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Ocean wave energy harvesting with a piezoelectric coupled buoy structure

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ABSTRACT

An expedient piezoelectric coupled buoy energy harvester from ocean waves is developed. The harvester is made of several piezoelectric coupled cantilevers attached to a floating buoy structure, which can be easily suspended in the intermediate and deep ocean for energy harvesting. In the buoy structure, a slender cylindrical floater is attached on a large sinker. The energy harvesting process is realized by converting the transverse ocean wave energy to the electrical energy via the piezoelectric patches mounted on the cantilevers fixed on the buoy. A smart design of the buoy structure is developed to increase the energy harvesting efficiency by investigation of the effects of the sizes of the floater and the sinker. A numerical model is presented to calculate the generated electric power from buoy energy harvester. The research findings show that up to 24 W electric power can be generated by the proposed expedient buoy harvester with the length of the piezoelectric cantilevers of 1 m and the length of the buoy of 20 m. The technique proposed in this research can provide an expedient, feasible and stable energy supply from the floating buoy structure.

1. Introduction

In the past decade, with the development of low powered devices and appliances, such as light-emitting diode (LED), low cost wireless sensors and wireless access points, the self-power technique and energy harvesting from ambient vibrations have attracted much attention [1–6]. Among the available mechanic-to-electric energy conversion mechanisms, such as electromagnetic, electrostatic and piezoelectric transductions, the energy density of the piezoelectric transduction is three times higher than electrostatic and electromagnetic transductions [7,8]. In addition, the structure of piezoelectric transducers is much simpler compared with the traditional generators. The piezoelectric materials can be easily attached to the electrical equipment and structures to provide the fast and convenient energy supply. Therefore, energy harvesting by piezoelectric materials has led to many different designs of piezoelectric energy harvesters [9–14]. To further improve the energy harvesting efficiency, different designs of electric circuits and structure optimisations were presented. By both numerical simulations and experimental studies, Liao and Sodano [15] studied a single mode energy harvester with different resistances to achieve a larger output electric power. Wang and Wang [16] proposed an optimal design of a collocated pair of piezoelectric patch actuators surface bonded onto beams. Wang and Wu [17] developed an optimal design of a piezoelectric patch mounted on a beam structure to achieve a higher power-harvesting efficiency through both numerical simulations and experimental studies. Xie et al. [18] developed a design of a piezoelectric coupled cantilever structure attached by a mass subjected to base motion to achieve an effective energy harvesting.

In addition, it is noted that there is a huge reservation of sustainable and clear energy on the earth, such as wind and ocean energy. The flowing power of winds is usually from a typical intensity of 0.1–0.3 kW/m^2 to 0.5 kW/m^2 on the earth surface along the wind direction, while the flowing power of ocean waves is round 2–3 kW/m^2 under the ocean surface along the direction of the wave propagation [19]. Therefore, based on the direct piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force), harvesting of renewable nature energies by piezoelectric materials has been initiated recently to pursue a clean and expedient self-contained energy source. Some research works have been conducted on development of new energy conversion technologies using piezoelectric materials to absorb the wind and flowing water energies in ocean and rivers. Ovejas and Cuadras [20] developed a wind energy harvester with thin piezoelectric films in a laminar wind tunnel and studied the electric power generation by experiments. Li et al. [21] also proposed and tested a bioinspired piezo-leaf architecture converting wind energy

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List of symbols

Y_0	length of the floater of the buoy under the average ocean wave level
Y_0'	height of the buoy sinker fixed at the bottom of the floater
l	length of the cantilever
h	thickness of the cantilever
Y_1	distance from the cantilever to the ocean surface
ζ_a	amplitude of the ocean wave
D_0	cross section area of the floater
D_1	cross section area of the sinker
b	width of the cantilevers and the piezoelectric patches
a	length of the piezoelectric patch
h_1	thickness of the piezoelectric patch
y	vertical direction of the wave motion
$w_o(y, t)$	water wave motion along the vertical direction.
ω_o	angular frequency of the ocean wave
H	ocean depth
k	wave number
λ	ocean wave length
ρ	density of the ocean water
C_m	coefficients of the inertia forces of the added mass when water particles pass through the buoy
Y	distance from the ocean surface to the bottom of the floater
Y'	distance from the ocean surface to the bottom of the sinker
C_D	coefficient of the drag force
N	number of the piezoelectric coupled cantilevers attached on the buoy harvester
$w(t)$	vibration displacement of the floating buoy
$w_{onb}(t)$	relative vibration displacement between the ocean wave and the piezoelectric cantilevers attached on the floating buoy
$w_b(x, t)$	deflection of the piezoelectric coupled cantilever subjected to the wave force
$P(t)$	water wave pressure applied on the cantilever
ρ_1	material density of the cantilever attached on the buoy
EI	flexural rigidity of the cantilever attached on the buoy
Q_g^i	charge on the surface of the ith piezoelectric patch attached on the cantilever
V_g^i	voltage on the surface of the ith piezoelectric patch attached on the cantilever
e_{31}	piezoelectric constant
C_V	electrical capacitance of the piezoelectric patches
C_V'	electrical capacitance per unit width of the piezoelectric patches
ω_n	natural angular frequency of the cantilever
$p_e(t)$	total electric power generated by all piezoelectric patches on the cantilevers attached on the buoy

