International Journal of Engineering Science 81 (2014) 41–48

Contents lists available at ScienceDirect

International Journal of Engineering Science

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

Energy harvesting from transverse ocean waves by a piezoelectric plate

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ARTICLE INFO

Article history:
Received 19 February 2014
Received in revised form 24 March 2014
Accepted 9 April 2014
Available online 6 May 2014

Keywords:
Energy harvesting
Ocean waves
Transverse wave motion
Piezoelectric harvester
Root mean square (RMS)

ABSTRACT

An ocean wave energy harvester from the transverse wave motion of water particles is developed by the piezoelectric effects. The harvester is made of two horizontal cantilever plates attached by piezoelectric patches and fixed on a vertical rectangular column. To describe the energy harvesting process, a mathematical model is developed to calculate the output charge and voltage from the piezoelectric patches according to the Airy linear wave theory and the elastic beam model. The influences on the root mean square (RMS) of the generated power from the piezoelectric patches, such as the ocean depth, the harvester location under the ocean surface, the length of the cantilevers, the wave height, and the ratio of wave length to ocean depth, are discussed. Results show that the RMS increases with the increase in the length of cantilevers and the wave height, and decrease in the distance of the ocean surface to the cantilevers and the ratio of the wave length to ocean depth. As a result, an optimum ocean depth is obtained to achieve a maximum RMS at different harvester locations under the ocean surface. A value of the power up to 30 W can be realized for a practical transverse wave with the values of the ocean depth, wave length, wave height and harvester location under the ocean surface to be 10.6 m, 21.2 m, 4 m, and −2 m, respectively. This research develops a novel technique leading to efficient and practical energy harvesting from transverse waves by piezoelectric energy harvesters that could be easily fixed on an offshore platform.

1. Introduction

Energy crisis and environmental problems such as global warming and atmospheric pollution have prompted people to study technologies of exploiting new energy. In the past decade, applications of piezoelectric materials in energy generation and harvesting have received much attention owing to their unique characteristics (Anton & Sodano, 2007; Cook-Chennault, Thambi, & Sastry, 2008; Kim, Kim, & Kim, 2011). A piezoelectric material is a type of smart materials exhibiting a direct piezoelectric effect of the internal generation of electrical charge resulting from an applied mechanical force and a reverse piezoelectric effect of the internal generation of a mechanical strain resulting from an applied electrical field http://en.wikipedia.org/wiki/Piezoelectricity, (Duan, Quek, & Wang, 2005; Wang & Quek, 2000, 2002; Wang, Quek, Sun, & Liu, 2001). Since early 2000, an amount of energy generators and harvesters by using piezoelectric effects, such as piezoelectric coupled cantilevers, shells, cymbals and stacks, with various designs of electrical circuits have been developed

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http://dx.doi.org/10.1016/j.ijengsci.2014.04.003
0020-7225/

(Cook-Chennault et al., 2008; Kim et al., 2011; Shu, Lien, & Wu, 2007; Wickenheiser, Reissman, Wu, & Garcia, 2010; Xie, Wang, & Wu, 2014; Xie, Wu, Yuen, & Wang, 2013). In addition, many research works were conducted on optimizing designs of piezoelectric coupled structures (Shenck & Pradiso, 2001; Wang & Wang, 2000; Yang, Yeo, & Priya, 2012) for more effective energy harvesting. These devices aimed to achieve practical portable microelectromechanical systems (MEMS) Cook-Chennault et al., 2008 via collecting energy of human actives, such as men's working (Wang & Wu, 2012) and the bikes' motions (Friswell & Adhikari, 2010).

Recently, many research studies were conducted on piezoelectric energy harvesting from ambient vibrations (Khaligh, Zeng, & Zheng, 2010; Li, Yuan, & Lipson, 2011; Nader, Zhu, & Cooper, 2012; Vatansever, Hadimani, Shah, & Siores, 2011; Wu, Wang, & Xie, 2013) by natural energies such as solar energy, wind energy, and ocean-wave energy. Vatansever et al. (2011) evaluated energy harvesting from ceramic based piezoelectric fiber composite structures subjected to different wind loadings. Li et al. (2011) introduced a bio-inspired piezo-leaf architecture, which was in dangling cross-flow stalk that converted wind energy into electrical energy, by wind-induced flutter motion. Wu et al. (2013) developed an effective and compact wind energy cantilever harvester subjected to a cross wind. Sufficient electrical energy output as high as 2 watts was realized by tuning the resonant frequency of the harvester with a proof mass on the tip of the cantilever. As is indicated, wind energy has a larger energy density than the solar energy, and ocean-wave energy is more persistent and spatially concentrated than the wind energy (Falnes, 2007). Generally, the density of the ocean wave-energy is 4–30 times of that of wind energy (Zhang & Lin, 2011). Therefore, it is more efficient and effective to develop new technologies in harvesting the ocean wave-energy with piezoelectric materials.

