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Wave energy harvesting using nonlinear stiffness system

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ABSTRACT

A nonlinear stiffness mechanism installed in a floating point absorber (FPA) in regular waves allowed for studying the influence of the nonlinear behavior on wave energy harvesting. Static analysis of nonlinear stiffness system and time domain numerical simulations based on Cummins' equation evaluated the effects of power take-off (PTO) damping, system stiffness and geometry dimensions. The results may apply to the evaluation of the balance between energy harvesting performance and practical design limitations. The nonlinear stiffness system improved the efficiency of wave energy harvesting, increasing mean power, by both pushing up the natural period, and broadening resonance, therefore proving more competitiveness.

1. Introduction

Ocean waves can work as a generous, sustainable and clean source of energy. In 2012, the Intergovernmental Panel on Climate Change (IPCC) reported a theoretical energetic potential around 29,500 TWh/yr, considering only ocean areas where wave energy density is higher than 5 kW/m [1]. Such an amount of energy corresponds to the total world electricity consumption in 2016 (21,190 TWh/yr [2]). From the total available ocean energy, the technical potential was estimated as 500 GW (around 146 TWh/yr) – IPCC (2007), if you only consider devices installed near coastlines in areas with wave climate >30 kW/m and assuming 40% operational efficiency [3,4]. Nevertheless, in the present stage of wave energy harvesting technology, the costs involved are not yet competitive if compared with other sustainable energy sources such as solar, wind or even sea tidal, based on the data shown in Table 1. The wave energy conversion technology is still in the pre-commercial stage.

Falnes, [6] conducted comprehensive and thorough theoretical researches on optimum response to maximize the power absorption of wave energy converters (WECs). Falnes also classified the types of control methods used to increase power output from wave energy as discrete and continuous [7].

In the former case, one may latch the oscillating body, if the wave period is longer than its natural period and, conversely, unlatch it after a given time interval. A sub-optimal oscillation mode may enable capturing larger amount of wave energy.

Babarit et al. [8] carried out numerical investigations on three different strategies of latching control of point absorber wave energy converter in irregular wave. The authors chose the latching duration to maximize the absorbed energy, increasing the amplitude of motion and synchronizing velocity and excitation force phases.

Feng and Kerrigan, [9–11] applied derivative-free optimization to determine the WEC optimal latching/declutching strategies. The authors also showed comparisons between the WEC performance based on the past wave data and the predicting excitation force some time ahead. They demonstrated that using predicted excitation forces improves significantly the WEC performance.

Continuous control usually is an optimal phase control method that controls the reactive power to maximize the active power.

Table 1
Estimated levelized costs of primary sustainable energy.

Technology	USD/MWh
Wave (fixed)	614.56
Wave (floating)	**1002.00**
Tidal stream	489.31
Tidal barrage	865.06
Solar PV	572.81
Offshore wind	282.23
Onshore wind	138.61
Nuclear	160.32

Source: Mott MacDonald: Costs of low-carbon generation technologies, 2011 [5]
Averaged exchange rates: 1.00GBP = 1.44EUR = 1.67USD.

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Therefore, it may be necessary to reverse the instantaneous power flow during certain fractions of the oscillation cycle. For this reason, the control strategy is also named as reactive control. Such a strategy needs parallel measurement, or at least, wave prediction (elevation/force) or motion over certain receding horizon.

Hals et al. [12] compared quantitatively and qualitatively power absorption considering no phase control, sub-optimal latching control and ideally optimal reactive control. Hals et al. [13] applied model predictive control (MPC) on the real-time optimal control to find the optimal Power Take Off (PTO) damping force profile over a receding horizon that maximizes the absorbed wave energy. Meanwhile, the optimization process took into consideration the motion and force constraints. In irregular wave, the wave force prediction over a receding horizon adopted Kalman filter analysis. They managed to assess even the influences of the predictor horizon, step length and accuracy.

Cretel et al. [14,15] presented one MPC strategy with an unusual form of objective function to maximize the production of energy by the floating point absorber. Bacelli and Ringwood, [16,17] applied an alternative approach, namely, the pseudo spectral method, to solve the optimal control problem. They described the state and control variables via a set of Fourier basis functions. Genest and Ringwood, [18] also carried on comparisons between MPC and pseudo spectral optimal control algorithm applied to WEC. Enrico Anderlini et al., [19] proposed an on-line, model-free reinforce learning (RL) algorithm to obtain optimal PTO damping in each sea state for the WEC resistive control. The authors computed the wave prediction using spectral analysis and Fast Fourier Transform (FFT) method from the wave elevation record fed-in by an external neighboring wave buoy.

Most of the above methods are active and based on discrete or continuous control strategies. Besides the complexity of some optimization algorithm, higher accuracy and longer time horizon of the prediction of wave or motion are also necessary. In contrast, the passive system with different types of nonlinearity, such as mono-stable or bi-stable characteristics of nonlinear stiffness mechanism, has already been widely applied in vibration energy harvesting to meet the low power requirements of some modern microelectronics [20].

