Parasitic Power Collection in Shoe Mounted Devices

by

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Abstract

Possibilities for the "parasitic" collection of power from human walking motion are explored. The focus is on the walking action as a source of power because of the extensive range of motion and large dynamic forces associated with the heel strike and the bending of the sole. Two piezoelectric systems: a multilayer laminate made from PVDF foil and a unimorph piezoceramic composite (PZT); as well as a mechanical system utilizing a shoe mounted electric generator are examined. Test results are given for prototypes of these systems and improvements and potential applications are discussed.

Thesis Supervisor: Joe Paradiso

Acknowledgments

I would like to acknowledge the help of our collaborators at AMP Sensors in Valley Forge, PA. (in particular Kyung Park and Minoru Toda) for working with us on the design of the PVDF stave and for providing the foil. I also acknowledge the support of the Things That Think Consortium and our other sponsors at the MIT Media Laboratory, and I am particularly grateful to my thesis advisor Joe Paradiso for his support and tutelage.

Chapter 1

Introduction

1.1 General Overview

This thesis is an investigation into the problem of capturing power “parasitically” from normal human-body-motion for use in personal electronics applications. The foot was chosen as the best site for power capture as it exhibits a large range of motion and larger dynamic forces than other areas of the body. Further, two actions of the foot -the bending of the ball of the foot and the strike of the heel- were targeted as the best candidates for power sources as there is a large amount of dissipated energy associated with these actions that could be usefully retrieved. Three different systems were built to capture power; two are piezoelectric in nature and one is a mechanical rotary magnetic generator.

1.2 Thesis Layout

This thesis is organized as follows. The next section will present some background and perspective on the problem of capturing power parasitically from human motion as well as outlining some of the motivations for doing so. Next, three different systems are detailed, including goals of the design and justification of design parameters. The pros and cons of each device will be discussed and a measure of power output from each device will be given. Some different power collection and storage options (voltage doubling bridges, inductive tanks, etc.) are presented as are some possible applications of the devices. Finally some possible improvements are discussed. Appendix A contains a calculation of expected power from the PVDF design.

1.3 Background Information and Motivation

With the proliferation of wearable electronic devices, there has arisen the need for portable power sources to power them. In the past, this need has been adequately met by batteries, but as the number of devices carried by any given person grows, batteries become a less attractive option because multiple sets of batteries are heavy and replacing them is expensive and inconvenient. One option would be to have a central power source, but this would entail running wires through the user's clothing which would be cumbersome and inconvenient to put on. A better option for many applications would be to generate power parasitically from normal everyday motion, bypassing the need to carry stored energy in the form of batteries or personal fuel cells. The amount of power that can be generated from human motion without noticeably interfering with that motion is small, but as the power requirements for most personal electronic applications drop, it is becoming more feasible to power several parasitically without hampering the motion of the user.

The idea of harvesting power from human motions is not new. Hand-crank generators, foot pedals, cigarette lighters, bicycles, etc. are examples of human-powered devices, but all need deliberate exertion on the part of the user to operate. The goal of parasitic power is to inconspicuously derive power from the user's motions without deliberate action being taken.

There have been several attempts to accomplish this goal including various electro-mechanincal generators -like the ones found in human powered wrist watches [1] - and even attempts to implant piezoelectric devices in animals [2]. All of the attempts to date have failed to demonstrate one or more of the following characteristics: low weight, low cost, relatively high power output and convenient power delivery, reliability, and (most importantly) unobtrusive "parasitic" action.

Chapter 2

Designs andJustifications

2.1 Placement of Devices

There are two ways to generate power parasitically from the human body. One is to collect energy that is already being wasted. The other is to harness human motion in such a way that an inconspicuous amount of resistance is added to the normal range of motion to generate power. Actions like the swinging of the arms, movement of the legs, respiratory motion, etc. present interesting opportunities, although unfortunately even the smallest added resistance is usually perceptible and can cause annoyance for the user.

Most of the waste energy generated by the human body is dissipated as heat in the joints or the general metabolism and is unusable as parasitic power due to its lack of density (it is spread out over the whole surface of the body)[3]. Also, to get energy out of the body, heat would have to be drawn away from the skin by some sort of converter which would cool the skin and cause discomfort to the user.

The largest usable source of waste energy is that dissipated into the ground and shoes while walking. Energy normally dissipated as heat could be converted directly to electrical energy by means of a piezoelectric device inserted into the shoe, without appreciably changing the “feel” of the sole.

The feet are also desirable as a site for parasitic power collection because of the large dynamic forces generated during walking. Calculations show that when walking quickly, a person can generate up to 67W (68kg person at 2steps per sec. and 5cm of deflection) [3]. This much deflection would be infeasible as far as parasitic power is concerned, but deflections on the order of 5mm (6.7W) could be managed with little or no discomfort and could power an electromechanical generator or stress a piezoelectric material such as PVDF (Polyvinylidineflouride) [12].

Devices implanted in a shoe could collect energy by both absorbing waste energy and by adding a small extra resistance which, because of the large forces involved, might not be noticed.

