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Design of a piezoelectric harvester fixed under the roof of a high-rise building

X.D. Xie [a], Q. Wang [b,c,*]

[a] School of Mechanical and Automotive Engineering, Hubei University of Arts and Science, Xiangyang, Hubei 441053, China
[b] Department of Civil and Architectural Engineering, City University of Hong Kong, Kowloon, Hong Kong
[c] Department of Mechanical Engineering, Khalifa University, PO Box 127788, Abu Dhabi, United Arab Emirates

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ABSTRACT

A theoretical model for a piezoelectric harvester device is developed by an iteration method to determine the maximum energy harvested from vibration of high-rise buildings. The piezoelectric harvester device is made of a cantilever fixed under the roof of a building and two groups of series piezoelectric generators connected by a shared shaft. The shaft is driven by a linking rod hinged on a proof mass on the tip of the cantilever. The influences of some practical considerations, such as the length of the cantilever, the radius of the proof mass, and the wall thickness of the main structure, on the root mean square (RMS) of the generated electric power and the energy harvesting efficiency of the piezoelectric harvester device are discussed. The research on the theoretical model provides a new method for an efficient and practical energy harvesting from high-rise buildings by a piezoelectric harvester device fixed under their roofs.

1. Introduction

The mostly available vibration-to-electric conversion mechanisms are electromagnetic, electrostatic, and piezoelectric transductions. Among the three types of energy transductions, the efficiency of piezoelectric transductions is preferred and much higher than the other two. It was reported that the energy density of piezoelectric transductions is three times higher than the other two transductions [1,2]. 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 [3–7].

Many research studies on applications of piezoelectric materials to energy conversion from ambient environmental vibrations have been developed. Rocha et al. [8] investigated an application of piezoelectric polymers to energy harvesting from people walking. Designs of shoes capable of generating and accumulating the energy were discussed. Ajitsaria et al. [9] provided a modeling of a lead zirconium titanate (PZT) bender for voltage and power generation by transforming ambient vibrations into electric energy to supply powers in a microwatt range for operating sensors and data transmission. Waleed et al. [10] proposed a design and testing of a vibration energy harvester with tunable resonance frequency, wherein the tuning is accomplished by changing the attraction force between two permanent magnets by adjusting the distance between the magnets. Wang and Wu [11] developed an optimal design of a piezoelectric patch mounted on a beam structure to achieve a higher power-harvesting efficiency by both numerical simulations and experimental studies. Juergen and Gerda [12] optimized a vibrating cantilever beam in a power harvesting application and studied the influence of different distribution of piezoelectric layers and attached electric circuits on the energy harvesting.

From the aforementioned works, piezoelectric devices based on structural vibration have been studied extensively in the literature and a considerable amount of effort has been made to optimize the piezoelectric structures to enhance the electrical outputs. However, it has been acknowledged that the electric power obtained from the ambient vibration with available electronic devices based on piezoelectric materials was only in an order of mW [13].

Vibrations from ambient environments can be very huge. For example, the flowing power of ocean waves is round 2–3 kW/m^2 under the ocean surface along the direction of the wave propagation [14]. Harvesting vibration energy from ambient environments with piezoelectric technologies would provide an effective and efficient way for numerous applications such as charging a vehicle

* Corresponding author at: Dept of Mechanical Engineering, Khalifa University, Abu Dhabi, United Arab Emirates. Tel.: +971 (0)2 501 8437.
E-mail address: quan.wang@kustar.ac.ae (Q. Wang).

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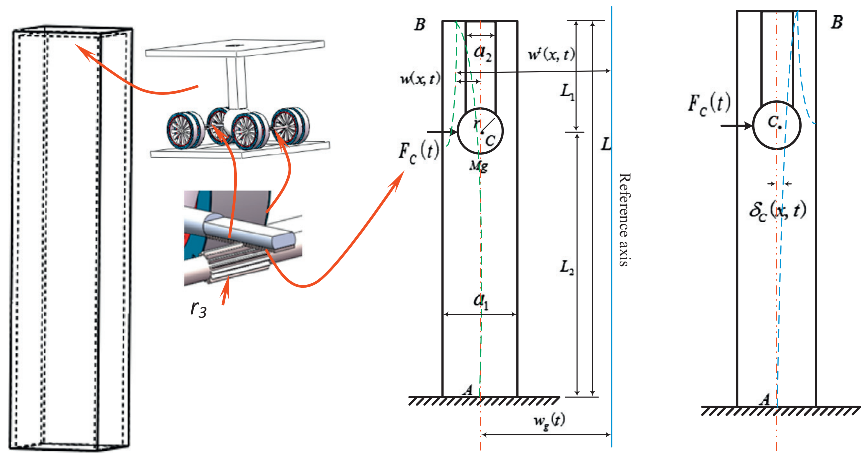

