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A piezoelectric fibre composite based energy harvesting device for potential wearable applications

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Abstract

Rapid technological advances in nanotechnology, microelectronic sensors and systems are becoming increasingly miniaturized to the point where embedded wearable applications are beginning to emerge. A restriction to the widespread application of these microsystems is the power supply of relatively sizable dimensions, weight, and limited lifespan. Emerging micropower sources exploit self-powered generators utilizing the intrinsic energy conversion characteristics of smart materials. 'Energy harvesting' describes the process by which energy is extracted from the environment, converted and stored. Piezoelectric materials have been used to convert mechanical into electrical energy through their inherent piezoelectric effect. This paper focuses on the development of a micropower generator using microcomposite based piezoelectric materials for energy reclamation in glove structures. Devices consist of piezoelectric fibres, 90–250 μm in diameter, aligned in a unidirectional manner and incorporated into a composite structure. The fibres are laid within a single laminate structure with copper interdigitated electrodes assembled on both sides, forming a thin film device. Performances of devices with different fibre diameters and material thicknesses are investigated. Experiments are outlined that detail the performance characteristics of such piezoelectric fibre laminates. Results presented show voltage outputs up to 6 V which is considered enough for potential applications in powering wearable microsystems.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Advances in wireless technology and low power electronics have seen an increase in wearable devices such as MP3 players and mobile phones. As the demand for wearable mediums increase, power issues become a major consideration. Many present devices use stored power in the form of electrochemical energy in a battery, a major problem with battery technology is the finite supply of electrical energy that must be replaced or recharged. Power harvesting devices capture normally lost energy, and this can produce devices less dependent on finite energy sources. Major sources of energy loss are environmental vibrations and motion of biological systems; these sources are ideal for piezoelectric materials which

have the ability to convert mechanical energy into electrical energy with high conversion efficiency (Umeda *et al* 1997). The concept of utilizing piezoelectric materials for energy generation has been studied greatly over past decades (Elvin *et al* 2001, Hausler and Stien 1984, Umeda *et al* 1996).

One ambient vibration energy source is human movement (Starner and Paradiso 2004), with energy rife in breathing, blood pressure and walking. Approximately 60–70 W of power is consumed during walking and a piezoelectric material in a shoe with a conversion efficiency of 12.5% could produce 8.4 W of power.

Intelligent clothing with flexible piezoelectric materials integrated into fabrics such as gloves (Siores and Swallow 2006), may be capable of collecting a portion of the mechanical

energy associated with daily activities. Converted electrical energy may then be used to charge wearable mediums giving greater battery life or in an ideal scenario a self maintaining power supply. Wearable devices will undoubtedly multiply in years to come due to a constant decrease in size and power requirements of electronic systems. Batteries will therefore present numerous problems, mainly their bulky size and the fact that they need to be periodically replaced or recharged. Piezoelectric materials respond to almost any type and magnitude of physical stimulus, including but not limited to pressure, tensile force, and torsion. Wearable applications have embedded piezoelectric materials into shoes to generate power from walking (Advanced Cerametrics Incorporated, Kymissis *et al* 1998, Shenck and Paradiso 2001).

2. Piezoelectric materials

Jacques and Pierre Currie discovered the phenomenon of piezoelectricity in 1880, a category of smart materials exhibiting unique and interrelated properties. Application of stress to a piezoelectric crystal generates a corresponding electric charge. Conversely the application of an external voltage will induce a shape change. Many materials display piezoelectric properties, some of which are naturally occurring e.g. Quartz, whilst others are engineered to display the properties, e.g. lead zirconate titanate (PZT), polyvinylidene fluoride (PVDF), and cellular or porous polymer electrets. Probably the most common piezoelectric materials are polymers (PVDF) and ceramics (PZT). The polymer materials are soft and flexible; however have lower dielectric and piezoelectric properties than ceramics. Monolithic piezoelectric ceramics are rigid, heavy and produced in block form, therefore add additional mass and stiffness to the host structure, especially when bonding to flexible/lightweight materials. This and their fragile nature limit possibilities for wearable devices.

The field of piezoelectric polymers have long been dominated by ferroelectric polymers of the PVDF family discovered in 1969 (Kawai 1969). The piezoelectric property of PVDF arises from the strong molecular dipoles within the polymer chain necessitating piezoelectric charge coefficients (d) in the range of 10–40 pC N⁻¹.

