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Parametric pendulum based wave energy converter

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ABSTRACT

The paper investigates the dynamics of a novel wave energy converter based on the parametrically excited pendulum. The herein developed concept of the parametric pendulum allows reducing the influence of the gravity force thereby significantly improving the device performance at a regular sea state, which could not be achieved in the earlier proposed original point-absorber design. The suggested design of a wave energy converter achieves a dominant rotational motion without any additional mechanisms, like a gearbox, or any active control involvement. Presented numerical results of deterministic and stochastic modeling clearly reflect the advantage of the proposed design. A set of experimental results confirms the numerical findings and validates the new design of a parametric pendulum based wave energy converter. Power harvesting potential of the novel device is also presented.

1. Introduction

Energy harvesting has been attracting much attention in recent years, which is reflected in a great number of publications. In some areas, like wind energy, there have been significant advances made allowing to pass from a concept up to a commercialization stage, implementing some novel ideas in practice. Wave energy is another promising area the development of which however has been progressing slower than expected due to a number of reasons. Over one hundred fifty various concepts of Wave Energy Converters (WECs) exist and new ones keep appearing quite regularly. Some of the ideas went through the commercialization stage and have been built and deployed, for instance Pelamis, Oyster, OWC, etc. [1]. Despite these developments, the cost of wave energy remains significantly high, almost ten times greater than that of coal and almost twice the cost of offshore wind energy [2]. The Carbon Trust identified three major directions where cost reduction can be achieved: device components, operation and maintenance as well as next generation concepts [2]. This becomes especially important in a view of recent bankruptcies of two major players in this sector - Pelamis and Oyster. Thus, it becomes obvious that the race for a new generation of more efficient, inexpensive and robust WECs is still on.

Relatively recently, a novel wave energy power take-off concept has been first proposed in [3]. Its main idea was based on the properties of a parametrically excited pendulum. It is well known that if a pendulum's suspension point is excited harmonically in the vertical direction with a certain frequency, rotational response of the pendulum is possible. The dynamics of such a system can be described by the following nonlinear equation:

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$$\theta'' + \gamma\theta' + [1 + \lambda\cos(\nu\tau)]\sin\theta = 0,$$
$$\lambda = \frac{A\omega^2}{L\Omega^2}, \quad \nu = \frac{\omega}{\Omega}. \tag{1}$$

Here L and Ω are the length and natural frequency of the pendulum, γ - viscous damping coefficient, A and ω - the excitation (waves) amplitude and frequency. Thus, using the heaving motion of waves as a parametric excitation of the pendulum's suspension point it is potentially possible to make the pendulum rotate, which can be used to generate electricity. The major advantage of this elegant idea is that electricity can be generated in a conventional way and would not require any intermediate auxiliary mechanisms. However, the implementation of a parametric pendulum as a power take-off system turned to be more challenging than it seemed. There are three, most important from the authors' point of view, challenges that prevented further development of the concept so far. The first two could be summarized as: how the pendulum would behave in a random sea environment and how to reduce the size of the device. These two challenges are outlined below whereas the third one, concerning the improvement of rotational potential of the pendulum, will be thoroughly addressed in this paper.

The first challenge was to understand whether a sustainable rotational motion could be observed under a sea-like environment excitation, since sea waves could barely resemble a harmonic process. There has been a number of publications related to the rotational potential of a parametrically excited deterministic pendulum, most of which were not concerned with energy harvesting but rather were focused on the deterministic and chaotic response of the pendulum ([4–7] and references therein). Rotational potential is defined as a percentage of rotational motion of the pendulum over the overall time and it directly influences the amount of power generated. Apparently, the average energy of a pendulum in rotations is larger than that of the pendulum in an oscillatory motion, which can be seen from the state-space trajectories of these motions. Later, various combinations of excitations and pendulums have been tested to understand how the direction of the excitation, as well as the interaction of two and more pendulums influence the rotational potential ([8–14] and references therein). Experimental investigations on the rotating parametric pendulum and energy extraction can be found in [15–21]. Recently the authors have published a number of papers where a stochastic excitation has been used to model the parametrically excited pendulum behavior under more realistic loading [22–26]. Namely, a harmonic excitation with a mean frequency and random phase modulations has been used to generate a sea like waves with a proper spectrum (Pierson-Moskowitz spectrum was used). It has been found that a sustainable rotational motion of the pendulum can be achieved under a narrow band excitation. Rotational domains with 10% to over 90% of rotational motion were identified and it has been shown that the increase of randomness (noise intensity) moves the domains of rotational motion to the region of higher λ values, thereby reducing the rotational potential.

The second challenge was related to the physical size of the pendulum. Since the primary parametric resonance occurs when the excitation frequency is twice the natural frequency and an average excitation frequency of waves is about 0.1 Hz (period of $T = 10$ s), the pendulum's natural frequency should be around 0.05 Hz = 0.314 rad/s to bring the pendulum to the primary parametric resonance. Such a frequency is extremely hard to attain for the lumped mass (mathematical) pendulum, since its squared natural frequency is inversely proportional to its length $\Omega^2 = g/L$ and therefore the pendulum should be around 100 meters long. The size can be significantly reduced if one considers a compound pendulum, which can have a relatively small size and low frequency. The latter can be achieved by a very small radius of gyration, which is impractical since it can be smaller than the diameter of a holding pin and also provide extremely low torque, which is essential for energy harvesting. A reasonable solution to this problem was offered by the authors [12], where dynamics of a pendulum with N arms, rigidly connected to a joint hub and equally distributed at intervals of $2\pi/N$, was investigated (not to be confused with N pendulums - a system where each pendulum is connected to the end of other). Each arm has a lumped mass, placed at some distance from the hub, so that by changing these distances one can control the pendulum's natural frequency. It has been shown that such an N-pendulum system not only can achieve low natural frequency at different distances of the masses from the hub, but also has a number of advantages, offering an opportunity to adjust the pendulum's frequency and moment of inertia (therefore torque) independently.

The third challenge, which is the focus of this paper, concerns the rotational potential of the pendulum, namely how to facilitate rotations of the pendulum under the standard sea state conditions. It has been outlined above, that it is possible to observe a rotational response of the pendulum, however, it is reached at values of $\lambda \geqslant 1$ for $\gamma = 0.3$ and $\lambda \geqslant 0.5$ for low value of damping $\gamma = 0.01$. Rewriting $\lambda = A\omega^2/g$, where g is the acceleration of gravity, one can see that for the low damping case $A\omega^2 \geqslant g/2$, which is impossible to satisfy in the regular sea state with a significant wave height of about 1–1.5 m, because $\omega^2 \approx 0.4$ rad/s for $T = 10$ s or $\omega^2 \approx 0.8$ rad/s for $T = 7$ s waves. This issue could be overcome by using some mechanism to increase the input frequency, for instance a gearbox. However, the latter are known, from the extensive experience with wind turbines, to be very capricious and not very much reliable, thus would not provide a feasible solution to the problem. In this paper we offer another way out of this predicament.

Since parameter $\lambda = A\omega^2/g$ depends purely on the property of the waves, which cannot be changed or controlled, the gravity force is the only component that can be varied. Apparently the acceleration of gravity itself cannot be changed, however, the influence of the gravity force onto the system can. That is the main point of the novel WEC design that makes it very practical. Therefore in Secton 2 the new idea of a WEC concept is outlined and a new governing equation of motion is derived. This equation is solved numerically for deterministic and stochastic wave models and presented in the form of