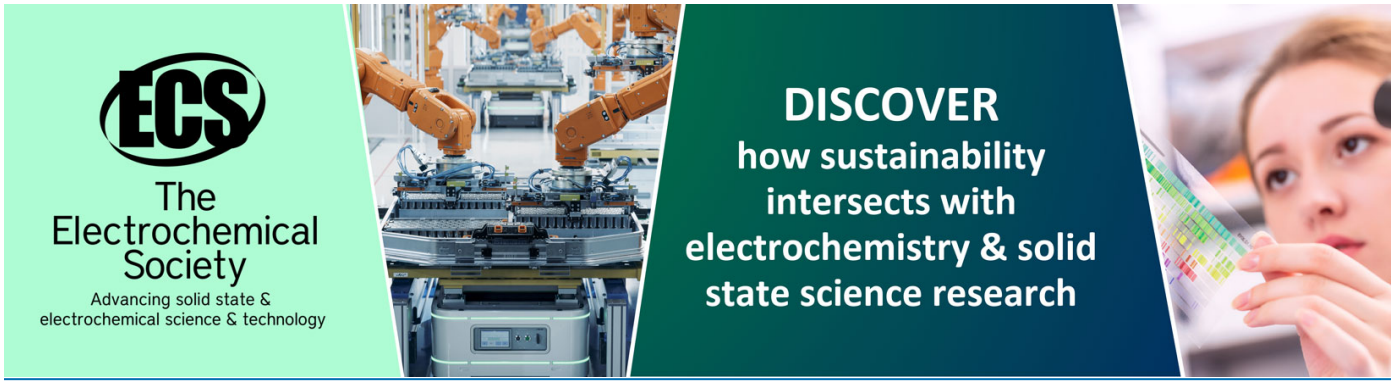
Application review of dielectric electroactive polymers (DEAPs) and piezoelectric materials for vibration energy harvesting



Application review of dielectric electroactive polymers (DEAPs) and piezoelectric materials for vibration energy harvesting

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Abstract. This paper reviews recent advances in vibration energy harvesting with particular emphasis on the solutions by using dielectric electroactive polymers (DEAPs) and piezoelectric materials. These smart materials are in essence capable of converting wasted vibration energy in the environment to usable electrical energy. Much previous researches have been devoted to studying the technology of harvesting mechanical energy using piezoelectric materials. The recent introduction of the DEAPs that exhibits large displacements under electric activation has led to their consideration as promising replacement for conventional piezoelectric materials. The properties of the two materials are described in this paper together with a comparison of their performance in relation with energy harvesting. Finally comparisons are made in the applications of vibration energy harvesting using these two materials. This paper has been written with reference to a large number of published papers listed in the reference section.

1. Introduction

Over the last decade there has been significant interest in the development of energy harvesting, seeking to capture energy from the surrounding energy sources, accumulating them and storing them for later use. Simply stated, vibration energy harvesting is the process by which wasted vibration is harvested and converted to some other useful energy, such as electrical energy. The investigation of vibration energy harvesting has become a major field of research, focusing on recycling the vibration energy to power small electronic devices [1]. Significant amount of researches has been devoted to studying the possibility of harvesting energy by means of various materials, such as the Tantalum-Polymer [2], ionic polymer metal composite [3,4], conductive polymers [5,25], dielectric electroactive polymers (DEAPs) [6-10] and the piezoelectric materials [11-14]. Much previous researches activities focus on classical piezoelectric materials and more recently, the development of DEAPs offers a potential improvement over the conventional methods [15].

Piezoelectric materials literally refer to as crystal materials that produce electrical charges across their boundaries in response to applied mechanical stress. The piezoelectric effect was discovered in 1880 by the Jacques and Pierre Curie brothers. They found that when a mechanical stress was applied

on crystals such as tourmaline, topaz and quartz, electrical charges appeared, and this voltage was proportional to the stress.

