Applied Energy 130 (2014) 148–156

Contents lists available at ScienceDirect

Applied Energy

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

# Wave heave energy conversion using modular multistability

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## HIGHLIGHTS

- An alternative power take off concept is explored for mobile wave energy converters.
- A multistable chain is developed for kinetic energy conversion from wave heaves.
- Bistable links join the chain cells and induce impulses due to extension–compression.
- Chain modularity enhances impulsive kinetics by local–global dynamics transformation.
- Numerical and experimental data indicate strong potential for multistable chain.

## ARTICLE INFO

*Article history:*
Received 26 November 2013
Received in revised form 10 March 2014
Accepted 20 May 2014

*Keywords:*
Mobile wave energy converter
Multistability
Impulsive dynamics
Electromagnetic induction

## ABSTRACT

In calm sea environments and for compact architectures, the power generation performance of wave energy converters may be drastically inhibited due to undesired dissipative effects in the conversion mechanisms. This research develops an alternative power take-off methodology to surmount these challenges and to enable practical wave energy conversion for mobile converter architectures that could power monitoring instrumentation or telecommunications. Building upon related research findings and engineering insights, the basis for energy conversion is the harnessing of impulsive kinetics induced as a multistable structure is extended and compressed. A prototype system is built and analyzed to evaluate the potential for this conversion framework. Composed of modular "cells", the chain-like platform exhibits an increased number of stable configurations with each additional unit cell. Extension and compression of one end of the multistable chain (representative of wave heaving) while the opposing end remains mostly fixed, excites high frequency inter-cell dynamics due to impulsive transitions amongst configurations that are converted to electric current through electromagnetic induction. An experimentally validated model is utilized to gain insight towards successful realization of the power conversion concept and design guidelines are derived to maximize performance and ensure viability.

## 1. Introduction and motivation

The heaving motion of sea and ocean waves is one of the most persistent and dense renewable energy resources in marine environments [1,2], making it appealing to power off-shore operational bases or to supplement or replace other supplies on a continental electrical grid. Numerous power take-off (PTO) solutions have been proposed over the years [3–6], while highly dissipative PTO mechanisms based upon pneumatics or hydraulics have become common choices for wave energy converters (WECs) intended for large-scale power generation and electric grid integration [3,4].

Since pneumatic or hydraulic coupling stages are eliminated, directly driven PTO concepts based on electromagnetic induction have been developed for improved large-scale WEC efficiency. In the context of wave energy applications, direct drive "describes the direct coupling of the buoy's speed and force to the generator without the use of hydraulic fluid or air" [7]. A breadth of research has demonstrated promise in laboratory and field testing for this PTO [7–14]. The experimental systems in these studies are often physically large and massive, may require fixed mooring, and regularly deliver average powers of 10–1000 W. While this power is too low for grid integration, it is acceptable during research development.

In contrast to large-scale energy conversion, the focus of the present paper is to realize mobile WEC architectures that power self-sustaining, waterborne instrumentation or telecommunication systems. For this purpose, power generation around 1–10 W is sufficient and platforms of <100 kg mass and <10 m length are preferred for improved mobility. Many of the designs in the previously

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http://dx.doi.org/10.1016/j.apenergy.2014.05.038
0306-2619/

cited literature are not suited for this purpose since they are large by mass and dimension and are not easily re-deployed. Fewer investigations have focused on mobile WEC platforms for low-power applications. Portable WECs using directly driven PTO based on transmissions with rotary generators [15–17] and linear electromagnetic induction [18–21] have been recently explored. In these studies, average power generation spanning around 0.01–100 W has been demonstrated through modeling and experimentation. One trend from the studies was that prototype development exceeded 100 kg total WEC mass [16] while some full-scale systems were predicted to have mass of 500 kg [19,20]. The need for large masses is partially due to the directly driven PTO since the resistance forces are a combination of friction and high, continuous electromagnetic damping. Although damping ratios are infrequently reported for comparison to the present research, in one example damping ratios of around 0.75–1 (critically damped) were experimentally identified, collecting together viscous and friction effects [18]. For large-scale WECs, the damping forces are more readily overcome by momentum of large moving inertia [2]. Yet for lightweight and mobile WEC and considering the high variability of sea activity [22], such dissipations are difficult to surmount, particularly to break through the stall forces of friction for small actuating wave motions [23].

These challenges are the stimulus of this research towards development of an alternative PTO concept well-suited to realize mobile WECs. The following sections introduce the new PTO mechanism and present the rationales supporting the chosen design. Following experimental validation, a model of the PTO is employed to study the influences of system modularity and excitation frequency on energy conversion performance due to controlled excitation and simulated wave input. Throughout the investigations, design principles are provided for successful realization of the proposed PTO for efficient and mobile wave energy conversion.

