Journal of Basic and Applied Engineering Research
p-ISSN: 2350-0077; e-ISSN: 2350-0255; Volume 2, Issue 21; October-December, 2015, pp. 1847-1852

http://www.krishisanskriti.org/Publication.html

Survey on Recent Development in Vibration Energy Harvesting using Piezoelectric Material

Vishrut Shah[1], Tarun Kumar[2], Rajeev Kumar[3] and Mohammad Talha[4]

[1,2,3,4]IIT Mandi

E-mail: [1]vishrutshah121@gmail.com, [2]kvtarun85@gmail.com, [3]rajeev@iitmandi.ac.in, [4]talha@iitmandi.ac.in

Abstract—*Due to the development of ultra-low power portable electronics and wireless sensors, the use of ambient energy, such as vibration energy for harvesting energy using piezoelectric materials has aroused great interests. A number of techniques have been proposed by the researchers for harvesting energy from the vibration source. Mostly, the techniques are classified as narrowband or broadband depending on the range of frequencies in which they produce maximum power. Substantial research has been done by the researchers in both these areas and countless techniques are proposed in order to harvest maximum power. A study is needed to compare these techniques to suggest a proper technique for a typical application. This paper presents a detailed categorization of the various piezoelectric energy harvesting techniques and also covering each of them with suitable examples. The pros and cons of each technique are also presented.*

1. INTRODUCTION

Great performance achievements are already well in hand for a class of materials called smart materials. In the 21th century virtually every facet of the familiar world would be intensely changed by these new class of materials. One member of such class of the materials is piezoelectric material. Vibration-based energy harvesting using piezoelectric generators has received growing attention over the last decade. The research motivation in this field is due to the reduced power requirement of small electronic components, such as the wireless sensor networks used in structural health monitoring applications [2].

The source of vibrations exists almost everywhere. The source can be movement of the human body, vibrating structures like bridges, flow of wind and vibrations in the moving parts of machines or vehicles. It appears from the literature that the idea of vibration-to-electricity conversion first appeared in a journal article by Williams and Yates in 1996 [3]. They described the basic transduction mechanisms that can be used for this purpose and provided a lumped-parameter base excitation model to simulate the electrical power output for electromagnetic energy harvesting. The ultimate goal of vibrational energy harvesting using piezoelectric generators is to power small electronic devices by using the vibration energy available in their environment. If this can be achieved, the requirement of an external power source as well as the maintenance requirement for periodic battery replacement can be minimized.

Due to this idea of developing a self-powered standalone system, researchers proposed various techniques for energy harvesting. The initial idea was to harvest at the resonant frequency of the system. Later the idea developed for harvesting in a broad band of frequencies not just at the natural frequency. Many techniques of harvesting energy from the vibration source using piezoelectric material using both of these methods were developed and are still developing. Due to this it became difficult to decide the type of energy harvesting technique to be used for the particular application.

This paper presents a complete classification of the vibration based energy harvesting systems.

The application of piezoelectric energy harvester (PEH) seems endless as the need for harvesting ambient vibration energy to electrical energy is increasing a lot. A primary motivation for self-charging structures is to use them for powering small electronic components in unmanned aerial vehicle (UAV) applications. Apart from this application the use of PEH for harvesting energy from walking also gained a lot of attention. John at. el. [4] presented different ways in which the energy from the heel strike can be scavenged out of the 3 techniques he proposed two were piezoelectric. Christopher A Howells [5] proposed using four proof-of-concept Heel Strike Units where each unit was essentially a small electric generator that utilized piezoelectric elements to convert mechanical motion into electrical power in the form factor of the heel of a boot. In the past few years the research focused on designing smart systems which led to the use of the PEH for generating power so that the system can be self-powered. As a result of this various designs were proposed like Lee at el [6] proposed to mount an energy harvester inside the tire of the vehicle. From the results of the experiments performed it was found that the piezoelectric energy harvester generates 380.2 μJ per revolution under 500 kgf load and 60 km/h. They studied the system by installing it with the PEH and a wireless sensor and concluded that it can be made self-sustaining with minor improvements.

Li at. el. [7] proposed a potential application of a commercial piezoelectric energy harvester in a central hub building at Macquarie University in Sydney, Australia by installing piezotiles. The piezotiles were deployed at 3.1% of the total floor area which had highest pedestrian mobility. The modelling results indicated that the total annual energy harvesting potential for the proposed optimized tile pavement model was estimated at 1.1 MW h/year. This potential energy generation may be further increased to 9.9 MW h/year with a possible improvement in piezoelectric energy conversion efficiency integrated into the system.