DEAPs known as emerging polymer or compliant capacitor have shown great promise due to their low cost, lightweight, simply actuating structure and good performance in low frequencies with large deformation. In principle, they are materials in which actuation is driven by electrostatic forces between two electrodes which squeeze the polymer. When a voltage is applied, the polymer compresses in thickness and expands in area in the electric field. Earlier research has shown that some DEAPs can exhibit up to a 380% strain, which is much more than any ceramic actuator [44]. A large actuation voltage is generally required to produce high electric fields (hundreds to thousands of volts), with low electrical power consumption. No additional power is needed to keep the actuator at a given position.

This paper reviews the application of vibration energy harvesting technologies using piezoelectric materials and DEAPs. The working principles are discussed to allow a comparison of their performance for the application of energy harvesting, and to demonstrate the advantages of DEAPs over piezoelectric materials. Finally recent advances of vibration energy harvesting using these two materials are discussed.

2. Working principles

2.1. Piezoelectric materials

Piezoelectricity has two distinct effects. The direct effect is the polarization of the material under a mechanical stress and the inverse effect corresponds to a mechanical displacement when electric polarization is applied to the material. In generator mode, a resonant structure imposes deformations on a piezoelectric material, which converts this mechanical stress into electric charge [22].

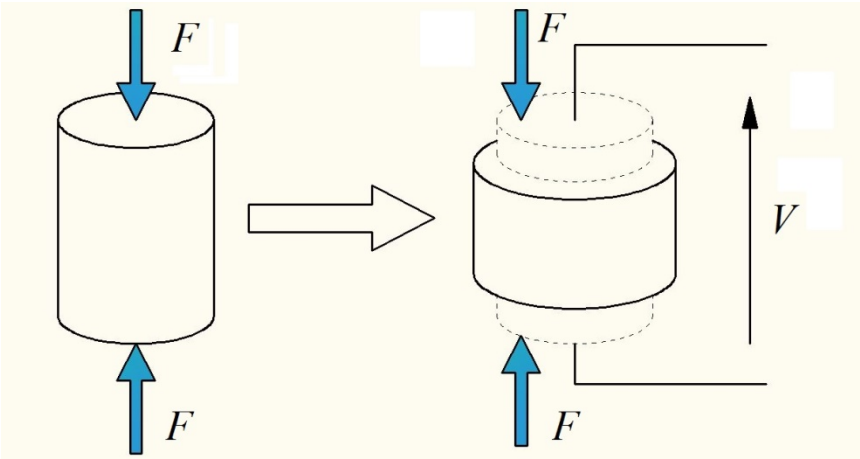

Figure 1. Piezoelectric direct effect. [22]

2.2. Electrostrictive polymers

Electrostrictive polymers and dielectric elastomers are two typical categories of DEAPs. Unlike piezoelectric materials, there is no direct effect on an electrostrictive polymer. This means that a stress does not induce electric polarization in the material. Electrostrictive materials are passive materials which need a primary electrical source to convert mechanical energy into electricity [45-49].

Under constant-field boundary conditions, ambient mechanical energy can be harvested in an operating cycle [46]. First, the polymer is stretched under a primary electric field E_0. Under maximal stress T_{max}, the electric field increases to a higher value E_1. Then, under this constant electric field E_1, the stress is removed and the polymer is free to move to an equilibrium position. Finally, the electric field decreases to its initial value E_0 and the polymer returns to its original dimensions.

2.3. Dielectric elastomers

Scavenging energy with dielectric elastomers needs energy cycles with a primary voltage source because of their passive nature [25, 50]. As illustrated in Figure 2, an energy cycle is composed of four phases: stretch, charge, active phase and discharge. The polymer is stretched in order to increase its capacity, showing in Phases A-B. Then, the material is charged by a voltage *V* and stores an input energy, showing in Phases B-C. To increase this stored energy, the material is relaxed and moves until equilibrium is reached between elastic and electrical stresses, showing in Phases C-D. The input electrical energy is amplified due to the mechanical movement. Finally, all charges are removed from the structure to enable the polymer to return to its initial dimensions, showing in Phases D-A.