PVDF is a lightweight, tough engineering polymer available in a wide variety of thicknesses and large areas. Shortages of PVDF are its relatively weak electromechanical coupling in comparison to ceramics and thermal stability, which limit operation temperatures below 100 °C. However new copolymers of PVDF have recently been developed extending its operating temperature range to 135 °C.

Piezoelectric ceramic materials are generally physically strong, chemically inert, and relatively inexpensive to manufacture. Ceramics manufactured from formulations of lead zirconate/lead titanate exhibit greater sensitivity and higher operating temperatures. A traditional piezoelectric ceramic is a mass of perovskite crystals. Each crystal consists of a small tetravalent metal ion in a lattice of larger, divalent metal ions giving each crystal a dipole moment.

Above the Curie temperature, each perovskite crystal in a fired ceramic exhibits a simple cubic symmetry with no

Table 1. Comparison of monolithic piezoelectric ceramic and piezoelectric ceramic fibre composite (Advanced Cerametrics Incorporated).

Property	Monolithic PZT-5A ceramic	Piezoelectric fibre composite of 250 μ m PZT-5A fibres	PVDF
d_{33} ($\times 10^{-12}$ m V ⁻¹)	380	260	-33
K_{33}	1725	495	12
g_{33} ($\times 10^{-3}$ V m N ⁻¹)	24.89	59.35	-310

dipole moment. At temperatures below the Curie temperature each crystal has a tetragonal or rhombohedral symmetry and a dipole moment. Adjoining dipoles form regions of local alignments called domains. The alignment gives a net dipole moment to the domain and thus a net polarization. The direction of polarization among the neighbouring domains in a piezoelectric ceramic is random so the ceramic has no overall polarization. Poling aligns the domains in the ceramic giving a net polarization.

Piezoelectric fibre composites (PFC) (Williams *et al* 2002) consist of piezoelectric fibres (Cass *et al* 2003) embedded in a polymer matrix resulting in a material with all the desirable properties of monolithic ceramics and mitigation of the detrimental characteristics. The PFC also has higher efficiency than traditional bulk piezoelectric ceramic materials owing to the large length to area ratio (Mohammadi *et al* 2003).

Due to the cyclic loading in the intended energy harvesting application, the specific samples selected should have no detrimental effects in endurance tests. The piezoelectric polymer (Brown 1999) and piezoelectric fibre composite (Wilkie *et al* 2002) have been tested to prove no detrimental effects appear in tests greatly exceeding ten million cycles.

3. Material consideration for power generation

The generated electrical charge of a piezoelectric material is proportional to the pressure applied and can be expressed in matrix notation in terms of dielectric displacement, D (charge per unit area, C m⁻²)

$$D_i = d_{ij}\sigma_j, \quad (1)$$

where d_{ij} is the piezoelectric charge coefficient (C N⁻¹) and σ_j is the stress (N m⁻²). i is the electrical axis and takes terms 1–3 and j is the mechanical axis having subscripts 1 through 6.

The piezoelectric strain coefficient (d) relates strain and charge. The piezoelectric coupling coefficient (k) is an indication of the material's ability in converting mechanical energy to electrical energy and vice versa, and defined by

$$k = \sqrt{\frac{Y}{\epsilon}}d. \quad (2)$$

Materials with larger strain and coupling coefficients have higher potential for energy conversion. Strain and coupling coefficients differ in 33- and 31-mode with the 33-mode generally depicting larger values. Also important in defining the coupling coefficient are dielectric constant (ϵ) and the elastic modulus (Y) of the material. A higher

Table 2. Tested piezoelectric polymer samples and their characteristics (Measurement Specialties 2003).

Material name	Film width (mm)	Electrode width (mm)	Film length (mm)	Electrode length (mm)	Thickness (mm)	Capacitance (nF)	Minimum radius of curvature (mm)
<i>LDT1-028k</i>	16	12	41	30	205	1.38	3.0
<i>LDT2-028k</i>	16	12	73	62	205	2.78	5.0
<i>LDT4-028k</i>	22	19	171	156	205	11	5.0
<i>DT4-028k</i>	22	19	171	156	40	11	1.0
<i>DT4-052k</i>	22	19	171	156	70	5.7	2.0

Table 3. Tested piezoelectric fibre composite samples and their characteristics.