PEH also found applications in structural health monitoring. Zhang at. el. [8] presented Piezoelectric-based energy harvesting in bridge systems while Priya at. el. [9] discussed its use in border security sensors where it can be used to continuously monitor border intrusion. The PEH also gained a lot of interest in biomedical applications [10-13]

2. CLASSIFICATION OF PIEZOELECTRIC VIBRATION ENERGY HARVESTING TECHNIQUES

Narrowband and broadband energy harvesting are the basic two divisions of Vibration energy harvesting. This division is made on the basis of the range of frequencies in which the energy harvester produces the maximum power. The narrowband energy harvester produces maximum power only at the resonant frequency while the broadband energy harvester produces the maximum power over a certain range of frequencies. Fig. 1 shows the complete classification of the piezoelectric energy harvesting methods.

3. NARROWBAND ENERGY HARVESTERS

Most of the initial research in vibration energy harvesting focussed on this type of harvesters. These Narrowband energy harvesters (NEH) focussed on harvesting energy at the natural frequency of the system, due to which the system became most efficient for a particular frequency range. So the NEH was designed in such a way that the natural frequency of it would be near to the frequency of the vibration source. The power output of the NEH drastically decreased as the frequency of the system shifts from the natural frequency, as shown in Fig. 2, the power output is maximum only at a particular frequency apart from that it is negligible. Out of the many prescribed substructure or host structure circular plate and cantilever plate structure became centre of interest.

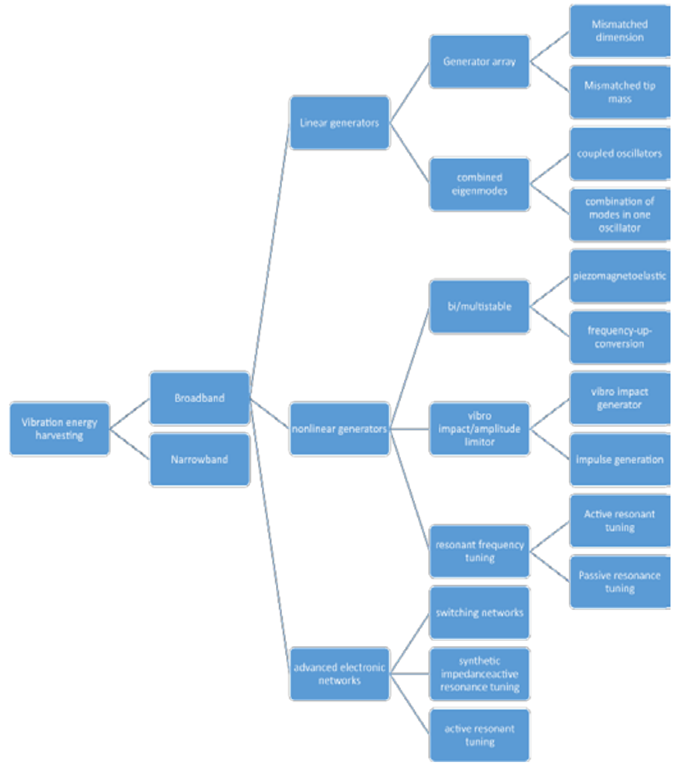

Fig. 1: Classification of Vibration Energy harvesting Techniques. Jens et. al. [1]

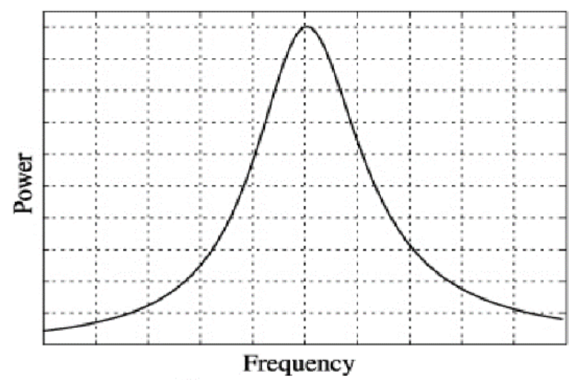

Fig. 2: Power vs. Frequency for Narrowband energy harvesting

4. BROADBAND ENERGY HARVESTING

In majority of the practical scenarios the frequency of the ambient vibrations is varying or totally random. Hence the need of increasing the operating bandwidth of the vibration energy harvester became one of the most critical issue that needed to be resolved before utilizing it on a large scale. The broadband energy harvesting basically means getting optimum power output on a particular frequency range rather than just at the natural frequency, so that slight alterations in the vibration frequency from the source can also be incorporated.