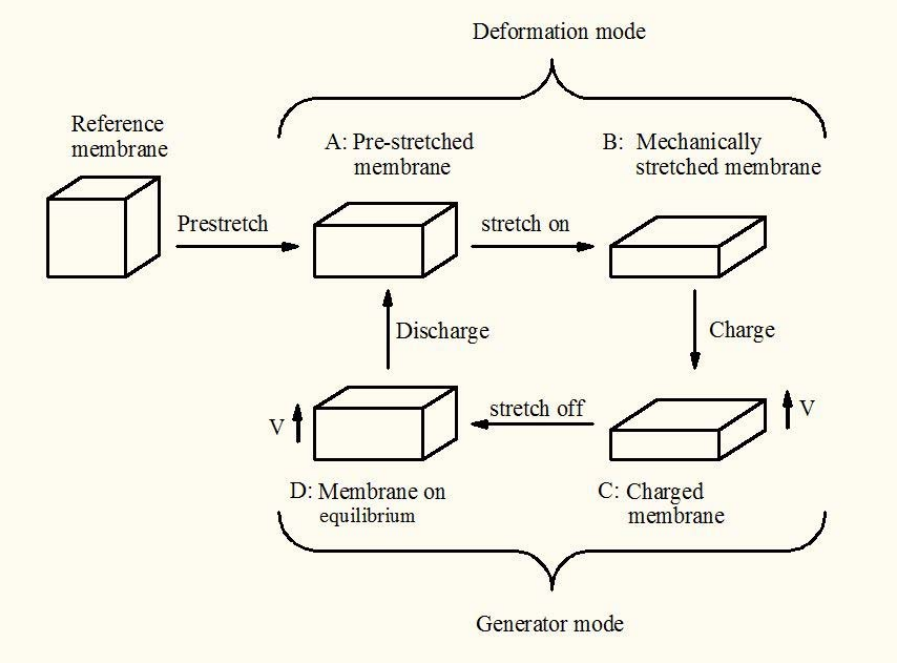

Figure 2. Scavenging cycle of a dielectric polymer. [25]

3. Comparison of the performance for energy harvesting

Piezoelectric materials and DEAPs are two representative materials used in energy harvesting. However their performance for energy harvesting follows very different principles. It is thus important to make a comparison in order to have a clear vision of the advantages and disadvantages of each of them.

Piezoelectric materials can be categorized into piezoelectric ceramic and piezoelectric polymers. Piezoceramics have the properties of mechanical simplicity, small volume, large useful bandwidth, efficient conversion between electrical energy and mechanical energy. PZT (lead zirconate-titanate) is a commonly used piezoelectric ceramic. Piezopolymers are polymer structures with integrated piezoelectric ceramics from which the piezoelectric effect is generated. These composites operate based on the mechanical flexibility of polymers and the high electromechanical coupling of the piezoelectric ceramics.

Two typical categories of DEAPs are dielectric elastomers and electrostrictive polymer. In general, they are lightweight, flexible, ductile, low-cost, with a high strength-to-weight ratio and low mechanical impedance.

Electrostrictive polymers can endure large strains, making them suitable for such high strain environments, and the ability to sustain large strains also allows the polymers to have a large stroke. Because of all these advantages, the use of electrostrictive devices has also attracted the attention of

the research community for energy harvesting systems [16-19]. Electrostrictive polymers have shown to be perfect candidates for smart materials with a great potential for harvesting mechanical energy.

Dielectric elastomers possess similar advantages as electrostrictive polymers. These materials can be used as generators, converting mechanical strain energy into electrical energy using their capacitive behaviour [20,21]. These polymers exhibit excellent performance levels in generator mode, particularly dielectric polymers with an energy density of up to 3.2 $J \cdot cm^{-3}$. Thus they are best suited for scavenging applications. The operating principle of DE generators depends on the change in geometry of the elastomer capacitor and a certain amount of initial charge, which characterizes an electrostatic energy conversion principle. Acrylate and silicone are two kinds of commonly used dielectric elastomers.