(a) A piezoelectric harvester model (b) An analytical model of a piezoelectric harvester (c) An equivalent excitation model

Fig. 1. An analytical model of a high-rise building with a piezoelectric harvester device fixed under its roof.

by harvesting its suspension vibration energy, supplying electricity for ocean equipment by harvesting wave energy, or providing housing power by absorbing the vibration energy from high-rise buildings under wind or earthquake motions. Though relative few, there are still some interesting initiatives in the research on harvesting vibration energy from piezoelectric materials on the order of Watts or even kilowatts. Xie et al. [15] introduced an optimal design based on a newly proposed model of a piezoelectric coupled cantilever structure with a proof mass to achieve a higher efficient energy harvesting from high-level buildings. A new kind of semi-active energy-regenerative suspension system was proposed to recover the suspension vibration energy, as well as to reduce the suspension cost and demands for the motor-rated capacity [16]. A design and optimization of tubular LETs (linear electromagnetic transducers) was further presented for vibration energy harvesting from vehicle suspensions, and an average power of 26–33 W was found to be achieved at a RMS (root mean square) of suspension velocity of 0.25 m/s for different LETs of an outer diameter of 3″ and a compressed length of 12″ [17]. A design, modeling, bench experiments, and road tests were proposed for a retrofit regenerative shock absorber based on a permanent magnetic generator and a rack-pinion mechanism for energy harvesting and vibration damping [18]. A peak power of 68 W and average power of 19 W were attained from one prototype shock absorber when the vehicle is driven at 48 km h^{-1} (30 mi h^{-1}) on a fairly smooth campus road. Xie and Wang [19] developed a dual-mass piezoelectric bar harvester for energy harvesting from ambient vibrations of a vehicle suspension system subjected to roughness of road surfaces. A power up to 738 W can be realized for a practical design of the harvester with a width and height of the piezoelectric bar of 0.015 m and 0.1 m respectively. Xie and Wang [20] presented a theoretical model for a dual-mass piezoelectric ring tire harvester by an iteration method to determine the energy harvested from excitations of vehicle tires by rough roads, and designed a practical harvester which has a RMS of electric power of 42.08 W. Two sea wave piezoelectric energy harvesters were introduced to harvest electric energy from longitudinal or transverse wave motions of water particles [21,22]. Their results show that the harvesters can generate a power up to 55 W and 30 W for a practical longitudinal and transverse wave motions, respectively. Murray and Rastegar [23] presented a two-stage electrical energy generators with two decoupled systems using the mechanism of strumming a guitar, in which wave energy can be efficiently harvested using piezoelectric elements from the resonant secondary system. Gao et al. [24] reported a flow-energy-harvesting device consisting of a piezoelectric cantilever (PEC) with a cylindrical extension. This device utilizes fluid forces on the cylindrical extension to directly drive the PEC to vibrate. Results showed that it is more effective and compact compared to the piezoelectric windmill, eel, and leaf. Xie et al. [25] developed a ring piezoelectric energy harvester excited by magnetic forces and found that a power up to 5274.8 W can be realized for a harvester with a radius around 0.5 m.

The above researches show that applications of piezoelectric harvesters can generate tens to thousands of watts of electric power by absorbing ambient vibration energy. However, the generating capacities of these harvesters are still limited compared to the energy from the large-scale vibration such as high-rise buildings under wind or earthquake. Zhuet al. [26] had verified that the vibration energy of a high-rise building can be effectively harvested by novel linear motion electromagnetic (EM) devices to weaken its kinetic response. Up to now, there has been no report on applications of piezoelectric harvester in large-scale buildings although piezoelectric converter has a much larger energy density than EM converter. In order to explore the potential of piezoelectric harvesters to maximize the harvested energy or energy dissipated from the building vibration, a design of piezoelectric harvester device which consists of a cantilever fixed under the roof of a building and two groups of series piezoelectric generators connected by a shared shaft is introduced. A new dynamic mathematical model for the harvester is developed. The theoretical model is aimed to explore a maximum amount of energy harvested from the high-rise building while dissipating the vibration excited to high-rise buildings.

2. Introduction of the analytical model

An analytical model of a piezoelectric harvester device fixed under the roof of a high-rise building is developed and shown in Fig. 1(a)–(c). The piezoelectric harvester device shown in Fig. 1(a) is made of a cantilever and two groups of series piezoelectric generators connected by a shared shaft. The shaft is driven by a linking rod hinged on a proof mass on the tip of the cantilever fixed under the roof of the building. The generators can transfer a large amount