The broadband energy harvesting is divided into three different groups. The first group is of the linear generators. As the name suggests the generators behave linearly i.e. they behave similar to a linear system. The second group consists of nonlinear generators. Here the nonlinearity is introduced using magnetic force or by applying prestress or other techniques. The main aim is to increase the working frequency range. The third group is related to the circuit part. The operating range of frequencies can be increased by these advanced electronic network circuits. In the current study emphasis is given to the mechanical systems rather than the electric circuits. The classification is given just for the sake of completeness. The broadband energy harvesting techniques are summarized in detail

Linear generators

Linear generators are simple structures and can be modelled as a single degree of freedom system, as shown in Fig. 3. The equation of motion of these generators can be given as

$$m\ddot{z} + c\dot{z} + kz = -m\ddot{y} \tag{1}$$

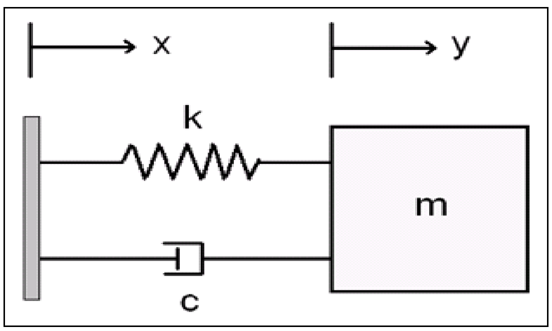

Fig. 3: Single degree of freedom model of the Linear Generator

Where m is mass, k is stiffness, c is damping coefficient, y is displacement of the structure and z is the relative displacement of the mass with respect to the structure.

The linear piezoelectric energy harvester is further classified as

- Cantilever Array Configuration
- Combined eigenmodes

Cantilever Array Configuration

It is the type of arrangement in which we can use linear generators to work on broadband energy harvesting. As linear generators are the most efficient energy harvesting system. The cantilever array is made up of cantilever designed with either different length or different tip masses, due to which the particular cantilever will have different resonant frequency as compared to the other. This type of arrangement helps in harvesting energy in a range of frequencies as there are various cantilevers having different resonant frequencies. So at a particular frequency one of the cantilevers will be in resonance so average power generated by the combined cantilevers will be optimum.

A Kumar et al [7] proposed the design for array of two cantilevers connected and optimized their dimensions using genetic algorithm. They made the finite element model of the system and compared with the single cantilever structure. Fig. 4 shows the graph of power and power density vs. frequency. As we can see from the graph that the range of frequencies producing optimum power increase there is also a drop in power density as the area of the structure also increases.

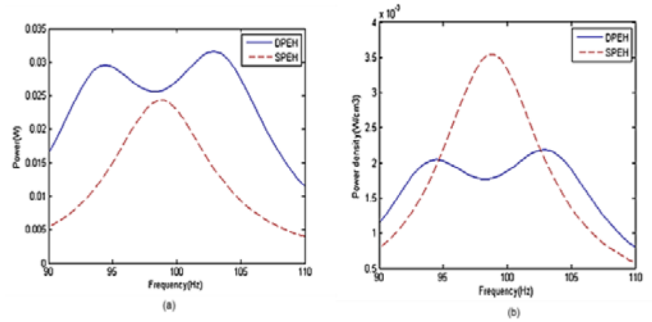

Fig. 4: (a) Power as function of excited frequency; (b) Power density as function of excited frequency for SPEH and DPEH. [7]

Combined Eigenmodes

As the name suggests it is the broadband energy harvesting technique in which the harvesting is done on the two modes of the harvester system. The first two eigenmodes of the system are mostly very far from each other so it is very difficult to harvest in both modes. But if the gap between these modes is reduced then the harvester can become broadband by harvesting in both of its modes. One way of reducing the gap between the first two modes is by coupling the two cantilevers so that the first two resonant frequencies become closer and the cantilever can shift from one resonant frequency to other.

Erturk at. el [8] proposed a L shaped beam-mass structure (as shown in Fig. 5) that can be tuned to have the first two natural frequencies relatively close to each other. They proposed the use of this technique in the landing gear mechanism of the unmanned air vehicle.