Table 1 sum up the main characteristics of five materials including piezoelectric materials and DEAPs.

Table 1. Comparison of the performance of different materials

	Piezoceramics [22,25,38]	Piezopolymers [19,22,25]	Electrostrictive polymers [19,23-25]	Dielectric elastomer[20,21,23-25]	
	PZT	PDVF	P(VDF-TrFE-CTFE)	Silicone	Acrylic
Density ($g \cdot cm^{-3}$)	about7	1.7-2.1	1.9	1	1
Young's modulus (GPa)	60	2.5-3.2	0.4-4	1×10^{-3}	2×10^{-3}
Maximum stress (MPa)	110	5	45	3	7.2
Maximum strain (%)	0.2	0.1	4	100	400
Dielectric constant (at 1 kHz)			65	3	4.8
Maximum energy scavenging density ($J \cdot cm^{-3}$)	0.06	0.06	0.3-0.6	1.63	4.1

As listed in the table, Young's modulus is a measure of the stiffness of an elastic material, and is a quantity used to evaluate materials. It is defined as the ratio of the stress along an axis to the strain along that axis in the range of stress. As can be seen in the table, the Young's modulus of PZT is about 60 GPa [22], which is extremely high compared to piezoelectric polymers and electrostrictive polymers. And the Young's modulus of dielectric elastomer is about 1×10^{-3} Gpa to 2×10^{-3} Gpa, suggesting much better performance.

The maximum stress of piezoceramics is about 110 MPa, which is much higher compare to dielectric elastomer, for the silicone is 3 MPa and acrylic is 7.2 MPa. On the contrary, dielectric elastomers have a higher maximum strain than piezoelectric materials, showing the great potential in the field that need large deformation.

The energy density is a vital value for energy harvesting materials. The density of piezoelectric materials is about 60×10^{-3} $J \cdot cm^{-3}$, which is incomparable to electroactive polymers. Electrostrictive polymers are able to scavenge ten times more energy than piezoelectric materials, and dielectric elastomer can rather reach a higher level. Pelrine *et al.* [23] estimate the energy density of the 3M's VHB 4910 polymer to be around 1.5 $J \cdot cm^{-3}$ in a scavenging application and Koh *et al*. [20] to be around 6.9 $J \cdot cm^{-3}$ at the maximum and 2.3 $J \cdot cm^{-3}$ for a specific cycle at constant charge Q. Jean-Mistral C *et al.* [25] developed an adaptive model for dielectric polymers in generator mode, using

3M's VHB 4910, reached the energy density of varies between 0.24 J·cm^{-3} and 3.2 J·cm^{-3}. The maximum energy density (3.2 J·cm^{-3}) is ten times greater than that obtained with electrostrictive polymers and the level of efficiency is good.

In terms of the Young's modulus and the Maximum strain, DEAPs are much more suitable for energy harvesting devices, compared to piezoelectric materials. With their high flexibility, DEAPs can be obtained in many different shapes and over large surfaces.

In particularly, dielectric elastomers are the best performing DEAPs in terms of energy density and maximum strain. Moreover, this technology is cheaper and very easy to apply for commercial purposes. New dielectric polymers are under development to improve the density of scavenged energy. These materials have a higher dielectric constant, a lower loss factor and Young's modulus.

As for piezoelectric materials, the applications using these materials are limited, for their inherent limitations include aging, stiffness, and brittleness. However, unlike DEAPs, piezoelectric materials can sustain much stress and impact, making them suitable in some places such as tires and shoe heels.

This section compares the difference between piezoelectric materials and DEAPs in their density, Young's modulus, maximum stress, maximum strain, dielectric constant and maximum energy scavenging density. It is demonstrated that the DEAPs have the great potential for mechanical energy harvesting. Currently, piezoelectric materials are in common use for harvesting mechanical energy because of their compact configuration and compatibility. However, their inherent limitations including aging, depolarization, and brittleness restrict their development. In comparison, electrostrictive polymers with cellular polypropylene electrets are promising candidates for replacing piezoelectric materials for vibration energy harvesting.