Heel Strike and Bending of the Sole

The two actions of the foot that exhibit the most potential as parasitic power sources are the strike of the heel against the ground and the bending of the sole.

The strike of the heel against the ground can be modeled as a force impulse that causes the sudden deceleration of the foot. The effect of the shoe sole (especially the cushiony sole of a sport shoe) is to widen this impulse as it does work compressing the sole[4]. When the sole springs back, it does not exert as much force in return as was imparted to it by the foot, and the loss is converted into waste energy manifesting itself as heat (see Figure 2.1:). With a piezoelectric device, some of this waste energy can be turned into electricity.

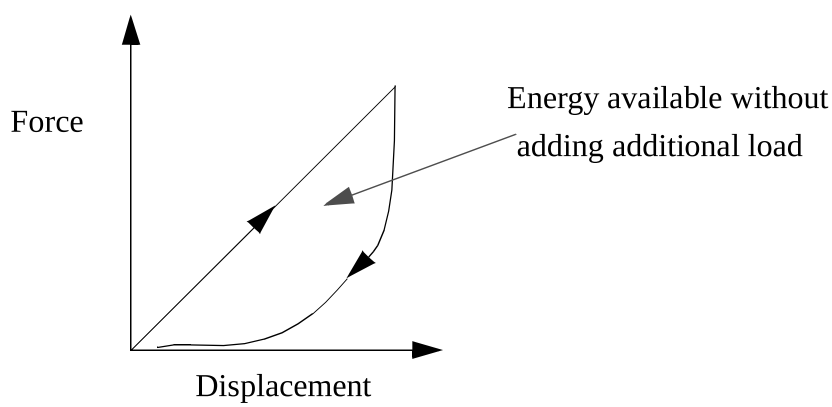


Figure 2.1: Force/displacement curve for a shoe sole

When the sole is bent as the foot leaves the ground, a similar process to the heel strike occurs. In addition to the direct force applied by the ball of the foot, the sole also experiences an induced stress from the bending action. As before, the stress curve for the sole as it returns to its normal shape exhibits a hysteresis effect, which indicates waste energy. This stress can be used directly to pull an inserted PVDF or PZT laminate, which will generate a voltage.

2.2 Heel Strike Systems

We developed two systems to take advantage of the heel strike action. One is a piezoelectric system that would be inserted into the sole of the heel of a shoe, and the other is a mechanical system that attaches to the outside of the shoe by means of straps.

PZT Unimorph

To tap the power generated by pressure during the heel strike we used a piezoceramic material that was modified to be flexible and bonded to a curved piece of spring steel. The modified piezoceramic, called RAINBOW (Reduced and Internally Biased Oxide Wafer), was originally developed by NASA [5]. The unimorph device we used (piezo., spring steel, and electrodes) is a variant of the RAINBOW technology know as a Thunder (Thin-Layer Composite-Unimorph Piezoelectric Driver and Sensor) and was fabricated by Face International Corp [6]. and is available commercially. Specifically it is a TH 6-R with 7 x 7 cm modified PZT (lead zirconate titanate) strip (180 nf capacitance) bonded to a curved piece of 7 x 9.5 cm spring steel (see Figure 2.2:). Thunder actuators provide inordinately large mechanical output displacements - laboratory demonstrations have shown displacements to be as high as 40-50 times the thickness of the device. The Thunder device owes its unprecedented output motion to the special pre-stressed state of its piezoelectric element which is attached to the curved spring steel with a special NASA-LaRC polyimide adhesive. This relatively large amount of displacement makes the Thunder device better suited to our application than other piezoceramics which must be struck with an impulse (which the foot would also experience) to get any useful power.

