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Novel piezoelectric-based ocean wave energy harvesting from offshore buoys

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ABSTRACT

Ocean wave energy is one of the huge energy sources, which easily wasted around us. Because of low frequency of the ocean waves, less attention has been paid on vibration-based energy harvesting from this energy source. In this study, a novel beam-column piezoelectric-based energy harvesting system is studied, which can be optimally used as an Ocean Wave Energy Harvester (OWEH). In doing so, the electromechanical equations of motion for the energy harvesting system are accurately derived. The results, which are obtained using the governing equations, are validated by experimental results. Then application of the presented energy harvesting system, which is installed in offshore buoys, is studied. It is shown that harvested energy is enough to provide needed energy of the electrical devices in the buoy. It is shown that the energy harvesting system in the buoy, which is subjected to large wave height and low frequency, is more efficient. Finally, application of the self-tuning buoy, which works based on the ocean wave frequency, is studied. The presented novel system opens new field of research that helps to use the ocean wave energy in a proper way.

1. Introduction

Nowadays, regarding to unlimited demand of energy, many studies are focused on energy harvesting [1,2]. The main aim of these investigations is producing useful energy from sources of energy, which are wasted [3,4]. The ocean wave energy is one of these sources of energy [5–8]. Energy density of the ocean waves is higher than other renewable resources such as solar and wind energy [5]. In case of the deep water ocean waves, average of the energy flux per width of waves is between 40 and 70 KW [5]. The Ocean Wave Energy Harvesting (OWEH) can be divided into three parts: (a) absorber; (b) transducer; and (c) power storage. An absorber collects ocean waves and can be categorized in onshore such as Limpet [9], near shore such as Wavestar [10] and offshore such as Pelamis [11]. The problem with these absorbers is the occupied space, which can negatively effect on environment. Furthermore, it should be noted that the wave energy decreases near coastline and the deep water in offshore is better place for energy harvesting [5].

Because of multifunctional application of buoy, which is originally a navigation device, in this study these systems are chosen as absorber. Between the electromagnetic, piezoelectric and turbine transducers, which have been used in OWEH [5–8], the piezoelectric method is chosen in this study. The energy density of piezoelectric energy harvesting is three times bigger than electromagnetic energy harvesting [12]. Also, piezoelectric transductions occupy smaller space than turbine transductions.

Historically, Persian windmills (500–900 A.D.) were the first wave energy harvesting systems [13]. Therefore, the wave energy harvesting is one of the human's ancient skills. In past decade, Zurkinden et al. introduced a wave energy harvesting structure, which includes piezoelectric layers with foam core [14]. Murray and Rastegar simulated and studied a piezoelectric OWEH [15]. They discussed about efficiency of converting the ocean wave energy to electrical energy. Orazov et al. studied dynamics of buoy-type energy harvesting system using the mass-spring model [16]. Erturk and Delporte used flexible piezoelectric composites as an energy harvester in underwater system [17]. Cha et al. investigated different geometry of underwater piezoelectric composite beams subjected to base excitation [18]. Xie et al. suggested an energy harvesting system, which focused on longitudinal motions of sea waves [19]. Piezoelectric-based energy harvesting from the transverse ocean waves was studied by Xie et al. [20]. Ionic polymer metal composite was used as transducer in special under water energy harvesting system [21]. Wu et al. presented OWEH with a several piezoelectric coupled cantilever attached to a buoy structure [22]. Viet et al. presented a floating mass-spring energy harvesting system with piezoelectric bar [23]. Hwang et al., in their study, focused on multi-directional systems to harvest energy of ocean waves [24]. Mutsuda et al. studied a novel painted piezoelectric device to use as an ocean energy harvester and

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investigated the relationship between output voltage and parameters of ocean [25].

In the present study, the main idea is present an OWEH, which both of the wave frequency and wave height are considered in its design. Unlike previous studies done on application of large-scale systems, which can work with low frequency, in the present study, a small-scale OWEH is considered. For this reason, a beam-column piezoelectric structure is proposed and a novel theoretical approach for studying behavior of this system is presented. By considering mass ratios, natural frequencies of system can simply be obtained based on parameters of the beam-column. Therefore, a small-scale OWEH, which can work near the frequency of resonance, can be designed. Consequently, the presented OWEH can provide maximum electrical energy. This system can be used in small-scale buoy for generating needed electrical energy of low power consumption sensors. In doing so, system is theoretically modeled and its governing electromechanical equations of motion are experimentally validated. Then regarding to the linear ocean wave assumptions and using the real data of weather stations, application of the presented system is studied.

2. Mathematical modeling

Consider a clamped-guided beam-column of length L and flexural stiffness EI with tip mass M_{tip} as shown in Fig. 1. Note that subscripts b and p respectively denote beam and piezoelectric. Furthermore, ρ, t_b and t_p are respectively mass density, beam thickness and piezoelectric thickness. The clamped-guided piezoelectric beam is connected to the moving mass (M_{base}), which is exposed to external load F and K and C are stiffness and damping coefficient. Variable w is the transverse displacement of the beam-column. The displacement of M_{base} is shown with Z. Furthermore, L is length of beam-column.