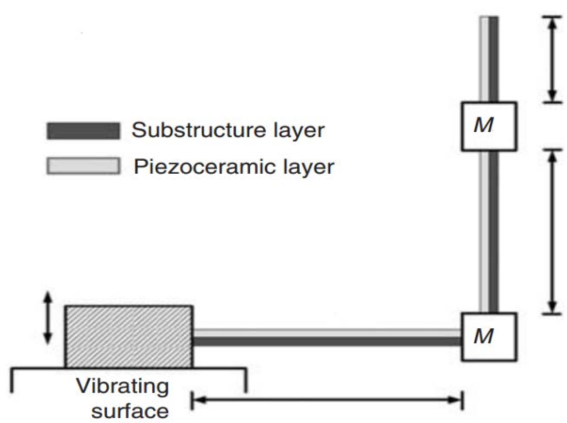

Fig. 5: L shaped beam mass structure [8]

Bistable/Multistable System

To scavenge the plentiful energy by using piezoelectric harvester and to make it more efficient, i.e. to increase bandwidth and power generation, many researcher introduced the nonlinear generators where by nonlinear stiffness effects are used to increase the operating range.

When harvester experiences oscillations with significant amplitude the nonlinear behavior become observable. Large amplitude is due to introduction of geometric and force type nonlinearities that leads to nonlinear stiffness of piezoelectric generator. The nonlinear energy harvester can be a Duffing-type oscillator with cubic nonlinear stiffness typically introduced by using magnets. It can also be a piecewise-linear oscillator with nonlinearity caused by a mechanical stopper.

Bistable nonlinear configuration

Bistable system is used to improve energy harvesting performance over a wide range of ambient vibration frequencies, subjected to either periodic forcing or stochastic forcing. A periodically forced oscillator can undergo various types of large-amplitude oscillations, including chaotic oscillation, large-amplitude periodic oscillation, and large-amplitude quasi-periodic oscillation. Similarly stochastic forcing can also induce transitions between the stable equilibrium of the system, and thus causing large-amplitude oscillations [9]. As shown in Fig. 6 Bistability is induced using the magnetic repulsive force the stability shifts from monostable to bistable to chaotic as we keep on decreasing the distance between the two magnets.

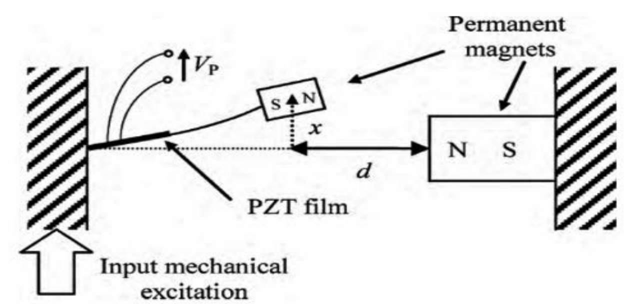

Fig. 6: Bistable system formed by a piezoelectric cantilever beam [9]

Frequency up conversion

In this type of energy harvesting techniques the low ambient frequency is elevated to high frequency using some mechanical frequency-up-convertors. Jung et al. [10] proposed an energy harvesting device that uses snap-through bucking for frequency-up-conversion. They generated 131 µW power at 30 Hz frequency and an acceleration of 30m/s2 using the device they proposed using buckled slender bridges with a proof mass and cantilever beam attached to them. Basically when this device is subjected to low frequency vibrations buckled bridges snap through between two equilibrium states, providing high acceleration to the attached piezoelectric cantilever beam and thus causing them to resonate at a high frequency. H Kulah et al. [11] generated 170nW power by using magnet and coils on top of resonating cantilever beams.

Vibro impact/amplitude limiter

Configuration with Mechanical Stoppers

Soliman et al [12] proposed a method of increasing the operating frequency bandwidth by using an amplitude limiter to limit the amplitude of the cantilever. When the excitation frequency was gradually increased i.e. during an upsweep, increase in the bandwidth of the generator was found. While when the frequency was reduced i.e. while downsweep the bandwidth remained same. Fig. 7a shows the schematic diagram of the mechanical stopper system and Fig. 7b shows the rms voltage vs. frequency graph indicating experimental and analytical results.