4. Applications

4.1. Piezoelectric materials

Piezoelectric materials can be used effectively in the development of smart systems. Significant research work has been devoted to investigating smart structures with piezoelectric actuation, with respect to strategies in practical applications in energy harvesting [30-36].

D A van den Ende *et al*. [38] studied manufacturing energy harvesters inside automobile tires, using piezoelectric power generators. During a revolution of an automobile tire, the tread of the tire is deformed when it contacts the road surface, as shown in Figure 3. And the piezoelectric material attaching to the inside of the tire will generate energy as a result of this deformation. At present the PZT ceramic provide an estimated power of 30 μW·cm^{-2} at modest traveling speeds of 50 km·hr^{-1}. The performance will be further enhanced in the development of materials.

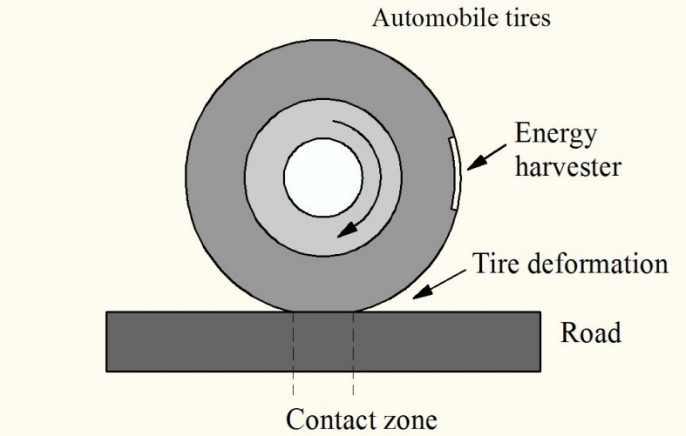

Figure 3. The deformation that an automobile tire experiences during a revolution. [38]

Mateu and Moll [39] analysed several bending beam structures using piezoelectric films suitable for shoe inserts and walking-type excitation. They obtained the resulting strain for each type in function of geometrical parameters and material properties. The optimum configuration was determined by comparing the energy harvested. Furthermore, they developed piezoelectric film inserted inside a shoe based on their initial study [40], as shown in the Figure 4. In this work, they evaluated different factors, such as piezoelectric type, magnitude of excitation, required energy and voltage, and magnitude of the capacitor, in order to find an appropriate choice of storage capacitor and voltage intervals.

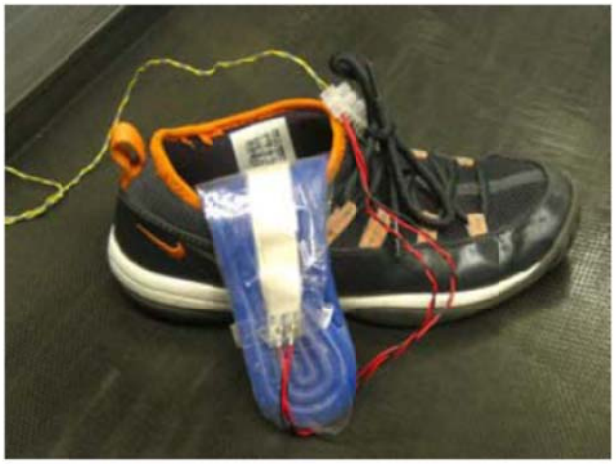

Figure 4. A piezoelectric film-based power generator. [39]

Shah *et al*. [41] compared micropower obtained by harvesting generators using PZT and PVDF membrane. They also evaluated the voltage response of ceramic based piezoelectric fibres composite structures (PFCs) and polymer based piezoelectric strips(PVDF), when subjected to various wind speeds and water droplets in order to investigate the possibility of energy generation from these two natural renewable energy sources for utilization in low power electronic devices [42]. They showed that piezoelectric polymer materials can generate higher power than ceramic based piezoelectric materials. Thus to produce energy from renewable sources such as rain drops and wind by using piezoelectric polymer materials is feasible.

