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An Investigation into Energy Generation using Pseudo-Piezoelectric Foam and its Applications in Smart Shoes

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Abstract

An alternative source of energy generation through piezoelectric foam shoe soles is introduced in this paper. The mechanism of the energy generation is through the repeated deflections of the foam by a foot during a walking motion. A foam sample is introduced that works via polar molecules embedded in a commercial foam product, and a shoe sample with an existing sole and epoxied piezoelectric patch works via the patch deflection. Mechanics of the foam sample are explained such as various polar molecules and poling methods. Ultimately, the foam sample is found to be inferior due to the requirement of high voltage to align the polar molecules. The piezoelectric patch is found to be expensive, but an effective way to generate small amounts of energy, with the idea that the high number of steps taken in a day would result in effective energy generation.

Introduction

The piezoelectric effect refers to the ability of specific materials to generate electricity as a result of an applied mechanical stress. The generation of this electrical energy is the result of the simultaneous coupling of the electrical and mechanical states of the material. The presence of piezoelectricity in a poled polymer known as polyvinylidene fluoride (PVDF) was first discovered in 1969 by Dr. Heiji Kawai. PVDF is a semi-crystalline thermoplastic with high microscopic piezoelectricity characteristics. The evolution of such polymers was made possible by the presence of electrets in dielectric materials, which have a permanent macroscopic electric field on the surface, and great quasi-piezoelectric sensitivity (Li et al., 2020). The term electret was coined by Oliver Heaviside in 1892 and used to define the dielectric materials with quasi-permanent charges otherwise known as dipoles (Li et al., 2020). Heaviside's paper investigates a space-charge electret, which accumulates charges through a corona discharge, with the purpose of creating a high electric field by breaking down the microscopic voids in the material to induce polarities within (Kressmann et al., 1996). The corona charge is quasielectric, therefore the electric, which is more electrochemical, appears to be electromechanical, which fits the purpose of the proposed model (GerhardMulthaupt, 2002). The advantage of a quasi-electrical approach is that it can be reversed engineered to create a molecular level structure with piezoelectric properties. In addition, doping foams with small polar molecules to create a system polar moment in the skeletal structure of the foam, producing dipoles and longrange polar order in the foam.

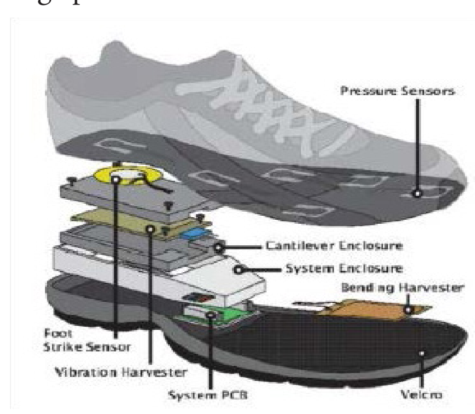

Figure 1: Basic composition of a smart shoe (Meier et al., 2014)

Figure 1 shows the composition of a smart shoe that can be used to generate electrical energy. This paper proposes the use of a piezoelectric polymer foam to generate electricity through daily and simple tasks, such as walking. The goal is to harness the polymer's ability to generate electricity and apply the electrical outcome from the mechanical stress exerted on the polymer as a form of energy that could be used instantaneously. The foam shoe sole system is meant to simplify current smart shoe compositions, reducing the number of parts required. Through experimentation, a foam sample was synthesized with doped chemicals capable of poling, as well as a shoe prototype using piezoelectric patches. The doped foam was not poled due to the high voltage requirement, but the shoe prototype can generate energy.

Objectives

The motivation in researching, synthesizing, and commercializing a pseudopiezoelectric polymer foam lies in its mechanical properties and ability to retain thousands of load cycles. Although none of the materials used in the synthesis of this modified foam are inherently piezoelectric, when combined properly, a piezoelectric effect is present. This is referred to as the artificial or pseudo piezoelectric effect (Moody et al., 2016).

Methods

Foam Prototype

The first prototype developed was a polymer foam that had poling chemicals within it to create an electric field in the foam. A commercial polyurethane foam, SMOOTH-ON Flex Foam-iT! VIII, Pillow Soft, was used to synthesize the samples. The foam consisted of two precursors, part A and B, where the ideal mixing ratio between the two was a 1:2 volumetric ratio. A control sample was first made to test the softness of the final foam. If the foam was too hard, then it would not be ideal to be a shoe sole. Figure 2 shows the cured control sample, which was soft and pliable. This meant that it would fit as a shoe sole, even with poling chemicals embedded within it.

