Shoe-Mounted PVDF Piezoelectric Transducer for Energy Harvesting

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Abstract—**Much energy harvesting research has been conducted with ceramic based piezoelectric transducers on account of their relatively large electrical response to mechanical excitation. However, notwithstanding their comparatively low piezoelectric coefficients, piezoelectric polymers too hold promise as energy harvesting materials due to their flexibility and strength which make them ideal candidates for use in more diverse applications. Yet in order to generate appreciable power, these polymers must be utilized in the most efficient manner possible. With these factors in consideration, a novel prototype for a piezoelectric transducer to parasitically harness the energy of heel strikes is designed and examined. This system of multiple vertical PVDF unimorphs is contained in an insert that fits into the thick rubber heel of a sneaker. Efficiency and output test results along with comparisons to calculated values are given. The maximum power from the heel transducer is found to be 0.06 mW and improvements in efficiency are achieved.**

I. Introduction

As compact, low power electronics become more prevalent in everyday use and as their increasing portability requires reliable power sources, ambient energy harvesting devices show much potential over batteries. Indeed, by relying on energy scavenged from the environment, such electronics are no longer restricted by the periodic maintenance that batteries demand. In particular, energy harvested parasitically from human movements has garnered much discussion [1]. Perhaps the most energy abundant and readily utilized form of ambient human power is walking.

One of the more notable methods of harnessing this energy from footfalls in previous work has been through the mechanical stress of piezoelectric materials incorporated into shoes. Specifically, transducers designed to harness the energy dissipated in the bending ball of the foot have been constructed as layered staves of piezoelectric polyvinylidene fluoride (PVDF) [4, 5, 6, 7]. As a polymer, PVDF has the advantages of being strong and flexible, but has relatively low charge coefficients [2]. Thus in order to be successful in an energy harvesting system, it must be paired with a structure that optimally converts the input mechanical energy to a useful direction and also uses every inch of the polymer to its fullest potential.

The aim of this paper is to describe a new, efficient design for a shoe-mounted PVDF piezoelectric transducer. To begin, the design of this structure is described in detail. Experimental results demonstrating the power output and efficiency of the system are presented. A model to describe the peak performance of the transducer is then described and its expected values are compared with actual results. Finally, discussion on the improvement of the transducer and its applications is provided.

II. Material

Piezoelectric polyvinylidene fluoride is manufactured as thin films which are stretched to align the polymer chains and electrically poled. They are then coated with silver electrodes on both surfaces of the film to act as capacitor plates to accumulate the charge of the stressed PVDF. Under stress, the polar molecules align due to the semicrystalline nature of the PVDF in such a way as to generate an electric field and a potential across the surfaces of the film. Of the three possible modes available to excite the PVDF, mode 31 is focused on here because more electrical energy, for the same mechanical input, can be harnessed in this mode than in any of the other modes [3]. Mode 31 involves a stretching along the direction that the PVDF was mechanically stressed during fabrication (the stretch direction). Some of the applicable constants for PVDF are given in Table 1.

Table 1
Constants[8] and characteristics of PVDF transducer

Property	Symbol	Value	Unit
Young's Modulus	Y	2.4	10^{-9} N/m^2
Strain constant	d_{31}	23	10^{-12} C/N
Total area	A	0.0095	m^2
Height	H	12.7	10^{-3} m
Distance from neutral axis to center of PVDF	x	51	10^{-6} m
Capacitance	C	11.4	10^{-9} F

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III. Overview of Design

The predominantly compressive forces of a heel strike have been harnessed to provide the tensile forces best suited to excite the PVDF by means of a heel insert. The advantage of situating the transducer beneath the heel of the foot instead of farther forward near the ball, lies in the fact that there is more energy dissipated in this location. The wearer's body weight initially falls wholly on the heel and is only gradually transferred forward with the step. The heel insert, Figure 1, was constructed around a horseshoe-shaped piece of rubber material cut out from the heel of a sneaker. Two horizontal heel-shaped polycarbonate plates were glued at their curved edges to the top and bottom rubber edges of the shoe's heel cutout. Fifteen elongated, rectangular unimorph strips were in turn glued vertically between the two plates, along shallow front-to-back grooves cut in the polycarbonate. The rubber cutout serves both to protect the strips from excess compression, i.e. to dissipate the forces which the strips do not absorb, and to maintain the natural feel of the shoe. Indeed, there is little to no difference in the sensation of walking with the transducer mounted in the sneaker.