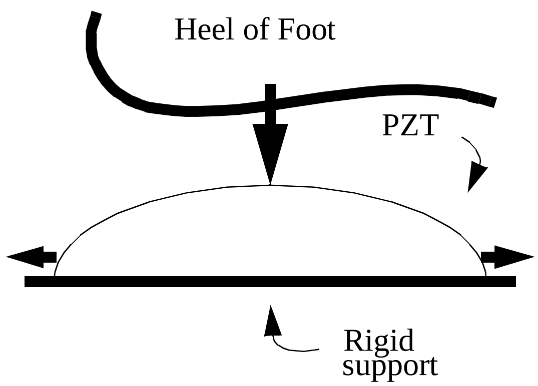


Fig. 2.2a Diagram of PZT unimorph working in the sole of a shoe

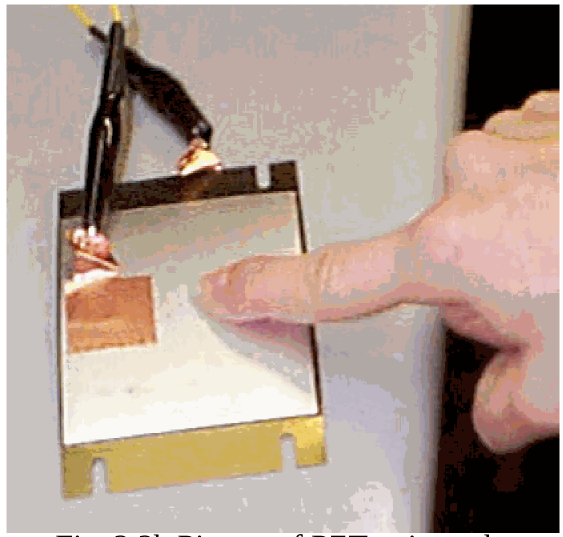


Fig. 2.2b Picture of PZT unimorph under test

Figure 2.2: PZT unimorph

The Thunder PZT unimorph can be pushed flat but will break if reverse bent so it must be supported rigidly from underneath when inserted into a shoe. This can be accomplished by laminating it into the sole on top of a rigid plate that allows the ends of the unimorph to move as it is compressed (see Figure 2.2:). The unimorph has a 7mm range of motion, however, which would be noticeable when walking. If it were embedded within the sole with some form of padding on top and if the strength of the spring were matched to the resistance of the sole material that it replaced, the action of the generator would be hardly noticeable.

Electromechanical Generator

The other strategy we tried for extracting power from the heel strike was to couple the downward force to a standard electromagnetic generator. For this purpose we used a hand-crank-generator driven flashlight (made by Fascinations Corp. of Seattle WA) with the flashlight mirror and light bulb removed. The generator was fixed to a structure whereby it could be attached to the side of a shoe (see Figure 2.3:). The generator is cranked by a lever that was allowed to extend below the heel of the shoe and is depressed by each downward step. Leads were attached to the coils of the generator, and the current was fed through a simple rectifier circuit.

Figure 2.3: Picture of electromechanical generator attached to shoe during tests

All in all, the device was very inelegant but served as a useful comparison with the piezoelectric systems. Electromagnetic systems in general have a much higher conversion efficiency than piezoelectric systems, which is one of the reasons they are so widely used in other applications. The problem is incorporating generators into a shoe and coupling them in a “user-friendly” way to the downward force of the step so that they do not interfere appreciably with the gait of the person. Certainly one could design a much more elegant solutions than the one we tried, but all would suffer from fundamental size and mechanical restrictions that would be difficult to overcome.

2.3 Sole Bending System

We developed one system to take advantage of the stress generated by the bend in the sole of the shoe during the up-step. This “stave” is composed of PVDF piezoelectric polymer sheets with silver-ink electrodes laminated onto a flexible plastic substrate.

PVDF Stave

The stave is laminated in a bimorph design around a 1mm plastic substrate. Sheets of 28 micron PVDF (polyvinylidine fluoride) [11] were inked with a stretched hexagon electrode pattern (foot note to amp) and laminated in two 8-layer stacks on each side of the substrate (see Figure 2.4:).

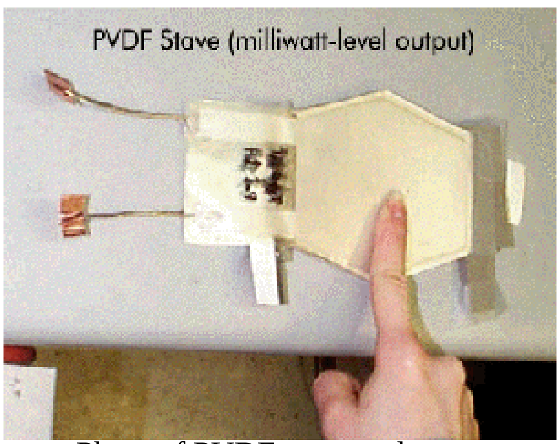
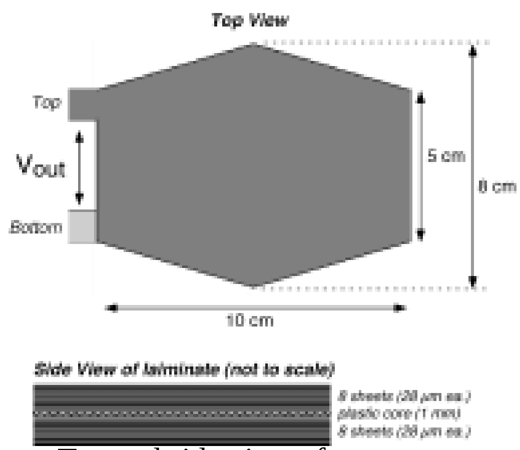


Photo of PVDF stave under test



Top and side view of stave

Figure 2.4: PVDF Stave

PVDF is a semicrystalline homopolymer - a polymer in both crystal and amorphous states. One of the crystal states (the so called β-crystalline phase), in which all the fluorine atoms align, is responsible for the piezoelectric properties of PVDF [7]. The special orientation of the molecules is achieved by two distinct operations performed in sequence. First the material is mechanically stretched at a temperature just below the polymer’s softening point, then subsequently annealed and stretched, which changes the crystalline structure to the β-phase. The film is then polled through its thickness which enhances and stabilizes the piezoelectric properties to levels where they are of practical use. The PVDF is then cooled under the applied field and a conductive coating is applied which functions as electrode.

