Study of Piezoelectric transducers used for Energy Harvesting Applications

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Abstract: To manage the soaring power demand, various types of Energy Harvesting Systems (EHS) are being developed. The energy harvesting from unutilized natural renewable sources using piezoelectric transducers is one of them. Day-by-day different analytical models are being reported with different piezoelectric transducers to improve the energy efficiency and output power of the energy harvesting systems. The latest Energy Harvesting Systems (EHS) technology includes the material with outstanding piezoelectric properties, compact fabrication style and distinctive design. They are capable of generating electric power of microwatt to milliwatt range from the unutilized energy sources such as environmental, industrial, vehicular sources and human motion etc. In this study, the reported research works on piezoelectric energy harvesting system (2007-2020) have been reviewed and discussed. The review basically focuses on the constitutional/compositional development of the piezoelectric transducers used in energy harvesting processes.

1. Introduction

In the era of ‘Emergence-of-Energy’, the waste management and the sustainable energy management techniques have become the highlighted topics of research. The recovery of energy in usable form from the waste and unused power has become the recent topics of discussion now-a-days. The waste and unused power exits in several forms in our surrounding and mostly generated from different environmental, industrial, structural, vehicular sources, human activities etc. These sources are schematically represented in fig-1. The useful electric power is generated from the unused physical energy by using different transducer materials, such as piezoelectric transducers, magneto-electric transducers, thermo-electric transducers, semi-conductor and capacitive transducers etc. The several ways to increase the efficiency of energy conversion process are improving energy density of electrical storage, reducing power-consumption of the sensors, using self-powered sensor for conversion of energy and transmitting power to the sensors through a central source. The most pragmatic way among these methods is to use an active or self-powered sensor for energy harvesting [1]. Secondly, when the mechanical stress is more prevalent over the other sources of unused power, the piezoelectric transducer comes into picture for energy harvesting.
Figure 1. Unutilized Physical Energy Source

The block diagram representation of the basic principle of conversion of unused physical energy to used electric-energy is represented in fig-2. Prime component of this conversion process is a piezoelectric transducer. The electric energy produced by the piezoelectric material as a consequence of the applied mechanical vibration is stored after proper signal conditioning. The mechanical loss in the conversion process is due to unmatched mechanical impedance ($z$), damping factor, reflector etc. the mechanoelectrical transduction loss is due to coupling factor ($k$) and piezo-electric coefficient, i.e multiplication of piezo-electric strain constant ($d_{eff}$) and piezo-electric voltage constant ($g_{eff}$). The electric loss is due to unmatched electrical impedance. [2]

Figure 2. Conversion flow of physical energy to electric-energy using piezo-electric transducers

The advancements in piezo-electric energy harvester focusses on the augmentation of piezoelectric properties, viz. piezoelectric strain co-efficient ($d_{eff}$), piezoelectric voltage co-efficient ($g_{eff}$), coupling factor
(k) etc. The optimized response of the energy harvesters are also greatly influenced by the structural design of the transducer. In this article the piezo-electric transducers with different structures, configurations and compositions used for various energy harvesters have been reviewed and discussed.

2 Energy harvesting using piezoelectric ceramics and single crystals

The piezoelectric ceramics and single crystal are broadly classified into two categories: Hard Doped and soft doped. As the hard doped piezoelectric materials are able to withstand a high mechanical or electrical shock/stress, they are suitable for high power applications. The soft piezoelectric materials are characterized by its relatively large permittivity, high electro-mechanical coupling factor and large piezo-electric constant. They are used as sensors, receiver, actuator and low-power transducer. [3]

S.Shahab et al. have done an experimental case study on PZT-5H for vibration-energy harvesting and reported a comparison study on soft(PZT - 5H, PZT - 5A) and hard(PZT - 4, PZT - 8) piezoelectric ceramics [Table1]. In Table1, the parameters compared are piezoelectric strain constant ($d_{31}$), relative permittivity ($\varepsilon_{r}$/ $\varepsilon$), electro-mechanical coupling factor ($k^2$), density ($\rho$) mechanical quality factor ($Q$) [4]. The vacuum permittivity is 8.85 Pf/m. Some other comparative studies on analytical and experimental parameters of piezo-electric ceramic and single crystal used for vibration EHS have also been reported [5-7].

