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Utilisation of smart polymers and ceramic based piezoelectric materials for scavenging wasted energy

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ABSTRACT

Piezoelectric smart polymer and ceramic materials can be deployed as a mechanism to transform mechanical energy into electrical energy that can be stored and used to power portable devices. This paper focuses on the development and comparison of a micropower based harvesting generator using piezoelectric PZT (lead zirconate titanate) ceramic, PVDF (polyvinylidene fluoride) membrane and PP (polypropylene) foam polymer with the intention of establishing power output from temperature fluctuations. Unimorph and bimorph strips of various sizes were prepared and subjected to vibration and impact experiments in order to directly compare the voltage output. The effect of the ceramic fibre diameter, laminate thickness, impact area, weight of the free falling mass, vibration frequency and temperature on the voltage output were studied. Experiments are outlined detailing the performance characteristics of such piezoelectric fibre laminates. Results show voltage outputs of nearly 40 V which is considered sufficient for potential applications in powering microsystems.

1. Introduction

After discovering a category of smart materials exhibiting unique and interrelated properties by Jacques and Pierre Currie in 1880, namely piezoelectricity, such materials became the base for a large number of sensor and transducer applications in diverse fields such as security systems, medical diagnostics devices and non-destructive testing [1]. The most widely used piezoelectric materials are PZT based ceramics, with a typical d_{33} coefficient of 220 pC/N [2], PP foam and PVDF membrane polymers, with a typical d_{33} coefficient of 30 pC/N [3]. Among the piezoelectric polymers, PVDF membrane exhibits strong piezoelectricity [4–6]. Under a force (or pressure), a voltage is built up on both sides of a piezoelectric materials through piezoelectric effect. This unique property can be utilized to generate/harvest electricity from environmental vibration such as human motion.

A previous modelling study [7] shows that 5 W of electrical power can be generated by a 52 kg person at a brisk walking pace using a PVDF power harvesting device integrated in a shoe. Umeda et al. [8] tried to harvest impact energy induced by a free falling ball to a plate with integrated PZT wafer and developed an electrical equivalent model of transforming mechanical impact energy to electrical power. Corresponding technologies for energy storage using a bridge rectifier and a capacitor have been developed. Kymissis et al. [9] examined the use of a piezoelectric film in a shoe sole to provide power to light a bulb. Energy harvesting by piezoelectric material through the impact of rain drops has been proposed and proven in principle [10].

The generated electrical charge of a piezoelectric material with a pressure applied can be expressed in a matrix notation in terms of dielectric displacement, D (charge per unit area, C/m^2)

$$D_i = d_{ij}\sigma_j$$

where d_{ij} is the piezoelectric charge coefficient (C/N) and σ_j is the stress (N/m^2) components, where i = 1–3 and j = 1–6. In a simplified term, it is expressed as $V = \mathrm{d}\sigma t/\varepsilon$. Here t is the thickness of piezoelectric material in thickness mode, and length in a lateral mode, ε is the dielectric constant.

Materials that can be easily deformed to induce larger strains and possess large coupling coefficients are good choices for energy conversion applications. Strain and coupling coefficients differ in d_{31} and d_{33} mode with the d_{33}-mode generally depicting larger values. Also important parameters in defining the coupling coefficient are dielectric constant, ε, and the elastic modulus, E of the material. Piezoelectric materials have generally high impedance which results in the generation of high voltage and low current outputs [11].

With rapid progress of microelectronics technology, electronics with extremely low power consumption have been development. Therefore, it is now possible to use piezoelectric micro-generator to power sensor network for remote sensing and control and even to power small electronics devices. Extensive research has been

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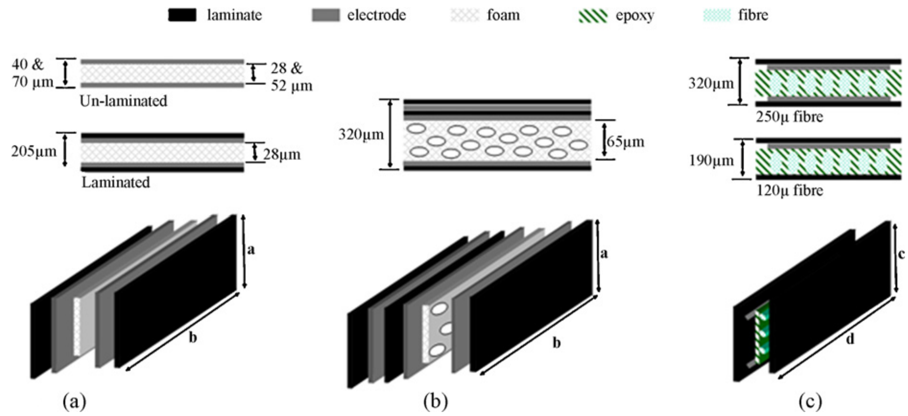