When treated PVDF is stretched under normal temperatures, the dipole crystalline structures realign, and an internal field is created, causing charge to build up on the electrodes. This produces a voltage difference across the electrodes, which function as a parallel plate capacitor. The reverse process is also observable. When a voltage is applied across the electrode surfaces the PVDF changes its dimensions, resulting in a force output.

The idea behind the PVDF stave is that when it is bent, the 8-layer stack on the top is pulled and the 8-layer stack on the bottom is compressed, with the axis of zero stress in the middle of the flexible plastic substrate. The stretched hexagon geometry was chosen to maximize both stress and area since power increases with both. If we start by calculating the radius of curvature of a cantilevered triangular beam [8]:

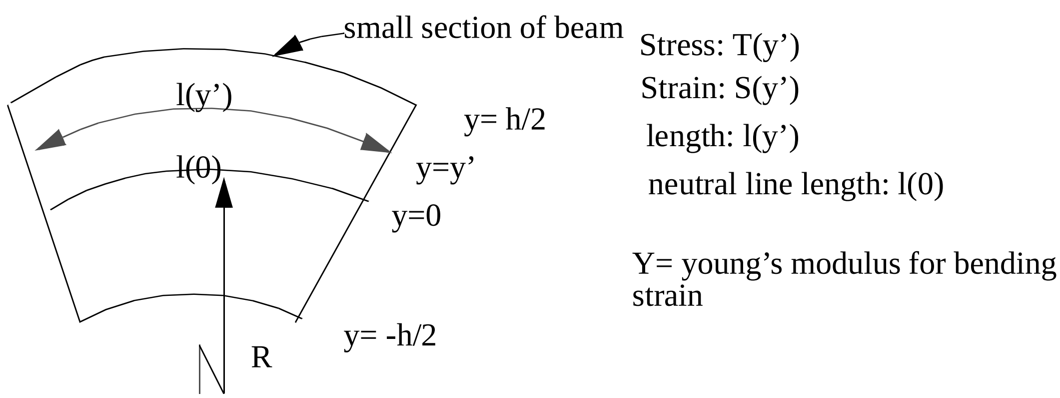


Figure 2.5: Small Section of Beam

$$(y') = \frac{l(y') - l(0)}{l(0)} \ldots and \ldots l(y') = (R + y')\Theta \ldots and \ldots \Theta = \frac{l(0)}{R}$$

$$\therefore S(y') = \frac{y'}{R} \quad \text{so} \quad T = YS = Y\frac{y'}{R}$$ and we have our elementary relations.

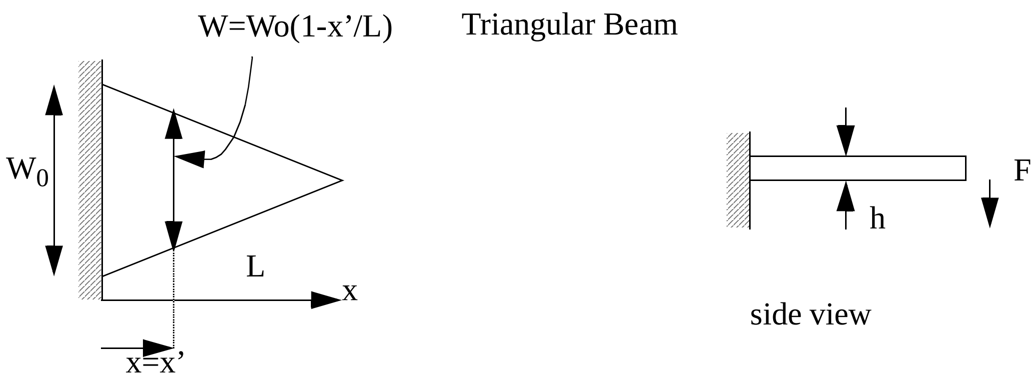
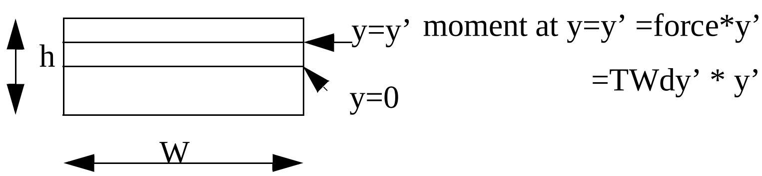


Figure 2.6: Top View and Side View of a Triangular Beam, cantilevered at its base and forced at the tip

Bending moment at x = x’ : $M_b = F(L\text{-}x')$

Internal stress at x= x’ : T(y’) (from above)

Moment over cross section due to T(y’) : $M_i = \int_{-\frac{h}{2}}^{\frac{h}{2}} T \times y' \cdot W dy'$



M_b should balance with M_i

$M_b = M_i$ -> $F(L - x') = \int_{-\frac{h}{2}}^{\frac{h}{2}} Ty'Wdy''$

When we complete the integral, we find that (note R is a constant):

$$F = \frac{Yh^3W_o}{12RL} \ldots and \ldots R = \frac{Yh^3W_o}{12FL}$$

For a rectangular beam a similar calculation yields:

$$F = \frac{Yh^3 W_o}{12R(L-x)} \ldots and \ldots R = \frac{Yh^3 W_o}{12F(L-x)}$$

From these equations we can see that - due to the 1/(L-x) factor - R for a triangle is smaller than R for a rectangular beam, and since:

$$S \propto \frac{1}{R}$$

We can see that the strain in the triangular beam is greater. Unfortunately, a triangular beam doesn't maximize area, especially in the context of the length constraints inside a shoe, so in order to create an optimal geometry we used a stretched hexagonal shape which approximates the bending characteristics of a double triangle beam, but has greater area.

