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Optimum resistance analysis and experimental verification of nonlinear piezoelectric energy harvesting from human motions

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ABSTRACT

The complex dynamic behavior of nonlinear harvesters make it difficult to identify the optimum mechanical and electrical parameters for maximum output power, when compared to linear energy harvesting devices. In addition, the chaotic and multi-frequencies characteristics of responses under realistic human motion excitations provide additional challenges for enhancing the energy harvesting performance, such as the traditional frequency domain method being inappropriate for optimum resistance selection. This paper provides detailed numerical and experimental investigations into the influence of resistance on the efficiency of nonlinear energy harvesting from human motions. Numerical simulations under human motions indicate that optimum resistance of a nonlinear harvester can be attained to maximize the power output. Moreover, simulations of linear and nonlinear harvesters under harmonic excitations verify the effectiveness of frequency dominant method to obtain optimum resistance in the absence of a change in the dynamic behavior of the harvester. However, numerical simulations and experiments are the effective methods when the harvester shows complex dynamic characteristics. Experimental measurements of harvested power under different motion speeds and resistances are in agreement to the numerical analysis for the nonlinear harvester. The results demonstrate the effectiveness of the proposed resistance optimization method for nonlinear energy harvesting from human motions.

1. Introduction

Vibration energy harvesting techniques have received considerable attention in recent decades due to its promising ability to convert ambient vibration energy to useful electrical energy for the supply of electricity for low-power consumption devices such as sensors and wireless transceivers [1–3]. In particular, the use of energy harvesting for body-worn or body-attached applications has been the subject of a significant amount of research interest as it has the potential to power modern low-power sensor systems and increase the mobility and independence of users [4–6]. Currently, there are a variety of transduction mechanisms based on piezoelectric [7–9], electromagnetic [10,11], or thermoelectric [12] effects for converting human kinetic energy and motion to usable electric energy. Among them, piezoelectric vibration energy harvesting has been considered to be a promising method to harness natural body movements to power wearable electrical devices such as healthcare watches, pacemakers, and mobile phones, due to its high energy density and easily miniaturized fabrication [13]. In order to overcome the inability of linear energy harvesters to perform well under stochastic excitations, such as ambient vibrations and low-frequency human motion, the theoretical analysis and experimental validation of the frequency bandwidth and performance enhancement of harvesters as a result of introducing nonlinear phenomenon has received significant interest [14–16]. This includes a number of investigations on monostable [17–19], bistable [20–22] and tristable [23–27] configurations under harmonic and stochastic excitations. The results of these studies indicate that the introduction of nonlinearity can improve the energy harvesting performance, but the efficiency is greatly influenced by the shape of potential energy function of the harvesting system [26]. Furthermore, extensive research had been carried out to determine the set of optimum mechanical and electrical parameters, such as the damping, electromechanical coupling coefficient and resistance, in order to maximize the output power of both linear and nonlinear energy harvesters [28–33]. Previous

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investigations on energy harvesters are almost all under harmonic and stochastic excitation. However, real excitation signals generated by human motion exhibit a degree of randomness and variability [11], which will increase the difficulty to determine the optimal performance only using electromechanical models and may result in the inability of the traditional analysis methods used for harmonic and stochastic excitation to determine the optimum conditions. Therefore, an effective method should be developed to optimize the mechanical and electrical parameters for maximum energy generation under real human motion excitation.

A number of research publications have been devoted to determine the optimum resistance for maximizing the power output of vibration energy harvesters under different ambient excitations. Roundy [31] developed an analytical model of a linear piezoelectric energy harvester and based on which the optimum resistance of a linear piezoelectric energy harvester under harmonic excitation was derived by applying the Laplace transform. Cammarano et al. [28] discussed the optimum load resistance for a linear electromagnetic energy harvester by applying a Fourier transform, and also gave the optimum resistance of nonlinear harvester under fixed frequency excitation based on the harmonic balance method by neglecting the high order harmonic. Moreover, the results of Wang [32] and Zhao [33] indicated that there always existed an optimum load resistance for the linear piezoelectric energy harvester under harmonic or white noise excitation. Although these analytical and experimental investigations of the optimum load resistance of linear or nonlinear energy harvesting under the ideal harmonic and stochastic excitation have been undertaken, the investigation of the optimum resistance of nonlinear piezoelectric energy harvester under real human motion has not been studied.

Therefore, this paper undertakes a detailed investigation into the relationship between output power and load resistance of the nonlinear piezoelectric energy harvester under real human motion excitations. Numerical simulation and experimental verification are conducted to obtain the optimum resistance of a nonlinear energy harvester under a variety of human motion speeds. Firstly, the electromechanical model of the piezoelectric energy harvester is derived according to Hamilton's principle and based on which the optimum load resistance of linear energy harvester is analyzed theoretically by applying a Fourier transform. Then, the numerical investigation of linear and nonlinear energy harvesters under real human motion excitation or fixed frequency harmonic excitation is presented to demonstrate that there is always a peak in the average power output for a range of load resistance when subjected to human motions or harmonic excitation. Finally, a nonlinear energy harvester is designed to harvest energy from human lower-limb motion under different speeds of motion for various load resistances, and the experimental measurements of the harvested power are in agreement to the numerical analysis.

