IJERST

International Journal of Engineering Research and Science & Technology

ISSN : 2319-5991
Vol. 5, No. 2
May 2016

www.ijerst.com

Email: editorijerst@gmail.com or editor@ijerst.com

Int. J. Engg. Res. & Sci. & Tech. 2016

International Journal of Engineering Research and Science & Technology

ISSN 2319-5991 www.ijerst.com
Vol. 5, No. 2, May 2016

Research Paper

A SHORT REVIEW OF PIEZOELECTRICITY-BASED VIBRATION AND ACOUSTIC ENERGIES HARVESTING

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This short review is to provide a brief introduction for the state of art for piezoelectricity-based vibration and acoustic energies harvesting. Compared with mainstream renewable energies such as solar and wind energies, vibration and acoustic energies have received relatively less attention due to challenges such as low output power density and insufficient understanding for relevant AC/DC converting technology. However, unlike solar and wind energies, vibration and acoustic energies can be obtained without influences from weather and time. Meanwhile, accumulation of wasted vibration and acoustic energies in long duration may be very considerable. Therefore, vibration and acoustic energies are worthy to be further investigated for long term benefits of our environment.

Keywords: Vibration energy harvesting, Acoustic energy harvesting, Piezoelectricity

INTRODUCTION

The majority of us have been familiar with usage of ambient renewable energies including solar,wind, thermal and biochemical energies to generate electricity. However, our environment is still full of wasted energies. Vibration (Tang and Zuo, 2012) and acoustic energies(Pillai, 2013) are two of the currently wasted energies. Vibration and acoustic energies are clean and renewable. But unfortunately, output power of vibration and acoustic energies are lower than solar and wind energies. This becomes a main issue for wide practical application of vibration and acoustic energies harvesting. However, vibration and acoustic energies exhibit several special advantagesthan solar and wind energies. Firstly, harvesting vibration and acoustic energies is not limited by weather and time. Vibration energy largely exists in motions from vehicle and airplane, human body, operating machine, etc. And, acoustic energy can be easily found in noise from traffics, airplane engine, stadium, etc. Ubiquity of vibration and acoustic energies will provide a great number of opportunities to allow us to utilize vibration and acoustic energies. Most importantly, storage of vibration and acoustic energies over a period of time may be significant. This short review aims to illustrate

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piezoelectricity-based vibration energy harvesting, acoustic energy harvesting, and the related AC/DC circuit design.

VIBRATION ENERGY HARVESTING

There has been numerous studies focusing on the conversion of mechanical vibration energy to usable electric energy mostly using piezoelectricmaterials (Kim *et al.,* 2011; Anton and Sodano, 2007; Saadon S and Sidek, 2011). A piezoelectric material generates an electrical charge when mechanically deformed (i.e., direct piezoelectric effect), or conversely, it physically deforms in the presence of an electric field (i.e., converse piezoelectric effect). It should be mentioned that, piezoelectricity is not the only way to scavenge vibration energy. For example, magnetic generatorcan also be used for vibration energy harvesting (Kim *et al.,* 2009). Since the predominated method for vibration energy harvesting is using piezoelectricity, this short review will only cover piezoelectricity-based vibration energy harvesting.

Many efforts in piezoelectric energy harvesting have sought to scavenge the ambient environmental vibration energy such as air flow, water flow and rain drop. Matova *et al*. (2011) reported an airflow energy harvester using with a Helmholtz resonator combined with a piezoelectric energy converter. The resonator stores and accumulates the airflow energy converted into electrical energy harvester. The maximum power of 42.2 μW was obtained when the airflow velocity is 20 m/s. Li *et al*. (2011) experimentally proposed and tested a bioinspired piezo-leaf architecture which converts wind energy into electrical energy by wind induced fluttering motion. The peak output power is approximately 600 μW with the maximum power density 2 mW/cm^3 for a single leaf. Erturk *et al*. (2010) studied piezoaeroelasticity for vibration energy harvesting. The electricity is generated at the flutter boundary of a piezoaeroelastic airfoil from aeroelastic vibration. An electrical power output is 10.7 mW at the linear flutter speed of 9.3 m/s. Ovejas *et al*. (2011) developed multimodal energy harvesters from wind to electrical power by piezoelectric films. Taylor *et al*. (2011) used piezoelectric polymers to harvest the mechanical flow energy, available in oceans and rivers, to electricity. The multielement-Eel system is capable of producing 1 W in a nominal 1 m/s water flow. Liu *et al*. (2012) employed an array of similar PZT microcantilevers in a self-sustained flow-sensing microsystem for harvesting wind-driven vibration energy. The output voltage and power were measured as 18.1 mV and 3.3 nW at the flow velocity of 15.6 m/s with the corresponding power density 0.36 mW/cm^3. Voltages generated by ceramic based piezoelectric fiber composite structures and polymer based piezoelectric strips were investigated by Vatansever *et al* (2011) with varying wind speeds, water droplet weights and releasing heights. It is worth mentioning that piezoelectric arrays have been introduced to increase the harvested vibrational energy (Majidi,xxxx; Lien, 2012; Liu *et al.,* 2008). Wang *et al*. (2011) proposed a shear mode piezoelectric energy harvester for harvesting energy from pressurized water flow. In their study, an instantaneous output power of 0.45 nW are generated when the excitation pressure oscillates with an amplitude of 20.8 kPa at 45 Hz. The maximum total power was found to be of the order of 0.2 μW. Guigon *et al*. (2008) scavenged the vibration energy using a piezoelectric flexible structure impacted by a water drop. The measurements conducted in various impact situations (different drop heights and drop sizes) show that the quantity of electrical energy that can be recovered using their structure is approximately 1 nJ of electrical energy and 1 μW of instantaneous power.

