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# A ring piezoelectric energy harvester excited by magnetic forces

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

[a] School of Mechanical and Automotive Engineering, Hubei University of Arts and Science, Xiangyang, Hubei 441053, China
[b] Department of Mechanical Engineering, University of Manitoba, Winnipeg, Manitoba R3T 5V6, Canada

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ABSTRACT

A ring piezoelectric harvester excited by magnetic forces with high excitation frequencies is developed. The harvester is made of a concentric outer ring stator and an inner ring rotator. The stator ring is made of a series of discrete piezoelectric patches with a rectangular shape surface mounted by magnetic ring slabs with the same size. All the piezoelectric patches and the magnetic slabs are placed on an aluminum ring. The rotator ring is made of a serious of magnetic rectangular slabs mounted on an aluminum ring with the exact size of the corresponding piezoelectric patches on the stator. Because of periodic magnetic forces between the stator ring and the rotator ring, a compression is induced to the piezoelectric patches leading to an electric charge for energy harvesting. To describe the energy harvesting process, a mathematical model is used to calculate the output charge and voltage from the piezoelectric patches. The influences of the size of the piezoelectric harvester and the rotating speed of the rotator ring on the root mean square of the generated electric power are discussed. Our results show that a power up to 5274.8 W can be realized for a practical design of the harvester with a radius around 0.5 m. This research develops a novel technique for an efficient and practical energy harvesting from the developed ring piezoelectric energy harvesters.



## 1. Introduction

Among the available vibration-to-electric energy conversion mechanisms such as electromagnetic, electrostatic and piezoelectric transductions, piezoelectric transduction is preferred because its energy density is three times higher than the other two transductions (Priya, 2007; Williams & Yates, 1996). Many research works on applications of piezoelectric materials to energy conversion from ambient environmental vibrations have been conducted (Duan, Quek, & Wang, 2005; Wang & Quek, 2000, 2002; Wang, Quek, Sun, & Liu, 2001). Wang and Wang (2000) proposed an optimal design of a collocated pair of piezoelectric patch actuators that are surface bonded onto beams. The design involves selecting the optimal locations and sizes (or lengths) of the piezoelectric actuators based on a controllability perspective. Rocha, Gonçalves, Rocha, Silva, and Lanceros-Méndez (2010) investigated an application of piezoelectric polymers in energy harvesting from people walking and designs of shoes capable of generating and accumulating the energy were discussed. Ajitsaria, Choe, Shen, and Kim (2007) 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. By both numerical simulations and experimental studies, Liao and Sodano (2008) introduced a theoretical model of a simply piezoelectric energy harvesting system for an accurate prediction of generated powers. Waleed, Matthias, Tobias, and Walter (2012) proposed a design and testing of a vibration energy harvester with tunable resonance frequency, wherein the tuning

* Corresponding author. Tel.: +1 204 474 6443.
*E-mail address:* q.wang@ad.umanitoba.ca (Q. Wang).

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is accomplished by changing the attraction force between two permanent magnets by adjusting the distance between the magnets. Wang and Wu (2012) 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. Xie, Wu, Yuen, and Wang (2013) introduced an optimal design of a piezoelectric coupled cantilever structure attached by a mass subjected to seismic motion to achieve a higher efficient energy harvesting.

There is a huge reservation of sustainable and clear wind and ocean energy on the earth. 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 (Anton & Sodano, 2007). In order to utilize these energies, developments of new energy technologies using the piezoelectric transduction to absorb flowing water and/or wind energy on the earth owing to the existing achievements on piezoelectric harvesters were conducted. Priya (2005) reported a theoretical model for determination of a generated electric power from piezoelectric bimorph transducers mounted on a windmill in a low frequency range far from the piezoelectric resonance. 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, Burns, Kammann, Powers, and Welsh (2001). 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. Li, Yuan, and Lipson (2011) also proposed and tested a bioinspired piezo-leaf architecture converting wind energy into electric energy by wind-induced fluttering motion. Zurkinden, Campanile, and Martinelli (2007) designed a piezoelectric polymer wave energy harvester from wave motions at a characteristic wave frequency and investigated the influences of the free surface wave, the fluid–structure-interaction, the mechanical energy input to the piezoelectric material, and the electric power output on the generated energy. Gao, Shih, and Shih (2013) reported a flow energy harvester by a piezoelectric cantilever (PEC) with a cylindrical extension. This device utilized the flow-induced vibration of the cylindrical extension to directly drive a vibration of the PEC for energy harvesting from ambient flows such as wind or water stream. Using the similar idea proposed by Gao et al. (2013) and Abdelkefi, Yan, and Hajj (2013) presented a model for harvesting energy from galloping oscillations of a bar with an equilateral triangle cross-section attached to two cantilever beams. Murray and Rastegar (2009) presented a novel class of two-stage electric energy generators on buoyant structure. These generators used the interaction between the buoy and sea wave as a low-speed input to a primary system to successively excite an array of vibratory elements (secondary system) into resonance. Electric energy may then be harvested from the vibrating elements of the secondary system with a high efficiency using piezoelectric elements. Wu, Wang, and Xie (2013) 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 by the electromechanical coupling effect of piezoelectric materials.

The existing piezoelectric harvesters can be classified into three main categories: (1) piezoelectric bimorph cantilevers mounted on a windmill to absorb wind energy or mounted on a buoyant structure to absorb the transverse ocean wave energy; (2) piezoelectric polymer ‘eels' or cantilevers attached by a triangular plastic leaf on the free end to absorb the vortex shedding energy caused by bluff body fixed in the seabed, and (3) piezoelectric cantilever slabs fixed on the tall slender structure to absorb wind energy or fixed on seabed to absorb longitudinal sea wave energy. In the aforementioned energy harvesting structures, frictions exist between the piezoelectric cantilever structures and excitation objects and hence dissipations of the vibration energy and reductions of the energy harvesting efficiency are inevitable. Meanwhile, energy harvesting techniques with the above structures are mainly excited by external loadings, such as the water wave forces and wind loadings, with low frequencies (usually in a range of 0.1–0.5 Hz for ocean waves (Murray & Rastegar, 2009) and 10–30 Hz for wind loadings with the vortex shedding phenomenon (Wu et al., 2013)). The low frequency excitations may lead to a long charging period on the piezoelectric materials leading to a small output electric current and corresponding low energy harvesting effectiveness.

In order to solve the above two problems in the existing piezoelectric harvesters and improve the energy harvesting efficiency, a new ring piezoelectric harvester excited by magnetic forces is developed in the research. The harvester is made of an outer ring stator and an inner ring rotator. The stator ring is made of a series of discrete piezoelectric patches with a rectangular shape surface mounted by magnetic ring slabs with the same size. The rotator ring is made of a serious of magnetic rectangular slabs mounted on an aluminum ring with the exact size of the corresponding piezoelectric patches on the stator. When the rotator ring is twirled, periodic magnetic forces between the stator ring and the rotator ring are induced to compress the piezoelectric patches leading to an electric charge for energy harvesting. In the new developed harvester, the frictions between the stator and rotator are made minimal since magnetic forces are used as excitations. In addition, the excitation frequency on piezoelectric patches can be increased by increasing the rotating speed of the rotator ring and the number of magnets embedded in the rotator ring. Thus, the two problems in the current piezoelectric harvesters can be solved in the new devices and hence generations of higher electric powers sufficiently for electric appliances of households become possible.

## 2. Design of a ring piezoelectric harvester excited by magnetic force

A mathematical model is developed to describe the principle of a ring piezoelectric energy harvester using magnetic excitation force for harvesting energy from the water current in an ocean and/or winds. Some important factors, such as