into electric energy by wind-induced fluttering motion. An electric power output of 0.61 mW was generated by the harvester with a size of 72 mm × 16 mm × 0.41 mm. Gao et al. [22] reported a flow energy harvester based on a piezoelectric cantilever (PEC) with a cylindrical extension. This device uses flow-induced vibration of the cylindrical extension to directly drive the PEC to vibrate for harvesting the energy from ambient flows such as wind or water stream. Wu et al. [23] developed an energy harvester made of a cantilever attached by piezoelectric patches and a proof mass for wind energy harvesting from a cross wind-induced vibration of the cantilever. From the aforementioned research works, it is found that the harvested electric power from the wind energy is usually low due to the low energy density of the wind flows. In view of considerable large energy density from water flows and wave motions, for example ocean wave motions, which can easily exceed 50 kW per meter of wave front [24], harvesting energy from water flows and waves to electric energy by piezoelectric effects has been pursued as an alternative or self-contained power source. An energy harvester using a piezoelectric polymer 'eel' to convert the mechanical flow energy, available in oceans and rivers, to electric power was presented by Taylor et al. [25]. Zurkinden et al. [26] designed a piezoelectric polymer wave energy harvester from wave motions at a characteristic wave frequency and investigated the influences on generated energy by the free surface wave, the fluid-structure-interaction, the mechanical energy input to the piezoelectric material, and the electric power output using an equivalent open circuit model. Xie et al. [27,28] developed piezoelectric coupled plate structures, which are fixed on the sea bed and a base structure, to harvest the ocean wave energy. Burns [29] provided a piezoelectric device consisted of a buoy floating on the ocean surface, a few anchor chains fixed on the ocean-bed and an array of piezoelectric micro thin films between the buoy and chains, and showed that the device can generate electric power when the piezoelectric films bear tension and compression alternatively duo to the up and down motion of the buoy. Murray and Rastegar [24] presented a novel class of two-stage electric energy generators on buoyant structures. These generators use the interaction between the buoy and sea wave as a low-speed input to a primary system, which, in turn, to successively excite an array of vibratory elements (secondary system) into resonance.

From the previous studies, it has proven that energy harvesting from ocean waves by piezoelectric materials is effective and is able to generate sufficient electric power for small electric appliances [27]. However, most of piezoelectric energy harvesting structures in current studies are designed to be fixed on the sea bed, and hence are costly and mostly applicable to shallow ocean. In addition, it is obvious that the amount of the ocean wave energy in the intermediate and deep ocean with larger wave heights is much larger than the one in the shallow-water. Therefore, an urgent request for a more efficient, convenient and economical energy harvesting by piezoelectric materials from intermediate and deep oceans call for challenging engineering designs. In this research, an expedient and economical floating buoyant energy harvester is developed for energy harvesting from the intermediate and deep ocean waves. Piezoelectric coupled cantilevers are attached to the buoy directly and located close to the ocean surface to absorb the transverse ocean wave energy. To achieve an efficient energy harvesting, the smart design of the buoy structure made of a slender cylindrical floater attached on a large sinker is proposed to reduce the vibration amplitude of the buoy for increasing the efficiency of the harvester. The floating buoy with the smart design will be more cost-effective and convenient than the traditional tension leg platform structures. In addition, to study the effects of different designs of the buoy structure on the energy harvesting efficiency, a numerical model is proposed to calculate the generated electric power.

2. Design of the piezoelectric coupled buoy subjected to vertical wave motions

A model is developed to examine the efficiency of the new developed expedient buoy attached by piezoelectric coupled cantilevers to absorb the energy from ocean waves.

Fig. 1 illustrates schematically an energy harvesting buoy structure that is attached by piezoelectric coupled cantilevers floating