Harne and Wang, [21] made a broad review of researches on vibration energy harvesting, via bi-stable systems. They also discussed the common analytical framework for bi-stable electromechanical dynamics. Based on the three well recognized dynamic regimes of bi-stable oscillators: low-energy intra-well vibration, aperiodic or chaotic vibration between wells and periodic inter-well oscillation (alternatively, known as snap-through), they confirmed that the last case would be able to improve dramatically the energy harvesting performance. The authors discussed and summarized not only the benefits, but also the remaining challenges and eventual solutions to explore bi-stable nonlinearities in vibration energy harvesting. Wiebe and Virgin, [22] have developed a heuristic method to identify the chaotic regime. They tested their method, both numerically and experimentally, on a bi-stable mechanical oscillator. Virgin et al., [23] investigated the robustness of a variety of coexisting responses, “single-well” and “cross-well”, that may occur over a range of forcing frequencies in the vicinity of resonance. They used a numerical indicator, based on the percentage of randomly generated initial conditions attracted to each long-term response, to access the relative dominance, when coexisting responses take place. Godoy and Trindade, [24] presented a study on the design and optimization of a nonlinear dynamic vibration absorber based on snap-through absorber geometry.

Actually, in recent years, nonlinear stiffness mechanism has already been adopted into WEC. Zhang et al., [25,26] applied a nonlinear snap-through PTO system to a hemispherical WEC. The authors presented an extensive analysis and comparisons featuring the influences of PTO damping, geometry dimensions and wave frequency on the power capturing, in both cases, linear and nonlinear WECs. Hals, [27] proposed a WEC with a passive pneumatic machinery component which can provide negative stiffness. Hals et al., [28] tested the new technology, named as WaveSpring, on their CorPower buoy prototype. The test results showed that the WaveSpring unit could be tuned to a given resonance range of periods and broaden the high response band. Younesian and Alam, [29] proposed a nonlinear multi-stable system which can result in systems with different stable characteristics depending on the chosen geometric parameters. They applied the solution on hemispheric buoy and analyzed quantitatively the influence of PTO damping ratio and frequency ratio on the capture width ratio.

In the present paper, a truncated cylindrical buoy running along a vertical column is connected with a classical nonlinear stiffness mechanism, supplying negative stiffness. Different system configurations are analyzed in a comprehensive way to explore the potential benefits from nonlinear stiffness to enhance FPA performance in typical real sea conditions. The systematic analysis of the characteristics of the system and the process of parameter selection will give an efficient approach for the preliminary design of FPA featuring nonlinear stiffness system.

The discussion starts analyzing the static characteristics of the nonlinear system and heaving truncated cylinder combination. Then, the fundamental equation of motion (EOM) of the complete system is set up, based on Cummins' equation [30]. The matched Eigen function expansion (MEE) method, proposed by Yeung, [31], calculates the hydrodynamic coefficients and wave excitation force acting on the buoy. The 4th order Runge-Kutta method together with state space model solves the EOM, in iterative solution. An extensive and large quantity of time domain numerical simulations generate results used to evaluate the individual and combined influences of the PTO damping, system stiffness and geometric dimensions for different regular waves acting on the FPA. In the end, based on the criterion of enhancing the system performance, a final set of parameter could be selected.

2. Basic principles

According to Newton's second law, the single degree-of-freedom EOM, in pure heave mode may be set up as Eq. (1):

$$M \cdot \ddot{z}(t) = F_W(t) + F_R(t) + F_{PTO}(t) + F_H(t) \tag{1}$$

where: M is the mass of floating buoy;

$z(t)$ is the heave displacement at time t;

“.” represents the second order time derivative, in addition to that “.” Represents the first order time derivative, which will appear in Eqs. (2) and (3);

$F_W(t)$, $F_R(t)$, $F_{PTO}(t)$, $F_H(t)$ are the wave excitation force, the hydrodynamic radiation force, the PTO damping force and the hydrostatic restoring force respectively.

In Eq. (2), A_∞ is the added mass for infinite frequency, the convolution term represents the fluid memory effect, and the kernel, K_I(t), is the impulse response function.

$$F_R(t) = -A_\infty \cdot \ddot{z}(t) - \int_0^t K_I(t-\tau) \cdot \dot{z}(\tau) \cdot d\tau \tag{2}$$

Eq. (3) considers only the linear damping (B_{PTO}) of the PTO system:

$$F_{PTO}(t) = -B_{PTO} \cdot \dot{z}(t) \tag{3}$$

Eq. (4) defines the hydrostatic restoring:

$$F_H(t) = -C \cdot z(t) \tag{4}$$

where: $C = \rho g S$, is the hydrostatic restoring coefficient;