Material name	Width (mm)	Length (mm)	Thickness (μm)	Capacitance (nF)	Minimum radius of curvature (mm)
250 μm PFC	15	140	320	4.96	19
120 μm PFC	15	140	190	5.74	27
250 μm PFC bimorph	15	140	750	8.41	Rigid

dielectric constant is generally preferable in energy harvesting applications as it lowers the source impedance of the device. Piezoelectric materials are generally high impedance devices resulting in the generation of high voltage and low current outputs (Sodano *et al* 2005).

Piezoelectric ceramic materials display the most desirable properties for energy harvesting applications with the exception of tensile strength which is usually much less than that of polymer material ($2.0 \times 10^7 \text{ N m}^{-2}$ for ceramic compared to $5.2 \times 10^7 \text{ N m}^{-2}$ for the polymer). However crystalline materials when in fibrous form typically have higher strengths (Williams *et al* 2002) due to the decrease in volume fraction. In addition to increasing the strength of the ceramic material, the flexibility of the polymer matrix allows the piezoelectric ceramic fibres to conform to curved surfaces in addition to providing a protective shell for the ceramic fibres allowing them to withstand impacts and harsh environments far better than monolithic piezoelectric ceramic materials. The minimum radius of curvature for all tested samples is shown in tables 2 and 3.

The piezoelectric voltage coefficient (g) relates electric field generated to applied stress and is given as

$$g_{ij} = \frac{d_{ij}}{\epsilon_0 K_j} \quad (3)$$

where ϵ_0 is the permittivity of free space ($8.85 \times 10^{-12} \text{ F m}^{-1}$) and K_j is the relative dielectric constant of the material. The piezoelectric voltage coefficient is low for bulk ceramics in comparison to piezoelectric polymers due to the large dielectric constant of ceramics. By incorporating ceramic fibres into composite structures the d_{33}/K_3 ratio increases.

Piezoelectric voltage constants can be calculated for the monolithic PZT and the PFC consisting of 250 μm PZT fibres. From equation (3) it is desirable for high d and low K values, integration of piezoelectric ceramic fibres into composite structures leads to a larger decrease in K than d (table 1), so an improvement in the piezoelectric voltage coefficient is achieved. A g_{33} value of $24.89 \times 10^{-3} \text{ V m N}^{-1}$ for monolithic PZT materials and $59.35 \times 10^{-3} \text{ V m N}^{-1}$ for the PFC with 250 μm PZT fibres can be achieved.

4. Experimentation

With the objective of comparing flexible piezoelectric materials for energy generation purposes, a variety of materials have been selected: a laminated piezoelectric polymer material, PVDF, where two 125 μm polyester laminates are attached either side of a 28 μm thick piezoelectric film element (*LDT4-028k*), two un-laminated PVDF materials of 28 and 52 μm thicknesses (*DT4-028k*, and *DT4-052k* respectively), two PFC materials, with active piezoelectric fibres of 250 and 120 μm diameters embedded in a polymer matrix and encapsulated in copper-clad laminate (250 μm PFC and 120 μm PFC respectively), and a PFC bimorph material consisting of two 250 μm PFC materials adhered either side of a rigid metal centre shim material (250 μm bimorph). In addition to these stated materials variable lengths of piezoelectric polymer were selected to quantify the effect of material size. The dimensions and names of the piezoelectric polymer materials are given in table 2. The piezoelectric polymer films are manufactured by an American company, Measurement Specialties Incorporated (MSI)³ and the piezoelectric fibre composites supplied by Advanced Cerametrics Incorporated (ACI)⁴. The properties of these PFC materials are given in table 3.

The first experiment mounted the piezoelectric material to a vibrating structure undergoing base excitation (figure 1) dimensions of each device are given in figure 2. Macro scale lengths were selected with the specific application of glove structures in mind. Material outputs were full wave rectified and used to charge a small capacitor.

The second experiment investigated the impact energy of a small mass dropping from a height of 7 cm onto the piezoelectric materials fixed to a rigid structure (figure 1); the samples were compared for response to 4.9 and 11.9 g masses.

The third test compared the voltage output of the different materials in a standard displace and release experiment. Each

³ Measurement Specialties Incorporated, 100 Lucas Way, Hampton, VA 23666.