4.2. Electrostrictive polymers

While much attention has been paid to piezoelectric devices for mechanical energy harvesting, electrostrictive polymers have shown their potential in a wide range of applications.

Pierre-Jean Cottinet *et al*. [16] displayed a new application of the synchronized switch harvesting on inductor (SSHI) applied to electrostrictive polymers for DC energy harvesting. An electrical switching device was added and connected in parallel with the electrostrictive elements. Most electrostrictive generators are fabricated by adding an AC-DC converter coupled to a load in parallel with the electrostrictive elements [39]. The approach is originated from the synchronized switch harvesting (SSH), previously developed as a nonlinear technique to address the problem of harvesting energy using piezoelectric materials.

Eddiai A *et al*.[26] studied the effect of cellular polypropylene electrets after high-voltage corona poling on an electrostrictive polyurethane composite filled with 1 vol.% carbon black at a low applied voltage, in order to increase the efficiency of the electromechanical conversion with electrostrictive polymers. Theoretical analysis with experimental validations showed that it was possible to obtain harvested power up to 13.93nW and a transverse strain of 3% at a mechanical frequency of 15Hz. Finally, it was found that the use of polypropylene electrets with electrostrictive polymers was the best

way to decrease the power of polarization in order to obtain a good efficiency of the electromechanical conversion for energy harvesting.

Lallart *et al*. [20] evaluated the energy scavenging abilities of P(VDF-TrFE-CFE) with 1% carbon. They also exhibit that the carbon filled terpolymer outperformed other investigated compositions, demonstrating a figure of merit as high as 2000 times higher than pure polyurethane. They extended their work to the AC-DC conversion for energy harvesting using electrostrictive polymer P(VDF-TrFE-CFE) to make the practical application of such material for self-powered devices more realistic [37]. Their theoretical and experimental analysis showed that an energy harvesting module with AC-DC conversion using a bias electric field of 10 $V \cdot \mu m^{-1}$ and a transverse strain of 0.2% is much more efficient than most of piezo-based harvesters.

4.3. Dielectric electroactive polymers

Dielectric elastomers have shown considerable promise for harvesting energy from environmental sources such as ocean waves, wind, water currents, human motion, etc. Dielectric elastomers have better performance for a good mechanical matching when the vibration source presents high strain and low frequency behaviour. In addition to this high strain capabilities, dielectric elastomers are cheap, highly conformability, processing simply, and can be obtained in various shapes over large surfaces.

Kee S. Moon *et al*. [27] designed the new kind of cantilever beam, which is made of a lead magnesium niobate-lead titanate (PMN-PT) material with polydimethylsiloxane (PDMS) coating applied. By bonding a ductile material to a brittle material, the stress reducing properties of the ductile material will reduce the stresses of the brittle material. PDMS increases the strength of PMN-PT by reducing the propagation of micro-cracks in the cantilever. The thin coating of PDMS evenly distributes stress along the cantilever and encourages uniform bending. These two factors allow the cantilever to have a greater deflection and therefore produce a higher voltage without fracture. Besides, they discuss the use of proof mass to decrease natural frequency of the harvester. According to the analysis the natural frequency will decrease by 115Hz for every milligram of mass placed on the tip of a 10 mm PMN-PT cantilever.

Aschwanden and Stemmer [28] demonstrated a low-cost, electrically tuneable diffraction grating based on soft dielectric elastomers, namely VHB 9410, an acrylic by 3M. Until recently, the state of the art in tuneable diffraction gratings for telecommunications and display device applications has relied on standard hard piezoelectric materials. Planar expansion of dielectric elastomers was used to induce change in the period of these tuneable elastomeric diffraction gratings. A 1mm thick acrylic film was pre-stretched and mounted on a frame. The tuneable diffraction grating can achieve a continuous grating period change of 19.2% with applied voltages of 500 V, an improvement by a factor of 90 compared with conventional tuneable diffraction gratings based on hard materials. In addition this dielectric elastomer based device achieved a tuneable angular range exceeding 100mrad.