In view of considerable large powers from ocean wave motions, which can easily exceed 50 kW per meter of wave front (Murray & Rastegar, 2009), harvesting energy from ocean waves to electrical energy by piezoelectric effects has long been pursued as an alternative or self-contained power source. Zurkinden, Campanile, and Martinelli (2007) designed an ocean wave energy converter consisting of a flexible foam substrate attached by piezoelectric layers and simulated the efficiency of converting wave energy to electric energy by considering influences from different aspects such as 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. Taylor, Burns, Kammann, Powers, and Welsh (2001) developed a flexible polyvinylidene fluoride (PVDF) "eel" device to convert the mechanical energy in ocean or river water flows into electricity using the regular traveling vortex behind the bluff body to strain the piezoelectric elements. Using a similar principle, Li and Lipson (2009) explored a "piezo-leaf" energy-harvesting system where the PVDF strip of the "eel" system was replaced by a PVDF cantilever with a large triangular plastic "leaf" attached to the free end of the cantilever to improve the power generation. Burns (1987) provided a piezo 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. Taylor (1980) developed a piezoelectric device made of a buoy, the supporting structure, and piezoelectric layered sheets floating on the surface and anchor chains. The dimensions of each piezoelectric layered sheet were designed according to the wave length to improve the efficiency of wave energy conversion. Murray and Rastegar (2009) presented a two-stage electrical energy generators with two decoupled systems using the mechanism of strumming a guitar, in which low-frequency heaving-buoy can successively excite an array of vibratory elements (secondary system) into resonance and wave energy can be efficiently harvested using piezoelectric elements from the resonant secondary system.

Previous studies on the source of the ocean wave energy harvesting with piezoelectric materials can be classified into two main categories: (1) vibrations caused by small longitudinal wave motions near the seabed or the vortex caused by the bluff body fixed on the seabed, and (2) vibrations of heaving-based buoy on the sea surface. In all these cases, only limited electric energy could be generated since the wave motions were not used directly and efficiently. Meanwhile, there has been very little amount of work dedicated to the theoretical framework of the energy harvesting from the transverse ocean wave motions using piezoelectric coupled structures. Therefore, a comprehensive model is indispensable in designs of the piezoelectric harvesters.

In the monochromatic linear plane waves in deep water, particles near the surface move in circular paths, making water waves a combination of longitudinal and transverse wave motions. As the depth below the free surface increases, the radius of the circular motion decreases. At a depth equal to half the wavelength, the orbital movement has decayed to less than 5% of its value at the surface (http://en.wikipedia.org/wiki/Ocean_wave). In other words, in deep oceans, the energy from the longitudinal wave motion near the surface decays exponentially, and only transverse wave motions could be used efficiently by a harvester under the ocean. Therefore, it is anticipated that a more efficient energy harvesting technique can be developed to fully utilize the transverse wave motion in contrast to the aforementioned techniques that benefit only from the vertex, longitudinal wave vibration near the ocean-bed or the heaving buoy. In order to achieve this goal, a mathematical model is developed to investigate and calculate the energy harvesting from a simple and portable piezoelectric cantilever that can be easily fixed on a fixed structure under ocean or floating structures such as an offshore platform (see Fig. 1(b)). The collected electrical energy is realized by the electromechanical coupling effect of the piezoelectric patches from the transverse wave motion near the surface of ocean according to the linear Airy wave theory and the Euler–Bernoulli beam theory. The energy harvesting under different conditions, such as the cantilever location under ocean surface, the ocean depth, the wave height, the length of the cantilevers and the ratio of the wave length to the ocean depth, is calculated and discussed. It is expected that the device directly makes full use of the energy from the transverse wave motion near the surface of ocean to generate higher electric power that is sufficient for small power electric appliances of offshore platform.