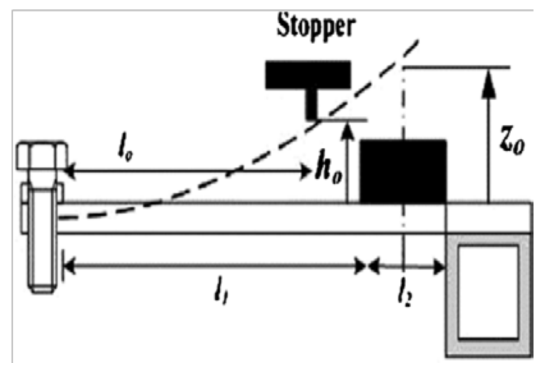

Fig. 7a: Broadband harvesting using stopper [12]

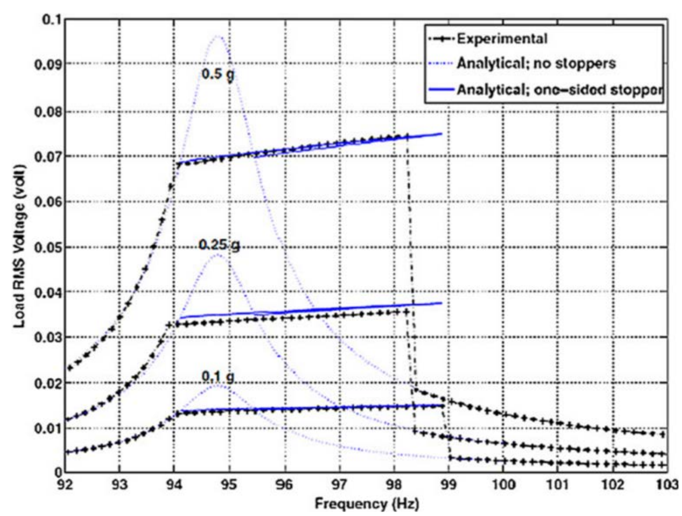

Fig. 7b: Voltage across load vs. excitation frequency [12]

Resonance frequency tuning

In most of the real life problems the vibration frequency is either not known or not constant so it is not feasible to use the predesigned conventional linear harvesters to match a particular resonant frequency. So in such kind of applications it is necessary to design a cantilever in such a way that it is able to alter the natural frequency of the cantilever depending on the vibration frequency. There are basically two types of tuning techniques active and passive tuning. Active tuning technique requires continuous power input to match the resonant frequency whereas passive tuning technique requires either intermittent power or no power at all.

Resonance tuning methods can also be classified by the technique used for frequency tuning like mechanical, magnetic, and piezoelectric methods. Also, the tuning process can be implemented manually or in a self-tuning way. Manual tuning is very difficult to implement during operation. A fine self-tuning implementation is expected not only to cover the targeted frequency range but also to be capable of self-detecting the frequency.

Table 1: Merits, demerits and applications of various PEHs

Method	Advantages	Disadvantages
	Simple design, Easier to implement, Most efficient system(Max power produced)	Working only at resonant frequency
Generator Array	Less sensitive to the system and simple mechanism and easy to incorporate changes	Bulky system and electronic network complex and expensive
Combined Eigenmodes	Easier to implement than resonance tuning techniques. More compact setup	Complex interface circuit to avoid voltage cancelation. Complex design, as proper parameters needed to cover frequency range with little energy density sacrifice.
Bistable/multistable generator	Compact with a large bandwidth, Good efficiency for high frequency excitation Much easier to implement than resonance tuning techniques	Low tolerances
Amplitude limiter	Increases bandwidth under random excitation with properly selected stopper parameter, Robust and compact setup, theoretically large bandwidth for high frequencies	Lowered power level Suffers from noise, fatigue, and mechanical wear
Active Resonance Tuning	Continuously power available during operation due to automatic controller	Limited Tunability Cost of tuning more than harvested power
Passive Resonance Tuning	Relatively large tunability	Difficult to achieve automatically and during operation

Resonance of a system can be changed either my changing its mass or its stiffness. As changing the mass is very difficult. The only practical solution is changing the stiffness. Manually the stiffness of the system can be changed by loading the system [13-15]. The system is preloaded to vary the natural frequency. The preload can be either tensile or compressive. If the load is tensile the resonant frequency will shift upwards while in compressive it shifts downwards. Eichhorn et al.[14] used this concept to fabricate a cantilever which can be tuned by prestressing. Screw mechanism was used to apply the compression force on the cantilever free end through springs.

5. CONCLUSION

There is been a lot of research in the piezoelectric energy harvesting field since the late 1990's. But it still is an emerging technology and main focus of interest. Table 1 shows the merits, demerits and applications of various PEHs. It is clear that all techniques have some specific applications but none of them is an ideal technique. So there is a need to research in this area. Also the use of nonlinearity has shown great results but there still is scope for more research. The harvested power from most of these techniques is still in µW range without any interface power consumption circuit so still there is a scope of work in this area to increase the power to some more usable range.

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