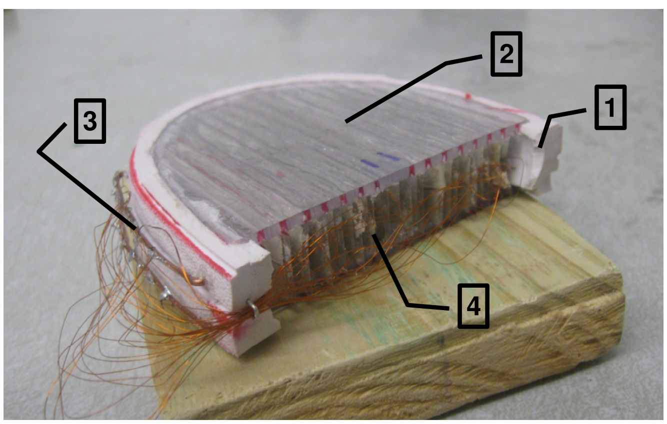

Fig. 1. Shoe insert composed of (1) rubber cutout, (2) polycarbonate plates, (3) copper terminals, and (4) unimorph strips.

The unimorph strips themselves were each constructed of one 0.5 inch tall, 52um thick silver laminated PVDF film (Measurement Specialties) bonded with cyanoacrylate to the side of a slightly wider and longer 4 mil thick PET plastic film substrate (the strips vary in length with the changing space available in the cutout from 1 to 2.25 inches). This particular substrate was chosen for its stiffness and spring-like qualities following much experimentation with different materials. Other plastics failed to return to their original shape after deformation, began to craze, or were too thick to be bent under a reasonable force. During a heel strike, the polycarbonate plates are compressed together, in turn bending all of the PET strips aligned between them. The bending plastic strips induce a strain in the bonded PVDF film, which is offset from the neutral axis. Compared to bending solitary strips, this unimorph configuration substantially increases the electrical response of the PVDF.

Each piece of film was glued to the substrate in the same orientation, with the stretch direction aligned vertically and the positively poled side of the film facing away from the substrate. A narrow copper wire was bonded to the inner electrode of each laminate with conductive epoxy. Another wire was taped to the outer electrode. These leads from each strip were connected to two copper terminals on the outer edge of the shoe insert so that all of the charge generators would act in a parallel configuration to maximize the generated current [3].

The back ends of the unimorph strips were purposefully cut slightly too large to fit perfectly straight between the two polycarbonate plates, causing them to remain very slightly bent when the shoe insert is not in compression. This pre-bending ensures that each of the strips bends in the same direction under compression so that each piece of film undergoes a tensile strain and the sign of the voltage produced from each strip is equivalent. This is important because a strip bending out of unison will cancel the voltage produced by another, decreasing the effectiveness of the transducer.

IV. Power and Efficiency

Two methods were utilized to determine the power output of the transducer system. In the first case, the potential drop across a known load resistor was measured. In order to determine the resistor best matched to the impedance of the transducer, the power output for various loads was measured while the transducer was compressed under a constant force. The results from this experiment, depicted in Figure 2, show that the power peaks at load of about 500 kΩ.

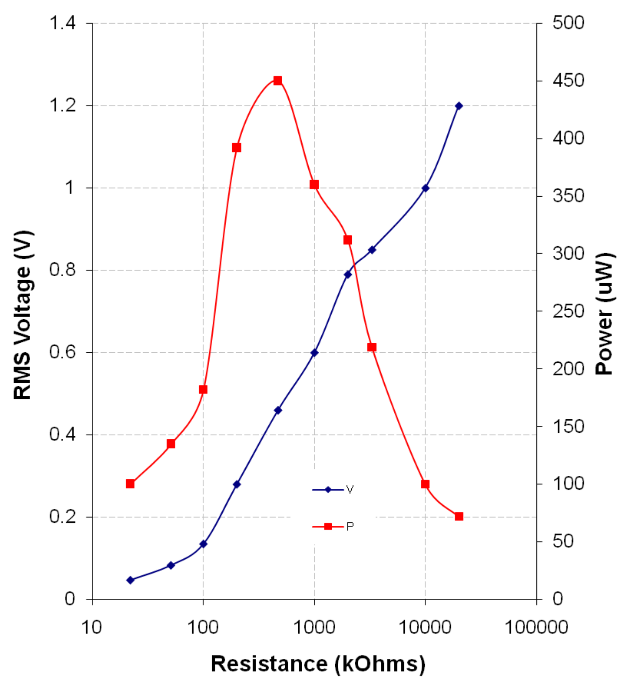

Fig. 2. Dependence of power on load resistance, showing best resistance match.