Figure 2: Control Sample of Foam

To synthesize the piezoelectric foam, a few polar dopant molecules had to be researched. The process entailed looking at molecular weight, polarity, and ease of access. This would ensure that the chemicals do not greatly increase the density of the foam prototypes, have high polarity to easily generate electric field responses, and are easy to access and not dangerous to use. Chemicals chosen included 2- Butanol, Ethylenediaminetetraacetic acid (EDTA), and Triethylamine (Bahulekar et al., 2020). The various chemicals were then mixed with the precursors to synthesize the foam. An example cure consisted of 0.575 mL of 2-Butanol with 8 mL of part A and 16 mL of part B foam, wherein the 2-Butanol is premixed into the Part B solution before the two precursors are mixed. The mixed precursors are then quickly poured into a beaker and left to cure for two hours. Figure 3 shows example cures for the poling chemicals. Butanol and EDTA foams had the most consistent cures, meaning the foam did not collapse during the cure.

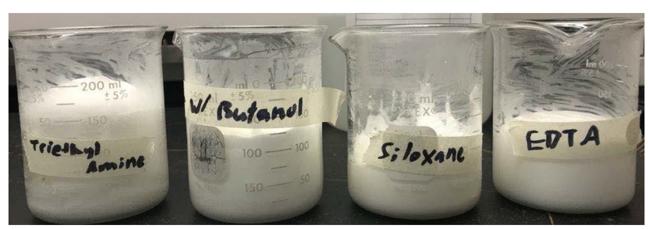

Figure 3: Foam Synthesis with various poling chemicals (Bahulekar et al., 2020)

While the curing process ensured that there were chemicals within the foam, the molecules were not very aligned. The random alignment of particles would not generate a strong electric field, so a process known as poling would need to be performed. This would ensure that the polarizing molecules are aligned to generate a strong electric field. The two poling methods that were best for foam were electrode poling and corona charge poling (Wei, 2017). In electrode poling, the sample is sandwiched between two polished conducting plates under a vacuum or immersed in an insulating fluid. Then, a Direct Current (DC) electric field of the order of 5-100 MV/m is applied across the two metal plates (Wei, 2017). An experiment by Moody et al. used plates with 5 mm separation with a 2 kV voltage to pole the foam samples using the electrode poling method. Corona charge poling involves depositing the electrode plate on one side of the foam over a hot plate. The top side of the foam uses a conductive needle tip subjected to a voltage on the order of 8-20 kV touching the sample. This is advantageous to the electrode poling method as corona poling can take seconds. Figure 4 shows the experimental setup for both poling methods. While corona charge poling requires more setup, it is faster to pole the foam than using the electrode poling method. While poling could be done after the cure, it is ideal to pole the foam as it is curing. This is because once the foam is fully cured, it is difficult for the poling molecules to freely move around the geometry. During curing, the foam is still rising and settling, so the movement of the poling molecules is easier. For example, the experiment done by Moody et al. poled the foam samples during the curing process (Moody et al., 2016). Another concept to consider in the foam synthesis is decomposition. Due to the foam being a soft and pliable object, the stresses from walking around would potentially cause the molecules to lose their alignment over time. Decomposition has been investigated for piezoelectric sensors due to high stress environment with experiments by Pillatsch et al., 2014.

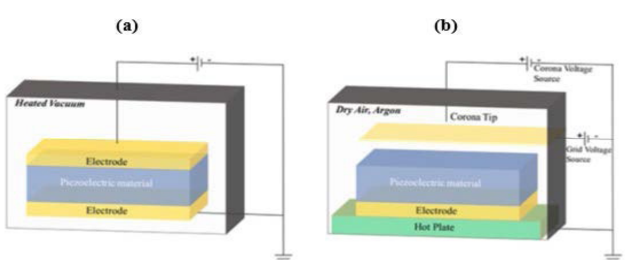

Figure 4: Setup for (a) Electrode and (b) Corona Charge Poling (Wei, 2017)