⁴ Advanced Cerametrics Incorporated, PO Box 128, 245 North Main Street, Lambertville, New Jersey 08530-0128.

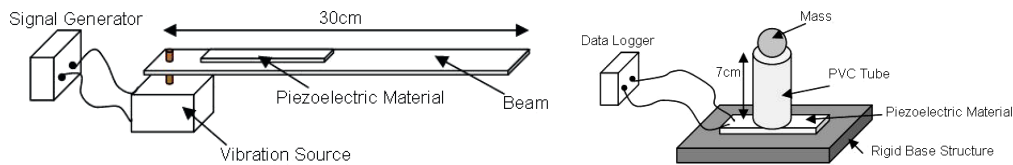


Figure 1. Experimental setup for vibration and impact tests.

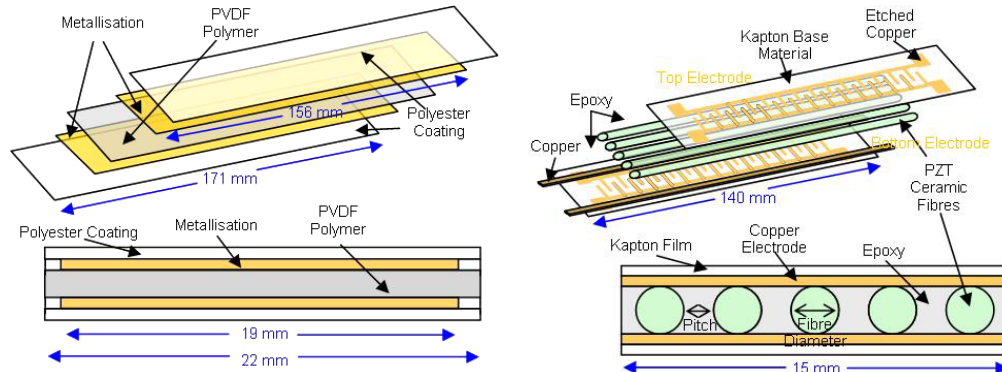


Figure 2. Physical properties and material labels of PVDF piezoelectric polymer and piezoelectric fibre composites.

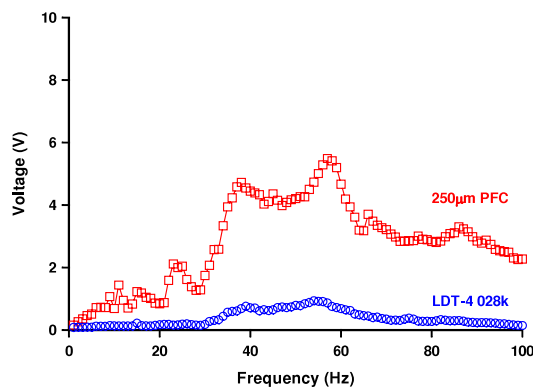


Figure 3. Generated voltage with respect to frequency comparing PVDF and PFC devices.

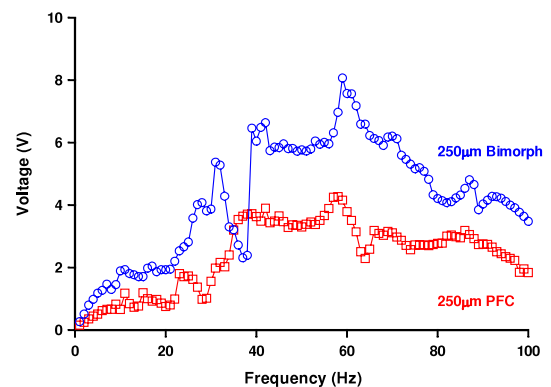


Figure 4. Generated voltage as a function of frequency to compare multilayer material.

sample was adhered to a flexible beam rigidly held at one side. The beam was displaced by a distance of 50 mm and released to oscillate, at which point the generated voltage was recorded.

5. Results

The response of the PFC and PVDF film at different excitation frequencies are shown in figure 3. Both samples display distinct beam resonances. Most noticeable is the fact that the PFC produces approximately five times the output voltage in comparison to the PVDF devices, consistent with the theoretical explanation discussed above.