The fairly high resistance required to match the transducer's impedance can be explained by imagining an equivalent circuit composed of the piezoelectric charge generator, a capacitor for the system's internal capacitance, and a resistor to model the dielectric leakage across the PVDF. For low frequency applications, however, the internal film resistance is very high and can be ignored [8]. The structure's low net capacitance of 17 nF requires that the matching resistance be large.

The best load value determined, the voltage from the transducer across a 470 kΩ resistor at a 1 Hz frequency, shown in Figure 3, was recorded and the root mean square voltage calculated, giving an average power of 0.06 mW. The peak voltage was measured at 21 V, for a peak power of 0.94 mW. The sharp initial peaks are caused by the fairly coherent compression of the strips as the weight of the body falls on the heel. The subsequent rolling transfer of weight forward towards the ball of the foot allows the strips to straighten, generating the ensuing oppositely signed voltage. The negative spikes between steps can be attributed to individual strips returning to their fully extended positions and also to small tensile forces within the heel.

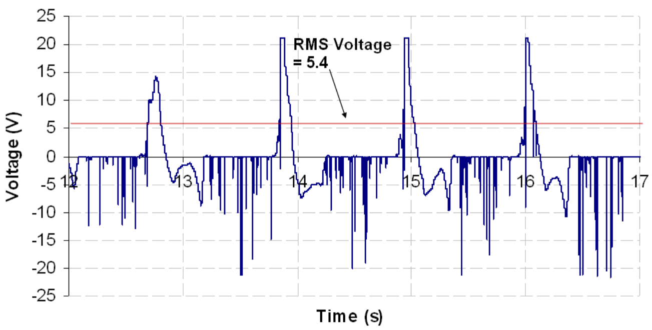

Fig. 3. Voltage waveform from transducer with 470 kΩ load.

In the second method, the energy stored on a bucket capacitor was calculated. The capacitor was connected to the transducer circuit through a full-wave bridge rectifier. With a 1 μF capacitor (1 Hz excitation), the peak voltage reaches 9.6 V over a 1 second period, yielding an average power of 0.05 mW. This result is slightly lower than that found with the resistive load because the 1 μF capacitor does not as closely match the impedance of the transducer. Tests were also conducted with a larger 100 μF capacitor to demonstrate the effects of a larger storage medium. Predictably, the stored energy was about an order of magnitude lower. This highlights the necessity for efficient power conditioning when converting the output energy to a useful form.

In addition, the electromechanical efficiency of the entire shoe insert was calculated by comparing the energy required to compress the strips inside the shoe insert with the energy generated during a corresponding period. The net energy required to compress a single 1 inch long unimorph strip a distance of 1mm was 0.2 mJ. This value can be extrapolated to the case of the complete transducer, for a total mechanical input of 5.9 mJ. Using the average power generated by the transducer over a 1 second period, the efficiency of the transducer is found to be approximately 1%. This measurement takes into account losses caused by the imperfect compression of the multiple strips along with losses in the transfer of power from the PVDF to the load. The PVDF stave developed by the MIT Media Lab achieved an electromechanical efficiency of 0.5% [4]. This calculation, however, used the open circuit voltage from the transducer to determine the raw electrical output. This approach proved to be extremely difficult in the case of the heel-mounted transducer because its much lower capacitance was not large enough to sustain a voltage long enough to be measured accurately. A dual unity gain buffer amplifier circuit was constructed of two high power op-amps in an attempt to measure the potential but the maximum supply voltage was not high enough to avoid capping. Very high power op-amps were not considered due to financial considerations. An accurate measurement of the open circuit voltage would theoretically give an approximate raw electromechanical efficiency of 2%.