The question arises as to whether the dynamics inside a shoe are anything like a cantilevered beam. If we use a set up like the one in Figure 2.7: with a small gap under the stave, we can think of the foot as the cantilever and the sole as the force and we can see that the stave will bend much like the cantilevered beam we used in our calculations.

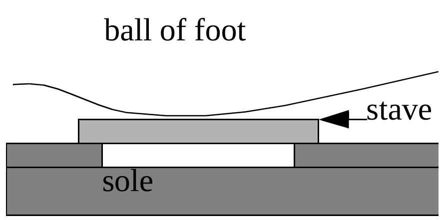


Figure 2.7: Stave Inside Shoe

Chapter 3

Output of Devices

3.1 Power Output

In order to measure the power output from the three devices each was attached to a test resistor (see Figure 3.1:) that approximately matched its internal impedance characteristics and was driven at 2Hz (the frequency of a fast paced walk). The two piezoelectrics were deflected approximately 7mm and the lever of the electromechanical generator went through a 3 cm range of motion.

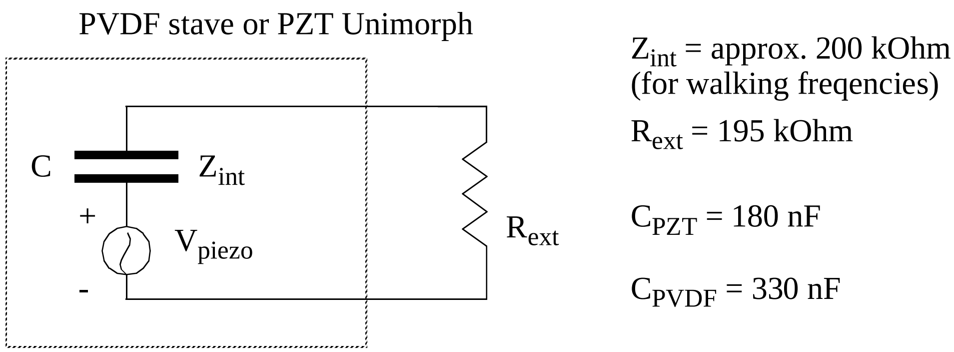


Figure 3.1: Circuit diagram of power test circuit

3.2 PZT Unimorph and PVDF Stave Power Output

To find the resistance that best matched the internal impedance characteristics of the PVDF and PZT at the excitaion frequency of 2Hz, the two devices were tested on a series of load resistors (R_{ext}) ranging from 46 kOhm to 1 MOhm in value. A polynomial fit was used to determine the resistance that gave the peak power output; the power output from the PZT peaked at R_{ext} = 234 kOhm and the PVDF peaked at R_{ext} = 208 kOhm. Figures 3.2 and 3.3 show plots of voltage and power over time (2 Hz excitation, 7 mm range) for both the PVDF and the PZT under the optimum resistive load. The PZT generated peak voltages of around 50 V corresponding to a peak power output of 15 mW and the PVDF generated peaks of around 15 V corresponding to peak power output of 2 mW. Predictions for the PVDF (see Appendix A) give 3.86 mW peak power.