2. Nonlinear electromechanical model

Introducing nonlinearity to energy harvesting system by applying magnetic force to alter the stiffness of the harvester has been investigated by many groups [13,14,16–18,21,22] and their results exhibited great performance enhancement. Fig. 1(a) illustrates the nonlinear energy harvester with two external rotatable magnets proposed by Zhou [21]. This configuration consists of a stainless steel substrate, two symmetric PZT-51 piezoelectric layers at the root, tip magnet attachments and external magnets. Monostable, bistable and tristable configurations can be obtained by adjusting the magnetic force actuating on the cantilever depending on the parameters h, d and α shown in Fig. 1(a).

When the external magnets are removed, the configuration will become a linear energy harvester. For the linear configuration, according to Hamilton principle, the variational indicator (V^I) should be zero all the time through Lagrange function. It is shown as

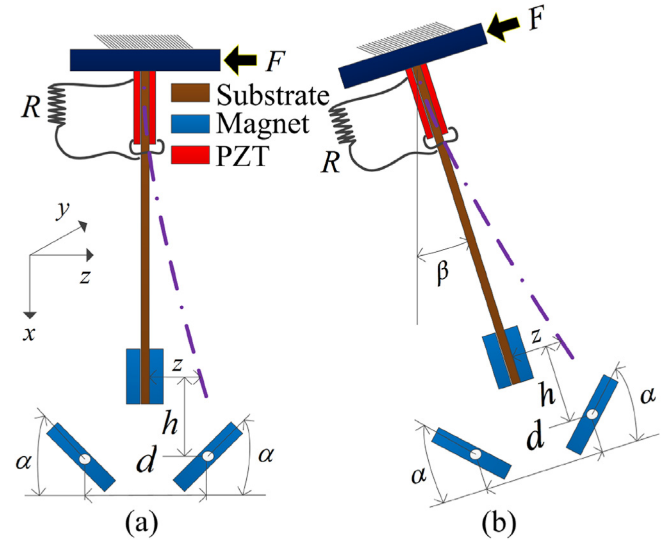

Fig. 1. (a) Schematic of the nonlinear energy harvester; (b) system swing a certain angle.

$$V^I = \int_{t_1}^{t_2} [\delta E_k - \delta E_p + E_a]\, dt = 0 \tag{1}$$

where δ is the variational symbol. And E_k, E_p, E_a respectively represent the kinetic energy, potential energy and the external work applied to the system, which can be expressed by

$$\begin{cases} E_k = 0.5\int_{V_s} \rho_s \dot{\boldsymbol{u}}_t \dot{\boldsymbol{u}} dV_s + 0.5\int_{V_p} \rho_p \dot{\boldsymbol{u}}_t \dot{\boldsymbol{u}} dV_p + 0.5 m_{tip} \dot{\boldsymbol{u}}_t(x_{tip}) \dot{\boldsymbol{u}}(x_{tip}) \\ E_p = 0.5\int_{V_s} \boldsymbol{S}_t \boldsymbol{T} dV_s + 0.5\int_{V_p} \boldsymbol{S}_t \boldsymbol{T} dV_p - 0.5\int_{V_p} \boldsymbol{E}_t \boldsymbol{D} dV_p \\ E_a = \sum_{i=1}^{N_f} \delta \boldsymbol{u}(x_i) \cdot f_i(x_i) - \sum_{j=1}^{N_q} \delta v \cdot q_j \end{cases} \tag{2}$$

where V_s, V_p are the volume of the substrate and piezoelectric layers, ρ_s, ρ_p are the material density of substrate and piezoelectric layers. $\boldsymbol{u}$ is the vector of deflection along x direction, while x and m_{tip} represent the position along the cantilever and the mass of tip magnets. f is the applied force, v is the applied voltage and q is the charge. N_f and N_q are the numbers of forces and charges applied to the cantilever. Also, the subscript $()_t$ signifies the transpose of matrix, while the subscripts $()_s$ and $()_p$ respectively represent the substrate and piezoelectric layers. Further, $\boldsymbol{S}$, $\boldsymbol{T}$, $\boldsymbol{D}$, $\boldsymbol{E}$ respectively are the vector of strain, stress, electric displacement and electric field, and they satisfy the constitutive equation expressed by

$$\begin{cases} \boldsymbol{T} = c_E \boldsymbol{S} - e^T \boldsymbol{E} \\ \boldsymbol{D} = e\boldsymbol{S} + \varepsilon_s \boldsymbol{E} \end{cases} \tag{3}$$

where c is the modulus of elasticity, e is piezoelectric coupling coefficient and ε is the dielectric constant. In order to solve the equations for the piezoelectric cantilever, it is supposed that the piezoelectric cantilever follows the Rayleigh-Ritz theory which says