energy conversion mechanisms have their own

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http://dx.doi.org/10.1016/j.apenergy.2017.04.019
0306-2619/

limitations and challenges including, for instance, optimal efficiency, survivability, endurance life, transportability, installation, maintenance and scalability. Specifically, dominant frequency of ocean waves may change from time to time, and waves also typically come in a spectrum of frequencies. Linear wave energy converters can be tuned to a single (resonance) frequency. Therefore, if this dominant frequency changes (which is typical in real oceans and from time to time) then the linear wave energy converter works off-resonance (detuned) and therefore performs with lower (sometimes much lower) efficiency. Similarly, for an irregular incident wave (i.e. spectrum), a linear wave energy is definitely suboptimal meaning it cannot take out energy from all frequencies equally well. Toward this goal, many researchers have applied different control techniques to enhance the efficiency of the wave energy converters. Latching control [14,15], de-clutching method [16,17], model predictive control [18,19], gain scheduling technique, and real-time extremum-seeking control [20] have been investigated and their performance have been quantified. Ringwood et al. [21,22] comprehensively studied strong potential of a broad range of control technologies and algorithms which can be applied to improve performance of single and arrays of the wave energy converters. Bacelly and Ringwood [23], applied the optimal control to a farm of wave energy convertors and showed that a significant performance is achieved when the control law globally applies to the complete model, compared to independent WEC control. Although feedback control systems are more precise and adaptable to the sea condition and can remarkably enhance the Power Take Off (PTO) performance, however, extra sensor/actuator and processor elements and the maintenance cost are still practical challenges.

Passive targeted energy transfer systems through the use of nonlinear systems have been of interest to the community of nonlinear mechanics in the last two decades [cf. e.g. 24]. In such systems, nonlinear mechanisms provide a one-way irreversible energy flow from environmental vibration to the energy generator. Potential capability of energy harvesting in broad-band random excitation is one of the main advantages of such nonlinear systems [25,26]. Among different nonlinear mechanisms, multi-stable systems have been recently highlighted particularly in MEMS and NEMS energy harvesting systems. Having different equilibrium points brings an extra freedom to the energy harvesting system so that it can behave differently in dissimilar frequency ranges. Bistable systems have two stable nodes and one middle saddle point (e.g. the dynamic behavior of a post-buckled column can physically describe behavior of such a nonlinear system). For a comprehensive review on the types, application and characteristic behavior of bistable systems, the reader is referred to, e.g. Elvin and Elturk [27], Pellegrini et al. [28] and Harne and Wang [29].

For harnessing energy of environmental vibrations, Cootone et al. [30] and Arrieta et al. [31] employed the concept of multistability for the broad-band energy harvesting by a buckled beam and a bistable plate. They could increase the frequency bandwidth up to 2.5 times. Remarkable performance of a bistable beam in energy harvesting was experimentally shown for a white noise spectrum input by Vocca et al. [32]. Through using a magnetic dipole, Ando [33] and Stanton [34] constructed a bistable beam and proved feasibility of the concept in board-band energy harvesting for piezoelectic generators respectively for white noise and harmonic excitation.

Tristable systems with two saddle points and three stable nodes have also been investigated for applications in energy harvesting systems. For instance, in a series of studies, Zhou et al. [35,36] numerically and experimentally showed that a tristable oscillator reciprocates more easily through the potential wells and this fact makes it more appropriate for generating higher level of energy over a broader frequency range. They used a cantilever beam set up with an attached piezoelectric energy generator and showed that the tristable configuration enhances the frequency bandwidth up to three times under low frequency excitations. Tekam et al. [37] conducted a parametric study on the influence of fractional order viscoelastic material on the performance of a tristable energy harvesting system.

Significant potential of the wave energy has recently influenced different disciplines of science and engineering communities in order to increase the total efficiency of such energy conversion systems. For instance, effects of the uncertainty in wave climate and seasonal/interannual natural variability on the wave energy extraction is nowadays a challenging area of research [36–39]. Optimal location of the wave energy devices also plays a key role in maximizing the amount of extracted power [40,41]. Beside these two important factors, remarkable amount of research has been devoted in modification and optimization of the power take off mechanisms. Just in case of the point absorbers, different design proposals have been recently addressed and tested. Pastur and Lue [42] and Goggins and Finnegan [43] optimized the shape and dimensions of the buoy and showed the optimal geometry is quite dependent to the sea condition. Son et al. [44] developed a new optimal design based on a dual coaxial-cylinder buoy and could get two-times increase in total efficiency without any active control. They used the concept of nonlinear model predictive control in their dual buoy and could get up to forty percent capture width in regular sea condition [45]. Application of nonlinear mechanisms in improvement of the WEC performance has also received attentions. Spanos et al. [46] developed a statistical linearization technique to solve large amplitude oscillation of a nonlinear monostable single-point energy harvester under random sea excitation. Based on the bistable impulsive interaction, a multi-cell chain has been developed and tested by Harne et al. [47]. They designed an appropriate magnetic generator and could convert low frequency input motion to high-frequency harnessed energy. Zhang et al. [48,49] investigated performance of a snap-through power take off system in regular and irregular sea conditions. They showed that the snap-through mechanism acts similar to a bistable system and could remarkably improve the generated power in low frequency range however the frequency band-width would decrease.

There are still several challenges and gaps in the context of optimal performance of the point absorbers in wave energy extraction. Active devices can be normally adapted to different sea conditions but they consume part of the extracted energy and apart from additional costs they are not technically easy to apply in real sea. Passive absorbers have still two limitations (i) low frequency bandwidth and (ii) lack of enough robustness with respect to the tuning parameters and irregular sea conditions. Here in this paper, we address a novel passive multisatble mechanism which is able to enhance frequency bandwidth and robustness of the linear WECs simultanously applicable for regular and irregular sea conditions. Without adding any extra elements to the conventional point absorber WECs, we still use the linear springs and a linear power generator. By adjusting the angle of inclined springs and their end positions as well as by an appropriate pre-tension or compression we can achieve different multistable wave energy extraction devices. By comparing performance of a monostable, bistable and tristable WEC, we show that additional equilibrium points with surrounded symmetric trajectories provide extra kinematic reciprocations and the consequent frequency bandwidth for conventional wave energy devices.

Toward proof of this concept, we investigate whether the proposed multi-stable system can improve the efficiency of the conventional ocean wave energy converters, and If so, how much and how efficient would it act over the frequency band of the irregular sea waves. In order to achieve different characteristic behavior for the multistable mechanism, different combinations