V. System Model

It is advantageous to develop a model to describe the strain along the length of the PVDF strips in order to compare with experimental results. The strips aligned in the shoe insert can be approximated as bending beams. Thus, the strain in the PVDF can be calculated in terms of the height of the strip (H), the displacement in height (d), and the distance from the neutral axis to the center of the PVDF film (x),

$$S_1 = \frac{\Delta L}{L} = \frac{x}{\rho} = \frac{2xy}{y^2 + \left(\frac{H-d}{2}\right)^2} \approx \frac{4x\sqrt{2\mathrm{H}d - d^2}}{H^2}$$

where ρ is the radius of curvature of the bending strip. In expressing the deflection of the strip (y) in terms of the displacement, the bending strip was approximated as an isosceles triangle. In order to test and validate this approximation, a single strip, identical to the ones incorporated into the shoe insert, was compressed at several different displacements. The experimental data in Figure 4 is accompanied by a graph of the strain to show the correlation. The voltage increases steadily with displacement, but begins to level off as the displacement nears the height of the strip. However, displacement of this magnitude (not shown on the graph) is impractical as it would result in destruction of the strips.

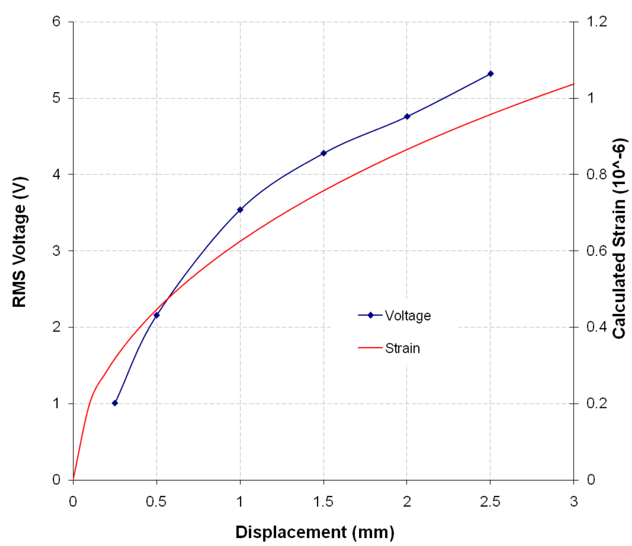

Fig. 4. Experimental output voltage plotted with strain as a function of displacement to show correlation. The voltage is a linear function of strain.

A dependent formula, developed by M. Toda [9] and derived from the piezoelectric fundamental equations (constitutive relations), gives the transducer's expected peak power based on the strain of the PVDF strip.

$$P_{peak} = \frac{|V^2|}{R} = \frac{(e_{31} A S_1 \omega)^2 R}{(1+\omega^2 C^2 R^2)}$$

where,

$$e_{31} = d_{31} Y$$

Using the constant values and physical characteristics given in Table 1, the expected peak power of the shoe transducer dissipated across a 470 kΩ load (1 Hz excitation, 3 mm displacement) is calculated to be 0.198 mW. This prediction is comparable with the measured peak power of 0.94 mW determined above, but does, however, underestimate it. It should be noted that the formula predicts a higher peak power with a larger load. As the experimental results from above saw a decrease in power beyond 500 kΩ, this suggests that other factors, not captured by the modeling equation, are at play.

VI. Discussion

An image of the shoe insert assembled in the heel of the sneaker is included in Figure 5. As the total power generated from this design is on the order of a few dozen microwatts, it is impractical for use as a power source for conventional personal electronics such as cell phones or audio players. However, it is sufficient for many MEMS, microelectronic devices and other very low power applications.

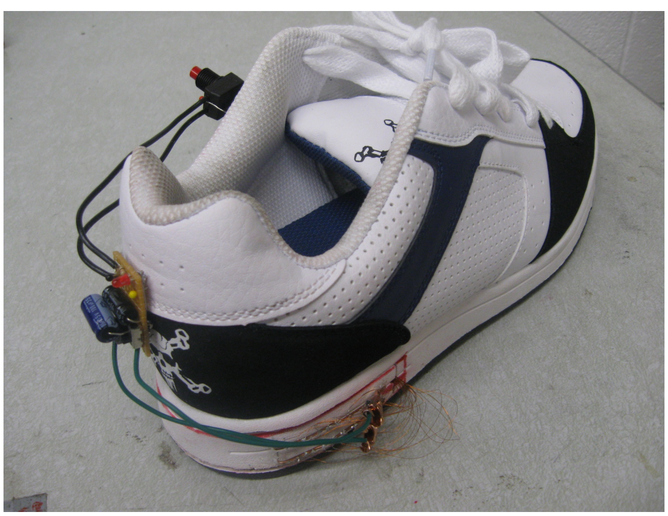

Fig. 5. Complete shoe with transducer inserted in the heel and capacitor circuit attached.