**Table 1. Properties of the soft & hard piezo-electric ceramic [4]**

| Properties | PZT - 5H | PZT - 5A | PZT - 4 | PZT - 8 |
|------------|----------|----------|---------|---------|
| $d_{31}$ [pm/V] | (-)274 | (-)171 | (-)123 | (-)97 |
| $\varepsilon_{r}$/ $\varepsilon$ | 3400 | 1700 | 1300 | 1000 |
| $\rho$ [kg/m$^3$] | 7500 | 7750 | 7500 | 7600 |
| $Q$ | 65 | 75 | 500 | 1000 |
| $K^2$ | 0.151 | 0.119 | 0.107 | 0.0924 |
| $k^2$ | 9.83 | 8.89 | 53.5 | 92.4 |

3 Energy harvesting using piezoelectric polymers

The piezoelectric polymers are preferred over the piezoelectric ceramics and single crystal because of their low acoustic impedance, flexibleness for fabricating them in required shape and size and their cost-effectiveness. The piezoelectric polymers are broadly classified into three categories (fg-3):

a) Bulk piezo-polymers
b) Voided-charged polymer
c) Piezo-electric polymer composite

The most dominant piezoelectric polymer used for energy harvesting is PVDF (Polyvinylidene fluoride). PVDF film of 6-25μm thickness goes through different stages/processes like polymerization, stretching and poling to become suitable for transducer applications [9].
J.B.Rocha et al. integrated electro-active $\beta$-PVDF with silver and aluminum electrode on shoe-sole and connected the electronic circuit required for enhancement of energy-transfer and electric storage-efficiency in the interest of harvesting energy from the walk. They reported that the power generated from PVDF ranges from 10 to 100 mw. The variation in the generated power is due to the area, position, dimensions and the no of PVDF foil embedded (fig-4) [10]. A multilayer structure of co-polymer of Vinylidene fluoride & tri-fluoro ethylene P (VDF - TrFE) with aluminum electrode has also been used for energy harvester [11].

The PVDF based energy harvester via displacement amplification module has been demonstrated by Y.H.Shin et al [12].

The advances in this type of transducers depend upon the developments in the in-organic ceramics, organic polymers [13, 14], 2-D materials [15] & biologically derived systems [16], enhancements in piezoelectric properties [17] and structural designs [18]. Now-a-days, researchers are focusing on multi-direction energy harvesting using 3-D piezo-polymer micro-system. M.Han et al. demonstrated a 3-D piezo-polymer micro-system to harvest vibration energy. The device is made up of PVDF(3mm x 50$\mu$m x 9$\mu$m dimension and 1.2 mm vertical displacement) with Cr (10 nanometer) / Au (100 nanometer) / Ti (20 nanometer) as top electrode and Cr(10 nanometer) / Au (100 nanometer) as bottom electrode. The harmonic vibration excites selected vibration mode of the 3-D structure, as a result the electrical energy is harvested through the metallic electrode contacts [19].

4 Energy harvesting using Piezo-polymer composite:
Piezo-polymer composite comprises of piezoelectric ceramic and polymer. There are two types of configurations of a diphasic composite, i.e. parallel and series configuration. MFC (Micro Fiber Composite) and NFC (Nano Fiber Composite) are more dominantly used in energy harvesting systems.

### 4.1 MFC (Micro Fiber Composite)

The MFCs are highly flexible, durable and mechanically tough. They have a high electro-mechanical coupling coefficient, good impedance matching and higher transducer sensitivity. So these are preferred over the conventional piezoelectric elements to be used in energy harvesting systems. [9]

A HPG (Hybrid Piezoelectric generator) for mechanical energy harvesting has been developed by Md.M.Alam and D.Mandal. They have used NCMF (Native Cellulose Micro Fiber) in active phase & PDMS (poly dimethyle siloxane) in inactive phase to form microfiber composite and used MWCNTs (Multi Wall Carbon Nanotubes) as conducting fillers. They reported, the NCMF-HPG delivers an O.C. o/p voltage of around 30 V and S.C. o/p current of around 500 nA (fig-5) and the power density is around 9.0 μW/cm² [20].

### 4.2 NFC (Nano Fiber Composite) or Nanohybrid

The Nano Fiber Composites (NFCs) are composed up of a piezoelectric fiber (Nano Scale range) and a polymer. The nano fibers have a small size and large surface area. They are not mechanically and chemically stable, when used alone. But when they combine with polymer and form a composite, their stability increases noticeably. Hence the nano fiber polymer composites are preferred over the microfiber composites [21].