It was reported that increasing layers will yield greater response (Sodano *et al* 2004). Due to inadequate bonding of the piezoelectric materials in our device, a decrease in output voltage was observed as layers were increased. The result was attributed to the fact that the bonding in the

multilayer structures allowed each layer to generate out of phase signals that led to a reduction in the total generated charge when summed. A bimorph material approximately doubles the response of the PFC showing that adequately bonded multilayer structures can increase the generated charge in devices (figure 4). However the metal centre shim of the bimorph adds additional mass and stiffness to the composite, limiting device flexibility and incorporation into the intended application.

The results of figure 5 indicate larger samples and fibre diameter yield better response. Material size is a valid argument with respect to mathematical models, where an increase in area gives greater electrical power.

The effect of different fibre diameter needs further investigation. The 120 and 250 μm samples have different composition; the 120 μm PFC has a hard laminate material on one side with the copper-clad electrode on the other. Creation of similar more repeatable devices would give better indication to the effect of fibre diameter.

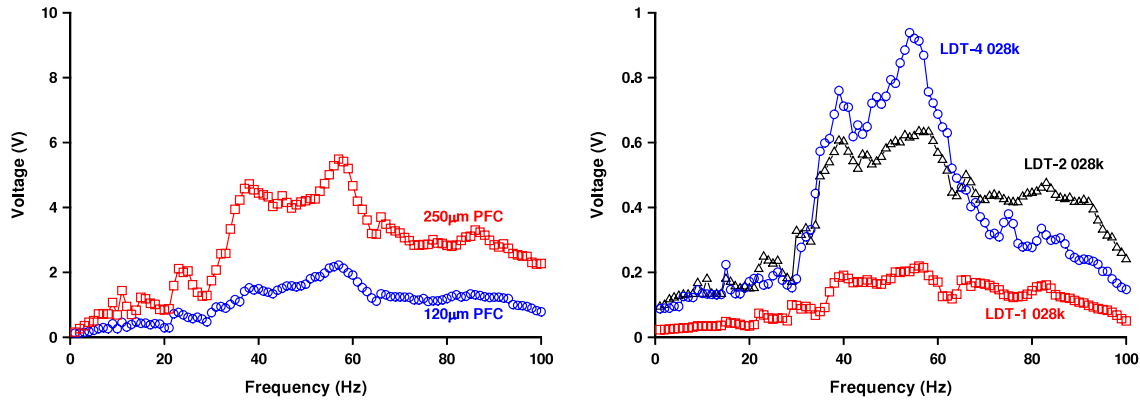


Figure 5. Voltage output against frequency to compare different material sizes.