In the presented study, regarding to the Euler Bernoulli beam theory, the piezoelectric device is modeled as clamped-guided beam with tip mass. Based on the Euler-Bernoulli theory, the equation of the potential energy for the presented system is as follows:

$$\pi = \int_0^L (EI_b + EI_p)\left(\frac{\partial^2 w}{\partial x^2}\right)^2 dx - \int_0^{L_e} zw_p V e_{31}\left(\frac{\partial^2 w}{\partial x^2}\right)dx + \frac{1}{2}KZ^2 \tag{1}$$

where V and L_e are electrical voltage and effective length. Furthermore, e_{31} is effective piezoelectric stress constant. The kinetic energy for the system can be written as follows:

$$T = \int_0^L (\rho_b t_b w_b + \rho_p t_p w_p)\left(\frac{\partial w}{\partial t} + \dot{Z}\right)^2 dx + \frac{1}{2}M_{base}\dot{Z}^2 + \frac{1}{2}M_{tip}\left(\dot{Z} + \frac{\partial w}{\partial t}\bigg|_{x=L}\right)^2 \tag{2}$$

where w_b and w_p are respectively the beam and piezoelectric width.

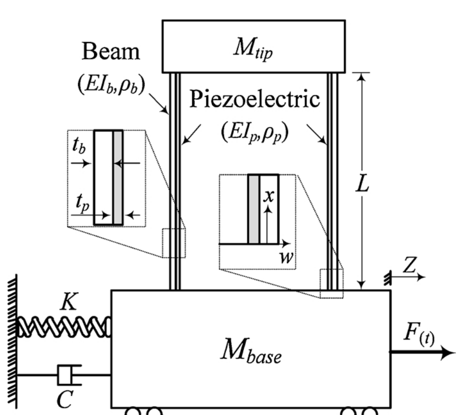

Fig. 1. Schematic of the clamped-guided piezoelectric beam with tip mass.

The internal electrical energy in the presented system can be given by:

$$W_{ie} = -\int_0^{L_e} zw_p e_{31} V\frac{\partial^2 w}{\partial x^2}dx - \int_0^L w_p e_{33} V^2/t_p\, dx \tag{3}$$

where e_{33} is permittivity component at constant strain and the piezoelectric layer width. Furthermore, z is distance from neutral axis. The non-conservative virtual work of the system is written as follows:

$$\delta W_e = F\,\delta Z + N\int_0^L \frac{\partial w}{\partial x}\delta\left(\frac{\partial w}{\partial x}\right)dx - Q\delta V - C\dot{Z}_i\delta Z - f_d\delta q_i \tag{4}$$

where N is the axial load and in this study it is equal to $M_{tip}g$ and F is the external load [26]. Furthermore, Q is the electric charge and f_d is the damping force. Using the separation of variable method, displacement of the beam can be given as follows:

$$w(x,t) = \sum_{i=1}^{n}\varphi_i(x)\,q_i(t) \tag{5}$$

where φ(x) and q(t) indicate mode shape and the time response. The electromechanical Lagrange equations can be expressed as [27]:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial \pi}{\partial q_i} - \frac{\partial W_{ie}}{\partial q_i} = N\,q_i\int_0^L\left(\frac{d\varphi}{dx}\right)^2 dx - f_d \tag{6}$$

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{Z}}\right) - \frac{\partial T}{\partial Z} + \frac{\partial \pi}{\partial Z} - \frac{\partial W_{ie}}{\partial Z} = F - C\dot{Z} \tag{7}$$

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{V}}\right) - \frac{\partial T}{\partial V} + \frac{\partial \pi}{\partial V} - \frac{\partial W_{ie}}{\partial V} = Q \tag{8}$$

Substituting Eq (5) into Eqs (1–3) and regarding to the Lagrange equations, the following relations will be obtained:

$$m_{eq}\ddot{q}_i + c_{eq}\dot{q}_i + (k_{eq} - k_g)q_i - \theta\,V = -m^*\ddot{Z} \tag{9}$$

$$M_{eq}\ddot{Z} + C\,\dot{Z} + K\,Z = F - m^*\ddot{q} \tag{10}$$

$$C_p\,\dot{V} + V/R + \theta\dot{q}_i = 0 \tag{11}$$

where the coefficients of the above equations and the capacitance of piezoelectric layer C_p are expressed as:

$$m_{eq} = 2\int_0^L (\rho_b t_b w_b + \rho_p t_p w_p)\varphi^2 dx + M_{tip}\varphi^2(L) \tag{12}$$

$$m^* = 2\int_0^L (\rho_b t_b w_b + \rho_p t_p w_p)\varphi\, dx + M_{tip}\varphi(L) \tag{13}$$

$$k_{eq} = 2\int_0^L (E_b I_b + E_p I_p)\left(\frac{d^2\varphi}{dx^2}\right)^2 dx \tag{14}$$

$$k_g = N\int_0^L\left(\frac{d\varphi}{dx}\right)^2 dx \tag{15}$$

$$c_{eq} = 2\zeta\sqrt{k_{eq}m_{eq}} \tag{16}$$

$$\theta = 2\int_0^{L_e} z\,w_p e_{31}\left(\frac{d^2\varphi}{dx^2}\right)dx \tag{17}$$

$$M_{eq} = 2(\rho_b t_b w_b + \rho_p t_p w_p)L + M_{tip} + M_{base} \tag{18}$$

$$C_p = 2\int_0^L w_p e_{33}/t_p\, dx \tag{19}$$

In the above equations, ζ is the damping. Regarding to the Euler-Bernoulli theory, the mode shape of vibration for the system can be written as follows:

$$\varphi_i(x) = C_i\{\cos(\lambda_i x/L) - \cosh(\lambda_i x/L) + \sigma_i(\sin(\lambda_i x/L) - \sinh(\lambda_i x/L)\} \tag{20}$$

where λ_i is the eigenvalue of the ith vibration mode, which can be obtained using the characteristic equation. This equation is derived regarding to the eigenfunction and the boundary conditions. The