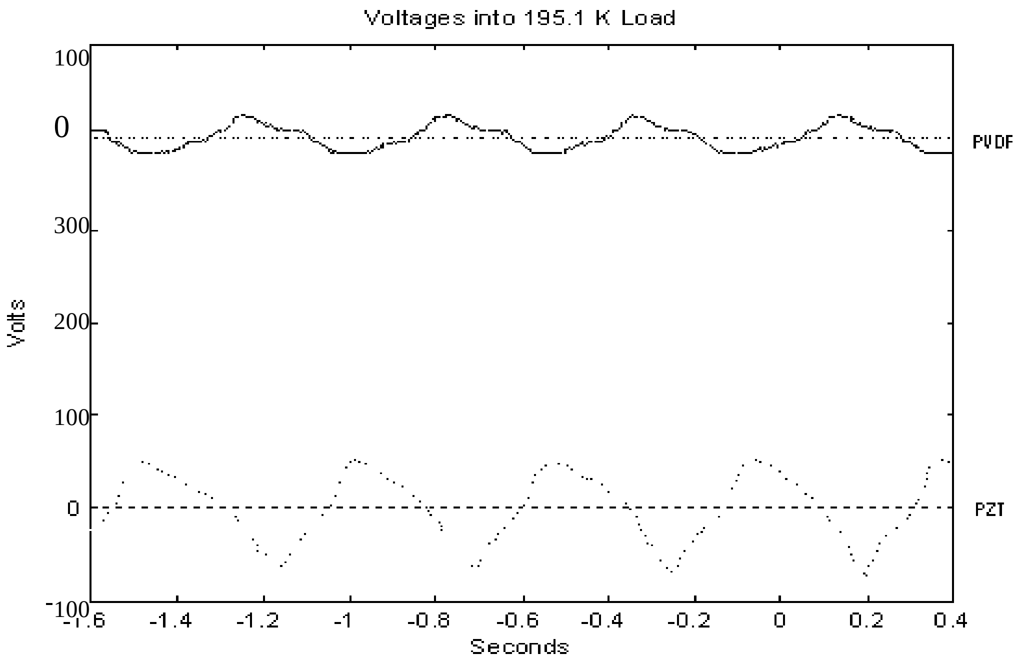


Figure 3.2: Voltage output from PZT and PVDF at 2Hz excitation

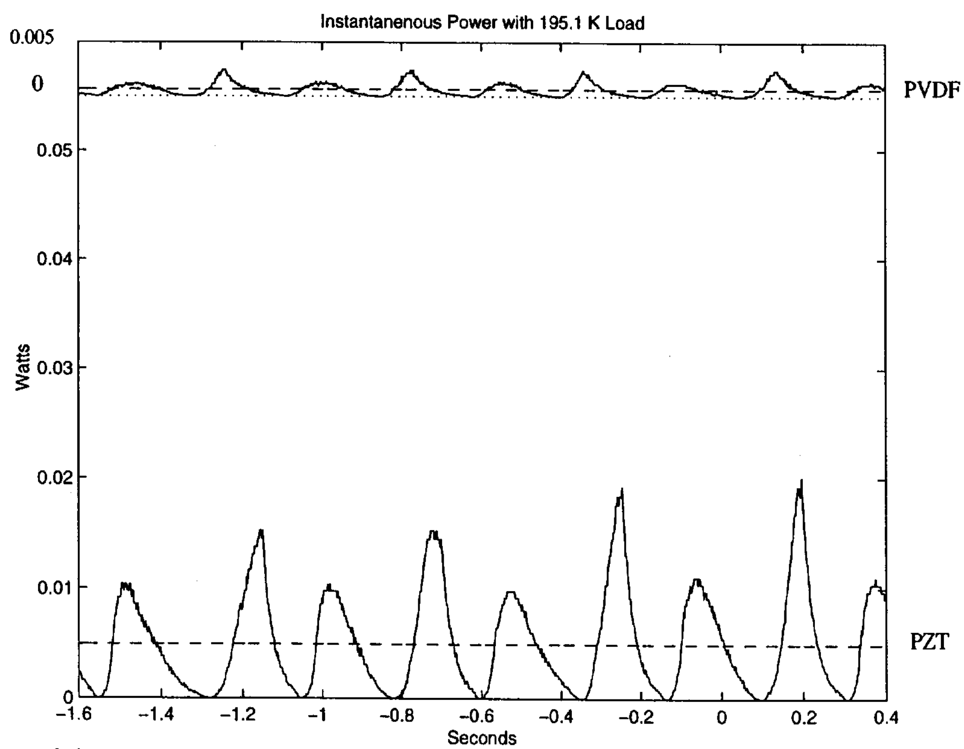


Figure 3.3: Power output from PZT and PVDF at 2Hz excitation, vertical lines indicate area of integration for average power calculation

Figure 3.4:shows that at optimal resistance, average power for the PVDF was .6 mW and for the PZT 5 mW.