The logical next step to increase the output of this kind of system is to add more PVDF material between the plates. An attempt was made to bond multiple laminates to a single substrate, but this approach suffered from slippage between the layers (reducing strain) and from difficulties maintaining electrical insulation. Consequently, increasing the number of unimorph strips remains the best option. The width of the space inside the insert is 60 mm, and with a conservative total strip width of 0.5 mm, 120 individual strips could potentially be fit into the cutout. The eight fold increase in voltage that this could easily allow would provide about 4 mW of power. Moreover, this would bring the efficiency up to 8%. The additional strips would have little effect on the feel of the shoe as the force required to compress each is relatively small. Even more promising, the vertical strips might be situated throughout the sole of the shoe, harnessing the full force of a footstep and perhaps replacing the function of the dissipative rubber sole. However, an increase in complexity of this type would require very accurate construction, not to mention assembly of large numbers of individual strips.

An increase in PVDF material such as that described would bring the total active area to only about 0.1 square meters. Indeed, the ratio of the square root of average generated power per unit area can be considered a metric for the comparison of piezoelectric PVDF energy harvesting systems. This ratio for the cutout transducer is more than double the value calculated for a PVDF stave, an increase that agrees with the other efficiency calculations above.

Besides adding to the concentration and mechanical efficiency of PVDF in piezoelectric transducers, efficient electrical energy conversion is vital to obtaining useful power from piezoelectric energy harvesting. Advances in more efficient power conditioning and electrical power interfaces [10, 11], better storage devices [12] and low power consumption electronics will undoubtedly lend more focus to this area.

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References

[1] T. Starner and J.A. Paradiso. Human Generated Power for Mobile Electronics. In: Piguet C, editor. Low power electronics design. CRS Press; 2004.

[2] J.S. Harrison and Z. Ounaies. Piezoelectric Polymers. ICASE Report No. 2001-43, 2001.

[3] L. Mateu and F. Moll, Optimum Piezoelectric Bending Beam Structures for Energy Harvesting using Shoe Inserts. J. Intell. Mater. Syst. Struct. 16: 835-45.

[4] N.S. Shenck and J.A. Paradiso. Energy scavenging with shoe-mounted piezoelectrics. IEEE Micro, 21(3):30–42, May 2001.

[5] C.J. Kendall, Parasitic Power Collection in Shoe-Mounted Devices, BS thesis, Dept. of Physics and MIT Media Laboratory, Massachusetts Institute of Technology, Cambridge, Mass., June 1998.

[6] M. Parker, Ambient Energy Harvesting, BS thesis, School of Information Technology and Engineering, University of Queensland, Brisbane, QLD, Oct. 2003.

[7] J. Kymissis et al., “Parasitic Power Harvesting in Shoes,” Second IEEE Int’l Conf. Wearable Computing, IEEE CS Press, Los Alamitos, Calif., 1998, pp. 132-139.

[8] Measurement Specialties. Piezo Film Sensors, Technical Manual, http://www.meas-spec.com.

[9] M. Toda. Shoe generator: Power generation mechanism. Technical report, AMP Sensors, now the Piezo Sensors Division of MSI, Valley Forge, PA, August 1 1997.

[10] E. Lefeuvre et al., Materials, structures and power interfaces for efficient piezoelectric energy harvesting. J. Electroceram. (2009) 22:171-179.

[11] J. Han, Novel Power Conditioning Circuits for Piezoelectric Micro Power Generators, Ph.D. Dissertation, School of Electrical Engineering and Computer Science, Oregon State University, October 2003.

[12] M.J. Guan and W.H. Liao. Characteristics of Energy Storage Devices in Piezoelectric Energy Harvesting Systems. J. Intell. Mater. Syst. Struct. 19: 671-680.