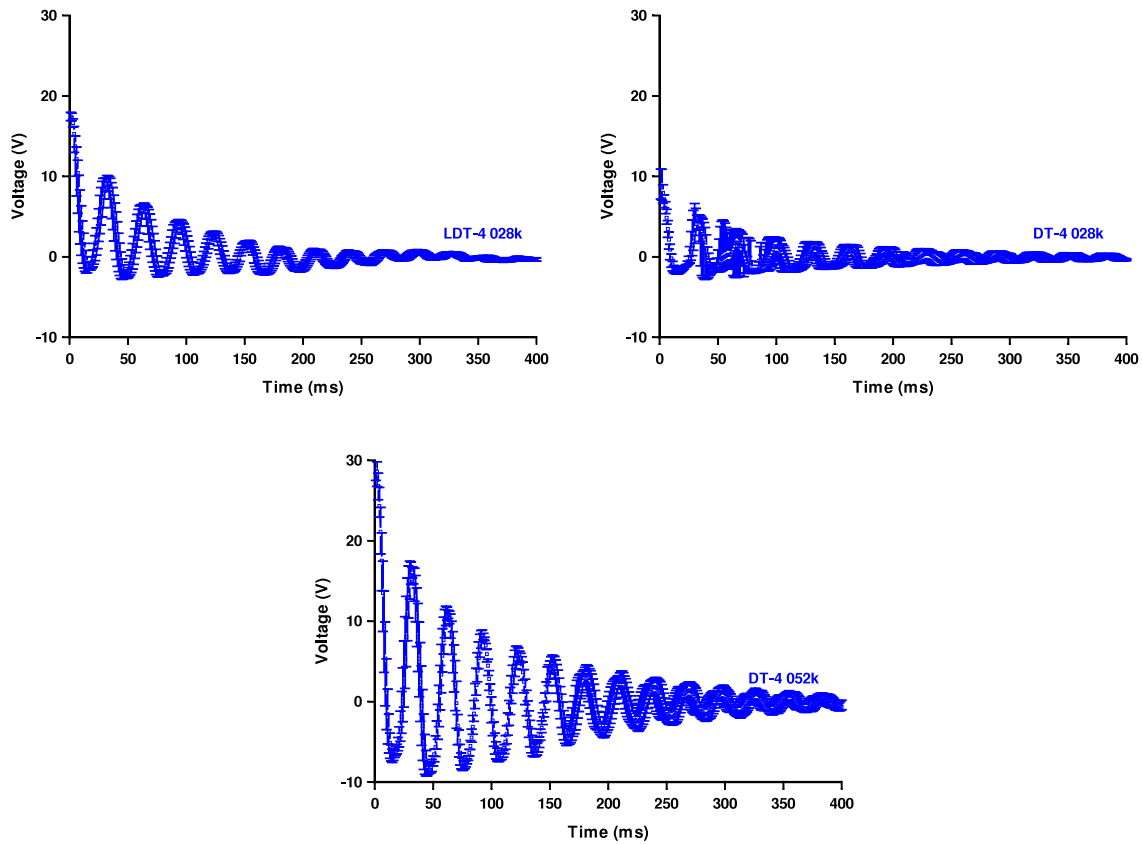


Figure 6. Output voltage with time for displaced cantilever structure showing the response of material thickness.

Material thickness is investigated by increasing the thickness of the active area and inactive phase of the material as shown in figure 6. An increase in the thickness of the active area yields a greater output voltage, this is in agreement with the results of increasing the fibre diameter. The addition of lamination to the PVDF sample increases the materials Young's modulus. Table 4 shows that the materials capacitance is related only to the active area of the material. Therefore d and ϵ of the material remain constant as the thickness of the inactive phase is increased.

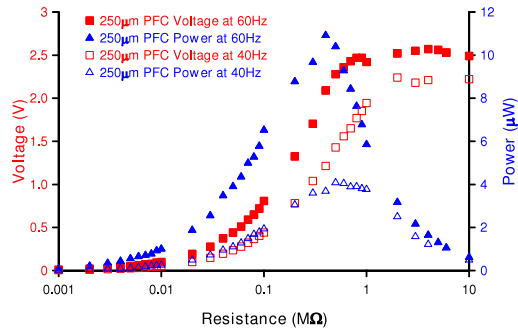
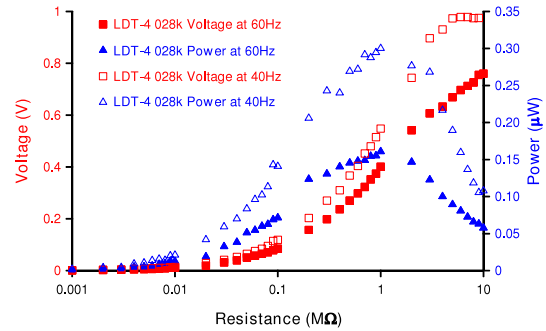
The electrical properties of the material are concerned only with the thickness of the piezoelectric layer. Relating to

equation (2) an increase in Y whilst ϵ and d remain constant should yield an increase in the materials electromechanical coupling coefficient and therefore an increase in the generated charge.

The PVDF samples were adhered to a cantilever structure clamped at one end. The cantilever tip was displaced by a distance of 50 mm and released to oscillate at its natural frequency. The principle relating to equation (2) is shown to be true; addition of inactive lamination will increase the materials stiffness without any effect on the electrical properties of the device, leading to an increase in the electromechanical coupling of the device and a greater output voltage.

Table 4. Relation between capacitance and thickness for PVDF materials (Measurement Specialties 2003).

Material name	Film width (mm)	Electrode width (mm)	Film length (mm)	Electrode length (mm)	Thickness (μm)	Capacitance (nF)
DT4-028k	22	19	171	156	40	11
DT4-052k	22	19	171	156	70	5.7
LDT4-028k	22	19	171	156	205	11

**Figure 7.** Generated power with respect to load resistance comparing excitation frequencies for PFC devices.**Figure 8.** Generated power with respect to load resistance comparing excitation frequencies for PVDF devices.**Table 5.** Peak impact voltages of materials stressed by different masses.