Due to the difficulty in setting up the two environments for poling and the potential dangers of using high voltages, the chemical prototypes were not poled. Instead, piezoelectric patches were used. The patch would replace the poling chemicals in foam synthesis. While costly, this would improve the design by removing the potential for decomposition due to weak foam structure and a known piezoelectric sensor that consistently outputs voltage with good reliability. As an example, the piezoelectric foam synthesized by Moody et al. reported a piezoelectric d33 constant of 244±30 pC*N^{-1} , while the piezoelectric patches used in this experiment report a d33 piezoelectric constant of 400 pC*N^{-1} in a low field and 460 pC*N^{-1} in a high field (Smart Material). In this project, the Z-direction is the vertical direction, which would be the most active during a walking motion. The piezoelectric patches were sourced from the company *Smart Material*, with the patches used being MFC M5628-P1 patches. This patch was selected due to the working area being a good size to fit the bottom of a shoe sole and being a P1 patch, meaning it operates with the d_{33} effect, which is ideal for the purpose of the current research. A preliminary experiment was run where the foam was synthesized without any chemicals, and the patch was placed in the foam as it was cured in a vertical manner in a small container.

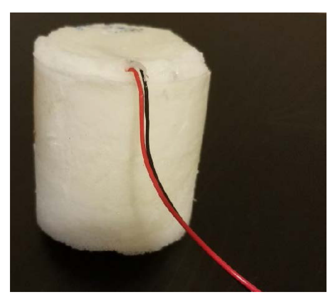

Figure 5: Foam Sample with Embedded Piezoelectric Patch

A quick test with an oscilloscope showed that the piezoelectric patch response was like the patch embedded in the foam and the patch sitting outside the foam. This shows the benefit of using the selected foam precursors, as the soft and pliable foam does not block the response of the patch. Therefore, the foam can be synthesized with the patch inside and used as a shoe sole without losing voltage response.

Shoe Prototype

SANYES USB Light Up Shoes were used as a way to test energy generation. These shoes featured Light Emitting Diodes (LEDs) on the bottom and a battery that could be charged via a MicroUSB port. Using the charging port, the patch can be attached to the charging port to continuously charge the battery. However, the patch cannot be directly attached to the charger; there needs to be a balancing circuit in between the patch and the port. This is because the patch does not output DC voltage, so a balancing circuit that takes the variable input from the patch and converts it into a stable DC voltage needs to be used. For this, the patch and the circuit were sourced from *Smart Material*. The patch used is the same M5628-P1 model shown in Figure 6, and the circuit is the CL-50, shown in Figure 7.

Figure 6: M5628-P1 Piezoelectric Patch

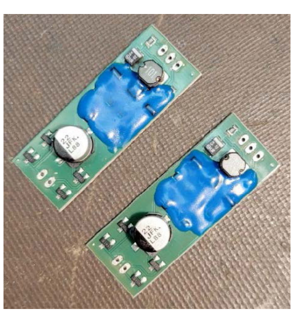

Figure 7: Two CL-50 Balancing Circuits

To setup the circuit, a MicroUSB cable is cut to expose the positive and negative wires. The wires are then soldered to the output ports on the CL-50 circuit. Then, positive and negative wires are soldered from the outputs of the piezoelectric patch to the input of the CL-50. The last step is to adhere the patch to the shoe sole. In the case of the shoe prototype, the shoe sole was not made from the foam precursors; rather the existing shoe sole was used. To adhere the patch, West System 105/205 epoxy resin and hardener is used as it cures within three hours. The finalized circuit is shown in Figure 8. The patch was placed approximately where the most deflection occurs in a shoe sole, based on a quick experiment of walking around and seeing what parts of a sole bend more than others. Figure 9 shows the shoe sole inside of the shoe with the balancing board hidden in the structure of the shoe. The wires are also pushed to the side of the shoe, in order to maintain the shoe's comfort.