Xi Chen et al. used PZT nano fiber (Diameter-60 nm & length- 500μm) with platinum electrode and polydimethylsiloxane (PDMS) to form a nano composite. They demonstrated Nano generator using PZT nano fibers for mechanical-energy-harvesting. The o/p power produced was 0.03 μW, when the load resistance was 6 MΩ [22]. S.H.Wankhade S.H. Wankhade et al. have fabricated a device using nanohybrid of PZT-PVDF for harvesting energy from different human motions/activities, such as fingers tapping, foot tapping & bending. It has been reported that the device is capable of producing an o/p voltage of 55volt and a power density of 36 microwatt per c.m² [23].
5 Energy harvesting using piezo-metal composite

Based on the design, the piezo-metal composites are classified as ‘Cymbal’ and ‘Moonie’. Both these types of transducers comprise of a piezoelectric disc with metal capping on top and the bottom fig-6 [21]. The displacement of moonie transducer is because of the flexural movement of end-caps and the displacement of a cymbal is due to both flexural and rotational motion of end caps. The cymbal is preferred over moonie for energy harvesting because of its higher displacement, high stability, high contact surface and its lesser fabrication cost [22].

S.Gareha et al. have simulated a compression based PCT traffic model, which can be used to generate electric power. On the basis of their simulation study, it has been concluded that a total electric power of 170 kw per km can be generated using a number of PCTs (Piezoelectric Cymbal Transducer) for a high way with a traffic density of 600 vehicles per hour [23] and the generated power cab be utilized for feeding power to the road side light systems, emergency communication units etc. Bo Ren et al. used 0.71 Pb(Mg_{0.33}Nb_{2/3})- 0.29 PbTiO_3 based cymbal for a vibration energy harvesting system and reported that the power density of this modified transducer is around 3 times larger than the Pb(Zr,Ti_{1-x}) ceramic [24].

6 Summary

From the review of the reported research works from 2008 to 2020 in the area of piezoelectric energy harvesting, it is observed that the most abundantly used piezoelectric material are PZT and PVDF because of their outstanding piezo-electric properties and large conversion efficiency. Now-a-days small powered ICs are being incorporated in the controlling circuit to decrease the input power requirement [30-35]. Some
of the important piezoelectric energy harvesting applications with the piezoelectric material used is listed in Table-2.

**Table 2.** Summary of important piezoelectric energy harvesting applications

| Type of Piezoelectric transducer based on composition | Composition | Energy harvesting Application | Physical energy used for energy harvesting | Reference |
|-----------------------------------------------------|-------------|-----------------------------|-------------------------------------------|------------|
| Piezoelectric Ceramics                               | PZT         | Shoe-sole insertion         | Human motion                              | 25, 26     |
| Piezoelectric Polymer                                | PVDF        | Shoe-sole insertion         | Human motion                              | 11, 26     |
| Piezoelectric Polymer                                | PVDF        | Wind generator              | Wind flow                                 | 27         |
| Piezo-Film                                           | PVDF        | Rain fall energy harvester  | Rain drop impact                          | 28, 29     |
| Microfiber Composite                                 | NCMF-PDMS   | Hybrid piezoelectric generator | Mechanical vibration                  | 14         |
| Nanofiber Composite                                  | PZT nanofiber-PDMS | Nano generator      | Mechanical vibration                  | 22         |
| Cymbal                                               | 0.71Pb(Mg_{1/3}Nb_{2/3})-0.29 PbTiO₃ | Vibration energy harvester | Mechanical vibration                  | 24         |
| Piezoelectric Polymer                                | PVDF        | Roadway energy harvester    | Vehicular vibration                      | 12         |
| 3D piezo polymer microsystem                         | PVD         | Biomedical, Vibration energy harvester | Body movement                  | 19         |
| Nano hybrid                                          | PZT-PVDF    | Nano Generator              | Human Motion                             | 23         |

**7 Conclusions**

The present state-of-art in piezo-electric transducers for energy harvesting have been reviewed and discussed in this article. The piezoelectric transducers, such as piezoelectric ceramics, piezoelectric polymers, composites, cymbals etc. are being used in energy harvesting processes since decades. The majority of piezoelectric EHS reviewed are able to generate power in μw to mw range depending upon the ambience. Recently, the development of multidirectional energy harvesting systems, use of Nano-hybrid piezoelectric transducers etc. are very impressive. From the review it is realized that even though the PEH technology have been developed a lot, still there is a scope of increasing the stability and consistency of the system.

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