Chiba S1 *et al*.[29] carried out ocean experiments on generating electric power from natural wave motion with the EAP generator installed on a buoy, as shown in Figure 5. The maximum measured electrical output capacity, verified in laboratory tests, was 12 J for one cycle of operation. Even with the small wave height of 10 cm, they were able to generate a peak power of 1.2 W with an average power of 0.25 W

In addition, they found that these measurements were made with a bias voltage of 2000 V applied to the dielectric elastomers. These numbers were extrapolated to estimate the potential of an EAP generator mounted on a buoy. In the laboratory test, nine times more energy was obtained from a bias voltage of 6000 V than from 2000 V. By simply raising the applied voltage to the 6000 V limit that the roll can withstand before risk of electrical failure, a peak power of 11 W and an average power of 2.2 W could have been generated under these same small wave conditions.

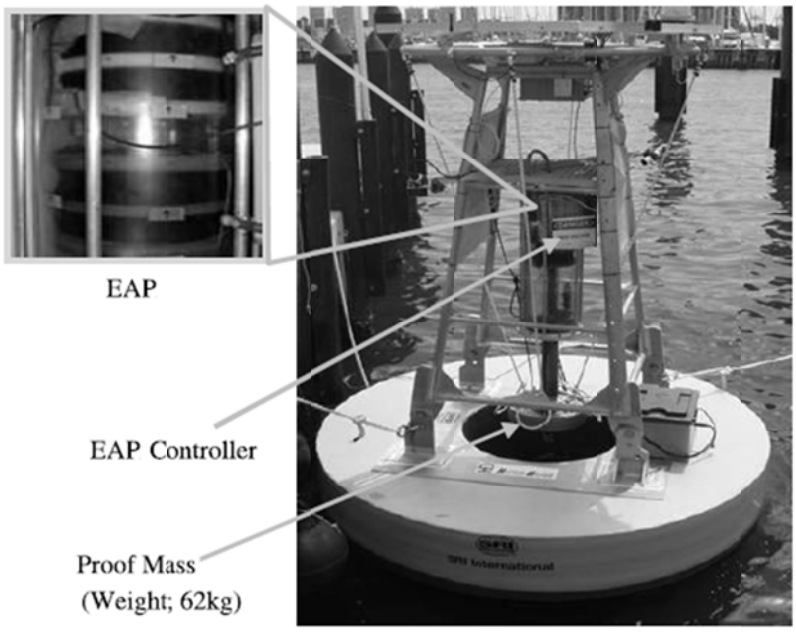

Figure 5. EAPs generator system on the test buoy. [29]

5. Conclusions

This paper gives an account of the development and recent advances in vibration energy harvesting using piezoelectric materials and DEAPs, together with some commercial products available. The large numbers of references reviewed have indicated that piezoelectric materials that are in common use have their inherent limitations such as aging, frequency, and brittleness become less attractive compared to electroactive polymers. The main advantages of polymers over ceramics are the lower stiffness and mechanical flexibility, with better performance provided by dielectric elastomers. The technology of energy harvesting using DEAPs is still in its emerging stages attempts to model the behaviour and either improves the performance, but the increased resources and interests related to these materials are leading to rapid advances in this field. Maintenance free, self-powered devices for their lifetime has become an industrial challenge for the next few years. The DEAPs can potentially replace piezoelectric materials commonly used as active materials of energy harvesting systems.

Current challenges in the field of energy harvesting using electroactive polymers concern the development of systems capable of ensuring a constant voltage on the polymer at a small energetic cost. This means that electrical charges have to be injected in the polymer to compensate small electrical resistive losses in DC and to maintain the bias voltage. Besides, dielectric polymers need a high voltage to realize energy cycles, for about 150 $V \cdot \mu m^{-1}$. This high voltage may result in the breakdown of the materials.

Acknowledgement

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