PFC material	Maximum strike voltage (V)			
	11.9 g		4.9 g	
120 μm PFC	3.96	-7.89	2.96	-5.46
250 μm PFC	7.37	-2.66	4.88	-0.5
250 μm bimorph	36.82	-9.38	15.53	-10.38
LDT-4 028k	1.03	-1.04	0.85	-0.44

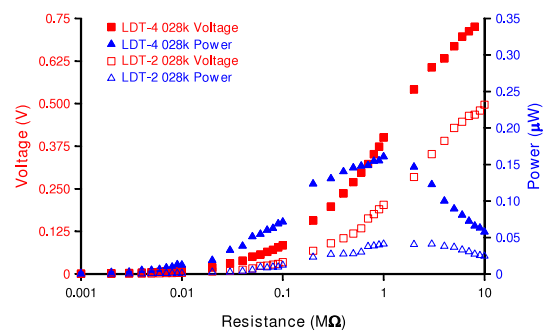
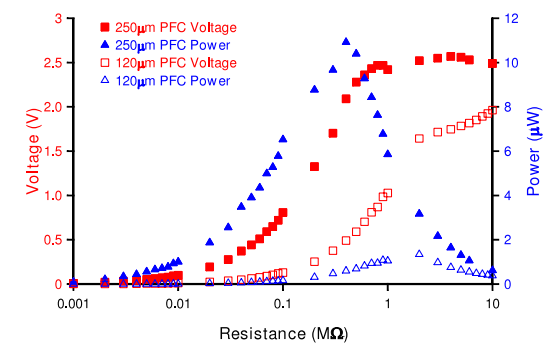
Finally the responses to different weight impacts are shown (table 5) with heavier masses producing the largest responses due to the greater stress exerted on the materials.

Observations from the vibration test hold, the PFC devices produce the largest outputs in comparison to the PVDF polymer devices and the bimorph material can further increase output.

Material output has so far been compared in terms of output voltage, simply as this gives any easy qualitative analysis. However energy harvesting applications require the energy source to be connected to a load, therefore it is useful to view material output in terms of power generated. For this a selection of the materials tested as in the vibration test (figure 1) were connected to a load of known resistance, this resistance was varied and the delivered power determined.

Figures 7 and 8 show the voltage and power output of the PFC and PVDF samples respectively, over a range of load resistances for two excitation frequencies (60 and 40 Hz). The optimum load resistance varies for the frequency of excitation and piezoelectric material. Figure 8 further clarifies that each specific material will have its own optimum load where power output is maximized.

From figures 7 to 9 we can see that higher power is achieved from the PFC devices, in agreement with the

**Figure 9.** Power output against load resistance to compare different material sizes at 60 Hz excitation.

results obtained in term of voltage shown above. The maximum output power is $\sim 11 \mu\text{W}$ for the PFC devices, about 40 times of the $0.3 \mu\text{W}$ output power for the PVDF devices. With respect to harvesting energy from human motion, specifically in proposed glove structures, multiple material sizes and a multitude of excitation frequencies are to be present. Therefore the optimum load resistance required to maximize the harvested power will continuously vary from

device and physical activity. Work has been reported on the use of DC–DC converter circuits (Ottman *et al* 2002, 2003) and maximum power point trackers (Santos *et al* 2006) where the impedance of the load is altered in order to continuously maximize deliverable power.

6. Conclusions

This work has shown the feasibility of micro composite materials for the purpose of energy harvesting applications. PVDF samples tend to give greater repeatability in comparison to PFCs, attributed to the stringent assembly controls. Further work will characterize fibre numbers and pitch variation of the PFC in order to draw some conclusions as to their repeatability. The greater piezoelectric properties of PZT in comparison to PVDF holds one reason for the increased voltage and power, with a second being the use interdigitated electrodes, taking advantage of the greater d_{33} piezoelectric constant (Werlink *et al* 2002).

This investigation has shown PFCs to be the choice material for flexible power harvesting devices, more work on electrode patterning, fibre diameter, and fibre pitch should yield more promising results for wearable power harvesting devices.