## 2. PTO mechanism design

A key challenge for WEC employing directly driven rotary or linear induction PTO is the high continuous electromagnetic damping that works against the inertial mass motions (relative to a mostly fixed opposing end), which for slow velocities can lead to stalling if inertial forces do not exceed friction thresholds [23]. The PTO mechanism developed in this research alleviates this concern by combination of a modular multistable design and the use of impulsive dynamics for energy conversion.

In the field of vibration energy harvesting, the concept of energy generation using *impulsive kinetics* has received recent attention [24–27]. The objectives of these works are the development of alternative means for powering small electronics using very low frequency excitations and minimization of the excitation level required to generate power. Of particular relevance to the present study, Karami et al. [27] developed a compact, vibration energy harvester excited by impulsive interactions between dynamic piezoelectric beams and a rotating wind turbine. Because the impulsive interactions could be directly adjusted to govern the minimum actuating energy (wind speed) required to generate power, the harvester system was shown to overcome damping, friction, and low wind speed limitations of conventional directly- and gearbox-driven wind energy conversion systems. The challenges faced in development of compact wind energy converters are similar to the wave energy application of present interest. As demonstrated in the comparable wind energy application [27], a PTO based upon impulsive interactions may be a suitable alternative for compact, mobile WEC which are less able to overcome minimum actuating force and displacement requirements of direct drive PTO because of their reduced mass. Apart from the early efforts [24–27], much remains to be known about feasibility and effective adoption of impulsive kinetics for *wave energy conversion*.

The common theme of the prior studies [24–27] is the use of *bistability* to obtain the impulsive responses. Two reviews [28,29] describe numerous research efforts in the field of vibration energy harvesting with bistable systems which are largely focused on utilizing continuous switching behaviors. Within this body of work, recent findings have shown that coupling bistable elements to other dynamic bodies may greatly enhance the net energy conversion per harvester mass [30,31]. These *coupled system* studies likewise focused on continuously switching bistable dynamics which are not easily obtained for very low frequency excitations.

Following the insights described above, the aim of this work is to bring together the two promising research developments – *bistable impulsive kinetics* and *coupled dynamic systems* for energy harvesting – to realize mobile WEC platforms for low frequency and large displacement wave motions.

Fig. 1 illustrates the framework of the proposed PTO developed to integrate the two energy conversion potentials. The PTO is shown as embedded within one possible WEC architecture. The WEC is composed of a mostly submerged spar constrained in position by sufficient resistance, e.g., a submerged plate or temporary anchoring, and a buoy that moves along with the transverse wave motions. The relative displacement between spar and buoy actuates the top end of a chain of modular "cells" housed within the spar. The chain of cells connects the bottom of the spar to the actuating rigid connection. Therefore, motion between the buoy and spar extends and compresses the multi-cell chain, Fig. 1(a and b), respectively.

As illustrated by the schematic in Fig. 1(c), each unit cell is composed of two halves secured together by a threaded connection. One part of the mass is the cylinder structure and inner magnet. The remaining cell mass is the frame structure, the radial array of outer magnets, an induction coil, and the threaded connection. Two adjacent cells interact through restoring forces due to a linear spring connection and magnetic fields. The polarity orientations of the outer magnet radial array and the moving inner magnet of the adjacent cell are such that the two cells' *relative* displacements exhibit *bistability*, which leads to an energetic transition from one stable configuration to the other when the interface of two adjacent cells is extended beyond a critical point. The stable states are illustrated in Fig. 1(a and b) showing the interface between adjacent cells in the (a) extended and (b) compressed configurations. Because the cell relative displacements from extended to compressed configurations (and vice versa) involve the inner magnet passing through the induction coil of the adjacent cell and impulsively vibrating at a high natural frequency after the transition, electrical current is generated in the coil due to the switch in stable configuration. Thus, the proposed PTO is not intended to be excited as if to resonate. Instead, via the bistable interfaces, an up-conversion occurs from very low frequency actuating wave heaves to higher frequency impulsive inter-cell dynamics for energy conversion.

The PTO system adopts a modular architecture aligned with the coupled system design strategy found to enhance performance per mass of bistable energy harvesting systems [30,31]. Connecting the cells of the proposed PTO in series, as in the experimental system shown in Fig. 1(d), the activation of switching dynamics between cells transmits impulses along the chain length, transforming otherwise local behaviors into global energy conversion dynamics. The successive and cascading impulsive electrical responses from chain extension and compression are then utilized to charge energy storage elements for powering instrumentation systems. The minimum threshold of actuating force which leads to an