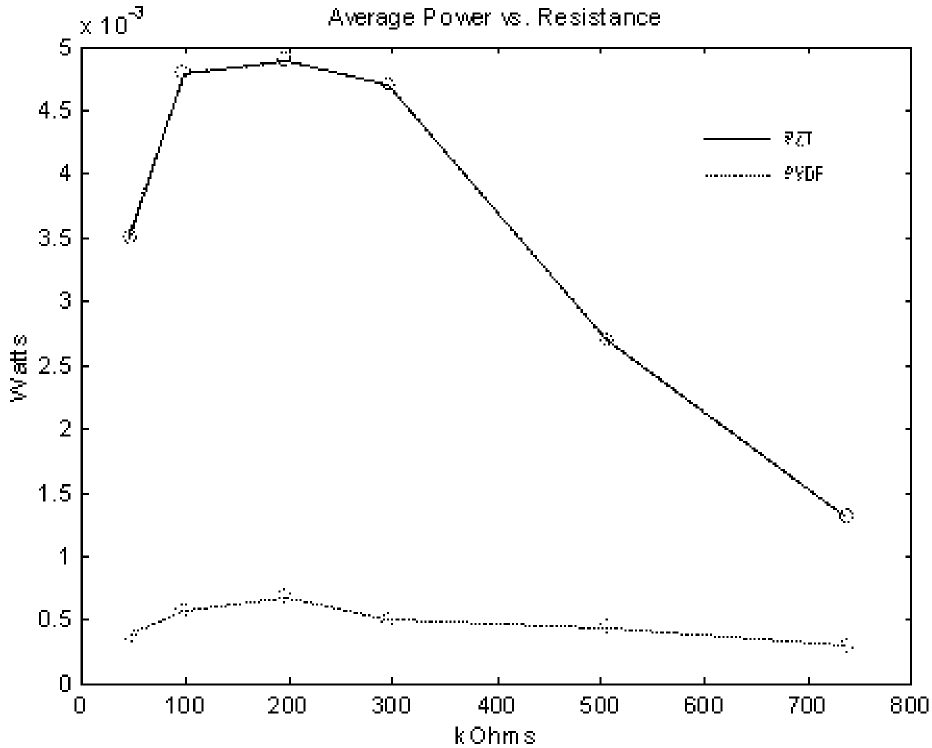


Figure 3.4: Power is averaged over two cycles, peaks are at 208 kOhms (PVDF) and 234 kOhms (PZT) from polynomial fit

3.3 Generator Output

The generator, when excited at the same frequency, produced a nearly steady-state 1.8 Vrms (the generator included a flywheel to store mechanical energy) across a 10 Ohm resistor (matching its internal impedance) which corresponds to a power output of 250 mW.

The large difference between the piezoelectric systems and the generator is not surprising. All the energy that is used to displace the generator's lever by 3 cm goes directly (via a simple gear train) into the mechanism that converts mechanical energy into electrical energy i.e. armature rotation. In the case of the PVDF and the PZT the displacement is only 7 mm and most of the energy becomes potential energy stored in the spring of the stave or the unimorph. Only the strain (1-3%) generated by the displacement (mechanical-electrical coupling occurs most efficiently through the longitudinal (3-1) mode) actually gets converted to electricity - and at a much lower efficiency than that of the generator (~25% for PVDF vs. ~50% for generator).

Although the power generated by the PVDF could be increased by an elaborate pulling mechanism that converts more of the downward force into strain, this would eliminate the major advantage of the PVDF, which is its innocuousness. If a complicated and more obtrusive device is to be used then a generator is a better candidate for a conversion mechanism as generators have a much higher mechanical-electrical conversion efficiency (some go as high as 80-90%) than PVDF or PZT.

Chapter 4

Discussion

4.1 Applications

Though a power output of .6 mW for the PVDF stave is relatively small it may still prove useful in applications where little power is needed or in low duty-cycle applications where energy could be built up and stored over time. One major advantage of the PVDF system is that is the least noticeable of the three and would be completely unobtrusive to the user if laminated into the sole correctly. In laboratory demonstrations we used the PVDF stave to power a PIC microcomputer driving tiny speaker, a digital watch, and an active RF-tag which transmits a short range wireless ID code after several effective steps. This has applications in active environments, allowing the user to transmit their identity to the immediate vicinity while walking through. In fact, the RF-tag and the rectifier circuit used to power it are small enough that they could be incorporated - with a PVDF system - into a shoe without further modification.

(possibly talk about not making predicted power levels)

At 5 mW, the power output from the PZT unimorph is higher than that of the PVDF by a factor of about 8.3, and so in addition to the devices already mentioned the PZT can drive more power intensive applications like a wireless pager. This device also has the potential to power a version of the Media Lab's PAN [9], which injects a low-frequency, low-voltage carrier signal into the body through the shoes, enabling digital communication with other people and intelligent objects when touched. The unimorph's main drawback is its curved shape, which is more difficult to incorporate into a shoe due to space considerations. Because of its shape, the unimorph must be able to slip as it is compressed in the shoe, allowing more opportunities for breakage and general wear while walking. If these obstacles to integration can be overcome, however, the PZT unimorph would be an optimal solution to many parasitic power problems.

The generator, in contrast with the PVDF and PZT, produces enough energy to power almost any hand-held piece of electronics. Here, there are no problems with lack of power, but the awkwardness of the device (both its weight and "chunkiness") and its interference with the natural gait pose daunting problems that will probably relegate any similar designs to very specialized applications. Assuredly there are many improvements on the design that could be made that would make it smaller and less cumbersome and improve the efficiency of the coupling between step and generator rotation, but such improvements will not be able to match the convenience of the piezoelectric systems without making large sacrifices in output power.

4.2 Improvements and Future Work

One large barrier to high power output from a PVDF system is finding efficient ways to stress the PVDF foil without adding to much complexity to the system. When the stave is bent, the amount of force imparted to the foil increases with the third power of the thickness of the substrate [8]. This indicates considerable gain by using a thicker substrate (perhaps 2 to 3 times thicker). The thicker substrate would make for a stiffer stave but power output could be boosted by enough to make the stave output comparable to that of the PZT. Also other methods of stressing the PVDF could be employed that would direct more force to the film. One idea is to make a sort of balloon, like the air cushions already incorporated into many basketball sneakers, that was either made of PVDF or had PVDF laminated onto the outside. The force down from the foot would be converted fairly directly, via air pressure, to stress on the PVDF. The difficulty would be one of lamination: getting the electrodes out of the balloon, and sealing the edges without shorting the electrode material or over-heating the PVDF which de-poles at high temperature.