The experiments performed have induced higher frequency and lower stresses on the materials than those experienced by the material when incorporated into glove structures. With the exception of the 250 μm bimorph sample the minimum radius of curvature for all samples will allow placement in a glove structure against the back of the bearer's hand. Stresses experienced due to daily activities should yield higher open circuit voltages at reduced intervals yielding similar levels of achievable power to the stated results. In addition the use of multiple materials and multilayer structures along the spines of every finger, the achievable harvested power will increase. These flexible materials can offer a non-invasive power harvesting medium able to collect energy lost in bending, stretching, and impact movements of the hand.

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References

Advanced Cerametrics Incorporated *Piezoelectric Ceramic Fibers*
http://acer.inforest.com/pdf/adcera/CERAMICINDSARTICLE_8-17-04.pdf

- Brown R H 1999 *Coin Sensor Endurance Test* (Valley Forge, PA: MSI, Piezo Sensors Division)
- Cass R B, Khan A and Mohammadi F 2003 Innovative ceramic-fiber technology energizes advanced ceramics *Am. Ceram. Soc. Bull.* **82** 14–5
- Elvin N G, Elvin A A and Spector M 2001 A self-powered mechanical strain energy sensor *Smart Mater. Struct.* **10** 293–9
- Hausler E and Stien L 1984 Implantable physiological power supply with PVDF film *Ferroelectrics* **60** 277–82
- Kawai H 1969 The piezoelectricity of poly(vinylidene fluoride) *Japan. J. Appl. Phys.* **8** 975–6
- Kymissis J, Kendall C, Paradiso J A and Gershenfeld N 1998 Parasitic power harvesting in shoes *Proc. 2nd IEEE Int. Conf. on Wearable Computers* http://www.media.mit.edu/physics/publications/papers/98.08.PP_wearcon_final.pdf
- Mohammadi F, Khan A and Cass R B 2003 Power generation from piezoelectric lead zirconate titanate fiber composites D5.51 *Mater. Res. Soc. Symp. Proc.* **736** 263–70
- Ottman G K, Hofmann H F, Bhatt A C and Lesieutre G A 2002 Adaptive piezoelectric energy harvesting circuit for wireless remote power supply *IEEE Trans. Power Electron.* **17** 669–76
- Ottman G K, Hofmann H F and Lesieutre G A 2003 Optimized piezoelectric energy harvesting circuit using step-down converter in discontinuous conduction mode *IEEE Trans. Power Electron.* **18** 696–703
- Santos J L, Antunes F, Chehab A and Cruz C 2006 A maximum power point tracker for PV systems using a high performance boost converter *Sol. Energy* **80** 772–8
- Shenck N S and Paradiso J A 2001 Energy scavenging with shoe-mounted piezoelectrics *IEEE Micro* **21** 30–42
- Siores E and Swallow L 2006 Detection and suppression of muscle tremors *Patent* GB0623905.7 Greater Manchester, UK
- Sodano H A, Inman D J and Park G 2004 A review of power harvesting from vibration using piezoelectric materials *Shock Vib. Digest* **36** 197–205
- Sodano H A, Inman D J and Park G 2005 Comparison of piezoelectric energy harvesting devices for recharging batteries *J. Intell. Mater. Syst. Struct.* **16** 799–807
- Starner T and Paradiso J A 2004 Human generated power for mobile electronics *Low-Power Electronics* ed C Piguet (Boca Raton, FL: CRC Press) Chapter 45, pp 1–35
- Umeda M, Nakamura K and Ueha S 1996 Analysis of the transformation of mechanical impact energy to electric energy using piezoelectric vibrator *Japan. J. Appl. Phys.* **35** 3267–73
- Umeda M, Nakamura K and Ueha S 1997 Energy storage characteristics of a piezo-generator using impact induced vibration *Japan. J. Appl. Phys.* **36** 3146–51
- Werlink R J, Bryant R G and Manos D 2002 Macro fiber piezocomposite actuator poling study *NASA Technical Report NASA/TM-2002-211434*
- Wilkie W K, High J W and Bockman J 2002 Reliability testing of NASA piezocomposite actuators *Proc. Actuator 2002—8th Int. Conf. on New Actuators (Bremen, Germany)*
- Williams R B, Park G, Inman D J and Wilkie W K 2002 An overview of composite actuators with piezoceramic fibers *Proc. IMAC-XX: Conf. on Structural Dynamics (Los Angeles, CA)*