Fig. 1. Schematic representation of non-symmetrical piezoelectric samples (a) PVDF membrane film, (b) porous PP with pores approx. 10 µm diameter and (c) piezoelectric PZT fibre embedded in an epoxy with copper clad electrodes etched on to the inner surface of the laminate which acts as electrodes. (refer to Tables 1 and 2 for relevant dimensions).

carried out on various piezoelectric materials to identify materials with better piezoelectric properties, and various device configurations and output circuits for best power output have also been investigated. The use of ceramic based piezoelectric material for actuators are being studied for reducing buffeting loads on twin-tail fighter aircraft flying at high angles-of-attack. These materials are embedded beneath the fiberglass shell of the model to counteract the bending and torsional stresses induced by the buffeting loads. Polymeric piezoelectric materials are being investigated to harvest otherwise wasted energy from walking. Active piezoelectric foams are interesting research materials however, there is little published information about the use of these materials in energy harvesting applications, particularly under the influence of temperature fluctuations.

With the technology progressing rapidly, new materials with better properties are emerging. Recently, piezoelectric foam has been developed which is extremely lightweight, flexible and can be made to form any shape such as curved surfaces. However, little work has been reported on the performance of PP foam based micropower generators (MPG). PP-based micropower generators can be used for a variety of applications in areas in which they will experience harsh environmental conditions, with extreme temperature fluctuations—such as in a remote area to power sensor networks, in aerospace and automobile tyres. Although progress in the development of MPGs has been made, but very little is known about the effect of temperature on their performance. The aims of the work reported here are to compare the performance of MPGs made from different types of piezoelectric materials (ceramic, polymer and foam), and to investigate the influence of temperature upon voltage output of the MPGs made from these materials.

2. Device structures and experiment setups

There are two common piezoelectric materials used for power generation: polymer membrane PVDF and ceramic based PZT. Conventional piezoelectric ceramic materials are rigid, heavy and can only be produced in block form. Polymer based piezoelectric materials possess lower dielectric and piezoelectric properties than ceramics, but they are soft, flexible, low cost and suitable for large area deployment. Recently a new PP polymer foam material has been developed which demonstrated some superior properties over other two common types of piezoelectric materials. PP foam has voided internal structure therefore it is capable of storing large amount of electrical charges within the voids. The charge is stored in the material structure by way of positive and negative electric charges on opposite internal void surfaces [12] and as a result, external force exerted to the films surface will change the thickness of the air voids, resulting in electrical discharge via conductive electrodes. The PP foam is even lower cost and lighter weight than PVDF.

2.1. Materials investigated

In order to develop a micropower generator with peak performance, a variety of materials and device structures have been selected for this investigation and directly compared. Both laminated and un-laminated piezoelectric elements were prepared and studied. The laminated piezoelectric specimen were prepared using PVDF film, where 125 µm polyester laminates were bonded to either side of a 28 µm thick piezoelectric PVDF film (28 µm laminate PVDF). The two un-laminated specimen used in this study were PVDF film elements of 28 µm and 52 µm thicknesses (28 µm and 52 µm un-laminated, respectively), see Fig. 1a.

A fully shielded, low mass, thin ribbon porous PP sample was fabricated. The sample consists of a sensing element constructed of elastic electrets and 3 layers of polyester film with aluminium electrodes. Crimped connectors were used for connecting electrodes and double-sided sticky tape for convenience (Fig. 1b).

Two ceramic materials, with active piezoelectric fibres of 250 µm and 120 µm diameters were embedded in a polymer matrix and encapsulated in copper clad laminate. A Bimorph element consisting of two 250 µm diameter ceramic fibre-based material adhered either side of a rigid metal centre shim (approx. 110 µm), see Fig. 1c.

The dimensions and names of the piezoelectric polymer and ceramic materials are given in Tables 1 and 2, respectively. The piezoelectric PVDF polymer films were supplied by measurement specialities incorporated (MSI). Piezoelectric PP foam samples polymer were supplied by Emfit and the piezoelectric PZT fibre composites were obtained from advanced cerametrics incorporated (ACI).

Table 1
Tested piezoelectric PVDF and PP samples and their characteristics (MSI).

Material	Width, a (mm)	Length, b (mm)	Thickness (µm)
28 µm laminated PVDF	16	41	205
28 µm laminated PVDF	16	73	205
28 µm laminated PVDF	22	171	205
28 µm un-laminated PVDF	22	171	40
52 µm un-laminated PVDF	22	171	70
65 µm laminated PP	20	100	320