The unimorph's high coupling coefficient and prestressed design are already very efficient, however there are several options for getting more power from the PZT system, including stacking multiple unimorphs and designing its characteristics specifically for power generation rather than for a general sensor/actuator. Most of the improvements that can be made are in the area of integration into the sole rather than in power production.

One of the ways in which to improve power output is by designing efficient power supplies. Thus far we have experimented with only simple rectifier circuits and voltage doublers to collect power. There are certainly many improvements that could be made, including charge pumps and more efficient methods of voltage conversion. The piezoelectric devices can be connected to inductors to create a resonant LC-circuit, the frequency of which could be tuned to the natural frequencies excited during walking [4], bringing the voltage accross the PVDF into phase with the current, hence compensating the power factor. Most of these excitation frequencies are in the 2 to 50 Hz range, however, which would call for prohibitively large inductors (on the order of hundreds of Henries for 10Hz). This problem might be averted by storing up charge, with a diac or similar device, then dumping it all at once across the inductor creating higher harmonics that would necessitate smaller inductors - perhaps into the millihenry range.

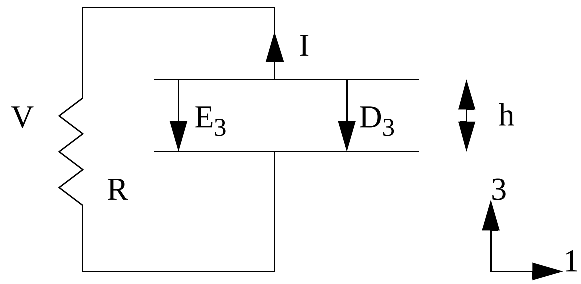
4.3 Conclusion

In order for these devices to be useful, several criterion must be met. First, they must generate enough power. For most of the applications discussed so far, the requisite 1-5 mW of power is already being produced by our prototype designs. As improvements are made and more power becomes available, new applications will be possible that will further extend the usefulness of parasitic power collection devices. Another requirement that parasitic power generation systems must meet is that they are innocuous to the user. Of the three systems we tested, the PVDF stave is the most innocuous, but the PZT unimorph has potential to be as innocuous if it is redesigned or if it is cleverly placed within the shoe sole.

One good way to evaluate the usefulness of parasitic power applications is to compare their cost and convenience to that of batteries. One study [10] predicts it would take 150 cm^3 of Lithium-thionyl chloride (highest energy density of all lithium-based cells) to match the power output from a piezoelectric transducer, assuming 10mW of power over two years. At this level of power output (which certainly seems feasible based on our research), piezoelectric systems become competitive with batteries, and since they are much smaller and lighter than this, provided one could be made that would last at least two years in a shoe, it would have many advantages over a battery.

Appendix A

Expected Power Calculation for PVDF[1]



S_1: Strain in 1 direction

D_3: Charge displaced/area in 3-direction

E_3: E-field in 3-direction

Figure A.1: Schematic of PVDF Stave

A = area
e_{31}= Yd_{31}
Y = Young's Modulus
d_{31}= piezo. coeffic.
R = external resistance

The fundamental equation is:

$$D_3 = \varepsilon\varepsilon_o E_3 + e_{31} S_1$$

if we integrate over the thickness:

$$\int_0^h D_3 = \varepsilon\varepsilon_o \int_0^h E_3 + e_{31} \int_0^h S_1$$

S_1 and D_3 are constant over the thickness and the integral of E_3 is just the voltage

$$D_3 h = \varepsilon\varepsilon_o V + e_{31} S_1 h \text{ and } D_3 = \varepsilon\varepsilon_o \frac{V}{h} + e_{31} S_1$$

If we assume D_3, V, S, all vary as e^{jwt} and that $\varepsilon\varepsilon_o \rightarrow \varepsilon$ then:

$$-I = j\omega DA = j\omega A\left[\varepsilon\frac{V}{h} + e_{31} S_1\right] \text{ but I = V/R so}$$

$$\frac{-V}{R} = j\omega A\varepsilon\frac{V}{h} + j\omega A e_{31} S_1 \quad \text{substitute for capacitance} \quad C = \frac{\varepsilon A}{h}$$

$$V = \frac{-e_{31} A S_1 j\omega}{\frac{1}{R} - j\varpi C} \ldots and \ldots |V| = \frac{e_{31} A S_1 \omega R}{\sqrt{1 + \omega^2 C^2 R^2}}$$

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

1. Based on calculations by M. Toda of AMP Sensors, Inc..

With the values from our stave we can use this formula to calculate peak power.

ω = (6.28)*2Hz

C = 330 nF

R = 200kOhm

A = .0065 m^2 *16 sheets = .104 m^2

e_{31} = .075

$$S_1 = \frac{h\Delta y}{\left(\frac{L}{2}\right)^2}$$

Where y indicates deflection of stave (7 mm), L is length (10 cm), and h is stave thickness (1 mm).

S_1 = .003

With these values P_{peak} = 3.68 mW, in close agreement with experimental results (~2mW).

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