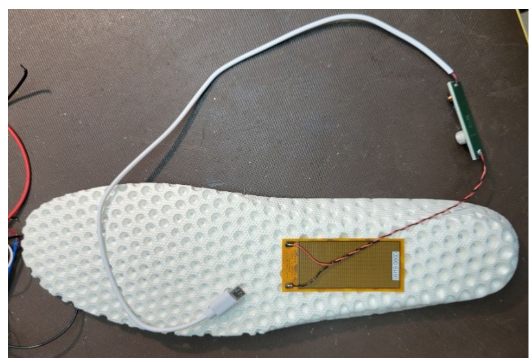

Figure 8: Finalized Piezoelectric Patch Circuit

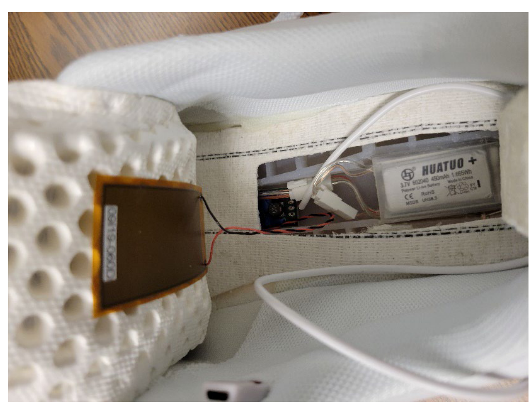

Figure 9: Shoe Prototype with Circuit Placed Inside

With the circuit in place and the charging cable plugged in, walking around will cause the shoe sole to deform slightly, which will deform the piezoelectric patch. The resulting deformation due to compression or deflection will generate a variable voltage, which will go to the balancing circuit. Once the capacitor in the balancing circuit is filled up, it will quickly discharge into the battery circuit, effectively charging the battery. With the CL-50 module, the output would be 0.5 to 2 mJ (Smart Material). This will slowly charge the 450 mAh battery in the shoe. Further experimentation will need to be done that finds the exact charge rate and how many steps would charge the shoe overall. An example circuit found by Garimella et al. highlights a 2 mW piezoelectric circuit that charges a 40 mAh battery in one hour. The paper claims that a shoe can achieve 8.4 W of available power (Garimella et al., 2015). With further research into the efficiency of the shoe prototype, this claim can be verified.

Conclusion

Piezoelectric foam shoe soles are introduced in this paper as a way to use walking as an alternative energy generation source. A foam prototype was initially developed using polar chemicals laid inside of a commercially bought foam to induce an electric current through deformation. Various chemicals were tested, but EDTA and Butanol resulted in the most stable polymers. Poling methods were also introduced as a way to align the polar molecules. However, difficulties were found in the poling methods, such as requiring a high voltage, or requiring a complex setup with electrode plates and corona probes. Therefore, an alternative foam prototype was introduced using commercially bought piezoelectric patches. As the patches were already set up to generate energy out of the box, experiments were performed to show that inlaying the patches inside foam does not degrade the patch's performance, which would allow the patch/foam combination to be used a shoe sole.

A secondary prototype was also presented using a light-up shoe. This prototype uses the existing shoe sole, epoxying the piezoelectric patch on the bottom of the sole and connecting it to a balancing circuit. This shoe prototype would generate electricity with every step, and the balancing circuit would use the patch generated energy to charge the battery. These patch/balancing circuits are found in literature, and can generate small amounts of energy from deformation, and are able to charge small scale batteries such as the ones found inside the light-up shoes.

With further advancements in the foam samples and poling methods, the foam prototype can be used in shoe sole applications, while current technology would allow for the patch/sole/balancing circuit to be used for initial smart shoe prototypes.

Future Work

Future revisions to this project would include experimentation on the poling of the molecular-doped foam samples. If this can be done successfully, the piezoelectric patches can be avoided as the sole would act as the patch itself. A deeper look into the decomposition of the foam would need to be done with this though, as the pliability of the foam could potentially cause issues over time with the foam degrading the alignment of the polarized molecules. Essentially, further research in the foam prototype can analyze whether it is feasible to create compared to piezoelectric patches, as current research requires large voltages and has possible performance degradation due to the decomposition. If advancements can be made that reduce the amount of voltage required to align the doping molecules, or better foams can be synthesized that maintain pliability but reduce the chance of decomposition, the foam sole would be preferred to the piezoelectric patch due to cheaper cost of manufacturing and a simpler circuit.

The shoe sample can also be revised. Multiple piezoelectric patches can be used instead of one to increase the working area of the energy generation, or even be combined in a bimorph (two or more layers) configuration. The placement of the patch could also be optimized to find the ideal location for maximum energy generation. Advancements in the efficiency of the circuit can be made as well, such as with a custom balancing board that can output a higher wattage. Calculations can be found as to how many steps it would take to charge the battery. Lastly, an investigation into direct-ink-writing could be done as well. This is a process wherein the piezoelectric patches are 3D printed, which would save on cost (Li et al., 2015).

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