ACOUSTIC ENERGY HARVESTING

Recently, increasing efforts have been expended on developing mechanisms to harvest acoustic energy available in airports, construction sites, factory, traffics, etc. Acoustic energy harvesters generally are composed of two components: an acoustic resonator and a piezoelectric oscillator. The amplified acoustic wave inside the acoustic resonator drives the oscillation of piezoelectric element and generates electricity. Actually, the electromechanical energy conversion via piezoelectricity in acoustic energy harvesting is same as vibration energy harvesting. Horowitz *et al.* (2006) first developed a micromachined acoustic energy harvester using a Helmholtz resonator with a lead zirconate titanate (PZT) piezoelectric composite diaphragm attached to the resonator's bottom wall. The output power of Horowitz's harvester is ~ 0.1 nW with an incident SPL of 149 dB at 13.6 kHz. Later, Electromechanical Helmholtz Resonator (EMHR) has been introducedby Liu and Phipps *et al.*and also use amplified acoustic waveto deform a PZT piezoelectric back plate (Liu *et al.,* 2008; 2007; Phipps *et al.,* 2009). The EMHR generated the power of 30 mWwhen incident 160 dB SPL at 2.6 kHz,. Lee *et al*. (2013) developed a Helmholtz resonator with single-layer and multilayer piezoelectric cantilever beams to harvest acoustic energy. The output power of multilayer PVDF composite cantilever is 0.19 ìW when incident SPL is 118 dB at 850 Hz. In addition to a Helmholtz resonator, a sonic crystal was also used to scavenge acoustic energy (Wu *et al.,* 2009; Wang *et al.,* 2010). A curved polyvinylidene fluoride (PVDF) piezoelectric beam was installed inside a defect region of sonic crystal toacts as a resonant cavity. The output power of sonic crystal acoustic energy harvester is ~ 35 nW with the incident SPL of 80 ~ 100 dB at 4.2 kHz. Very recently, a novel and practical acoustic energy harvesting mechanism to harvest a travelling sound at a low audible frequency (180 ~ 200 Hz) wasdeveloped and studied both experimentally and numerically (Li, 2011; 2012; 2013; 2014; 2015). This acoustic energy harvester used a quarter-wavelength straighttube resonator with multiple piezoelectric cantilever plates installed inside the tube. The maximum output power of the acoustic energy harvester is measured as 10.129 mW when the incident sound pressure level is 112 dB.

VIBRATION AND ACOUSTIC ENERGIES HARVESTING CIRCUIT DESIGN

Overall speaking, essentials of piezoelectricity-based vibration and acoustic energies harvesting are both to apply vibration to piezoelectric transducer, and then generate a vibration deformation to create AC electrical output. In piezoelectric energy conversion, the efficiency strongly relies on the impedance of external circuit which converts AC to DC to charge a storage component (e.g., electrochemical battery). A vibrating piezoelectric element (piezoelectric oscillator) generates AC output while the battery generally require a stabilized DC because of the electronic compatibility. Therefore, a high efficient

AC/DC conversion external circuit needs to be considered to achieve a high efficiency electromechanical energy conversion.

The most simple AC/DC interface circuit for piezoelectric energy harvesting system is the standard interface circuit (Roundy *et al.,* 2003; Kim *et al.,* 2011). In the standard energy harvesting circuit, the piezoelectric element is directly connected to a storage capacitor through a full-bridge rectifier, andtheexternal loading resistance is used to match the impedances of the piezoelectric element with the external circuit in order to maximize the harvested electrical power (Lien *et al.,* 2010 and 2012). In addition to the standard energy harvesting circuit, nonlinear electronic interfaces have been developed to increase the energy harvestingefficiency of piezoelectric elements (Guvomar, 2011). The Synchronized Switch Harvesting on Inductor (SSHI) interface circuit is one of the most improtant nonlinear electronic interfaces by adding a digital switch and an inductor to the piezoelectric element in series (S-SSHI) and parallel (P-SSHI). In both S-SSHI and P-SSHI, the piezoelectric output voltage is inversed when the switch is triggered at the maximum piezoelectric displacements measured by a displacement sensor. SSHI circuits are found to not only enhance the harvested power by 400~900%, but also broaden the system bandwidth compared with standard circuits (Lallart *et al.,* 2010). Thus far, most studies focusing on the AC/DC conversions for a single piezoelectric oscillator (Lien, 2012). In order to realize an AC/DC conversion for multiple piezoelectric oscillators, the effect of external circuits has beeninvestigatedboth numerically and experimentally (Li and You, 2015; 2013). Furthermore, the size of vibration and acoustic energy harvesters may need to be minimized to more easily embedded into energy sources. Thus the size and volume effect of electronic components in circuit may need to be considered (Li *et al.,* 2013, 2010; Qin *et al.,* 2011, 2014, 2010) in future circuit design for vibration and acoustic energies harvesting.

CONCLUSION

In this short review, piezoelectricity-based vibration and acoustic energies harvesting are discussed in terms of harvester conversion mechanism, operation frequency, output power and potential application aspects. The overview of electronic circuit designis also included to demonstrate AC/DC conversion for vibration and acoustic energiesharvesting system.

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ISSN 2319-5991