Design and Characterisation of A Wearable 33-Mode PVDF Energy Harvester

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Abstract. The conversion of biomechanical energy from human movement into useful electrical energy to power wearable electronics has become a topic of extensive study. This paper studies a model suitable to design and characterize 33-mode energy harvester based on piezoelectric polymers for wearable applications. The aim is to describe adequately the 33-mode energy harvester behavior, with a reasonable number of parameters and based on well-known physical equations. The connection mode is been considered and the corresponding open circuit total voltages are derived, which are verified by the experiments. Moreover, the experiments prove that all the three harvesters can be used to scavenging energy.

1. Introduction

Wearable electronics are becoming smaller and increasingly widely used, resulting in an increasing research on the development of harvesting energy from human motion to provide renewable and clean energy[1-3]. According to previous research, it is identified as a feasible way to harvest energy from human foot which can produce great mechanical energy.

There are many energy harvesters mounted in shoes based on different mechanisms, such as electromagnetic, electrostatic, thermoelectric, nano-triboelectric, piezoelectric harvesters. Specifically, piezoelectric energy harvester can convert mechanical energy into electric power directly, thus it owns a simpler structure and easier fabrication [1, 4]. Hence, it can be especially suitable for wearable sensors.

Kymissis, et al. [5]explored an insole which made of eight-layer stacks of PVDF sheets with a flexible plastic substrate, to harness the energy dissipated in bending of the sole and a PZT unimorph to tap the energy from heel strikes. Zhao et al.[1, 6] proposed a sandwich structure PVDF energy harvester which is readily compatible with a shoe and works in the 31-mode and studied a series of models. Mateu et al.[7] did a study for different piezoelectric beam structures made of PVDF and found that triangular cantilever generates more energy than the rectangular shape.

As discussed above, 31-mode energy harvester for wearable applications has been studied widely. The studies are rarely conducted in 33-mode harvester for it’s difficult to implement in a real structure, but with the reduction of power consumption of wearable applications, the 33-mode can meet its needs. In this research, in order to study the 33-mode harvester for wearable applications, the insole is chosen as a good place for the 33-mode harvester to implant. A sandwich structure thin flat harvester is designed for it can be fitted without any sacrifice of comfort or radical alterations in design, which is readily compatible with a shoe. To obtain higher power, parallel and series configurations of the piezoelectric film are taken into consider, so two segmented electrode harvesters consisted of two equal area PVDF
units which are connected in series or parallel with its neighbor are designed. A series of experiments are performed to characterize the harvester prototypes and study the impact of the connection way on the energy harvesting performance.

2. Description of the Harvester

2.1. Piezoelectricity

The piezoelectric properties of a material can be described by the four quantities of concern in piezoelectricity: stress (T), strain (S), electric field (E), and electric displacement (D). The constitutive relationships between the mechanical and electrical components of piezoelectricity can be described using (1) and (2) [8]:

\[ S_i = s_{ij} T_j + d_{ni} E_n \]  
\[ D_m = d_{mj} T_j + \varepsilon_{mn} E_n \]  

Where i, j = 1,…,6; m,n = 1,2,3; \( s_{ij} \) is the elastic compliance under constant electric field, \( d \) is the piezoelectric constant, \( \varepsilon_{mn} \) is the permittivity under constant stress.

By considering an electric field equal to 0 and due to the fact that the PVDF films are only metalized in the plane perpendicular to direction 3, the charge developed on the surface of the PVDF, Q can be expressed as the integral of electrical displacement over the effective surface area of the electrodes on the material[8]:

\[ Q = \int_A D_3 \ dA = d_{3ji} \int_A S_i \ dA \]  

Where \( c_{ij} \) represents stiffness matrix component and A is the effective area of the electrode.

For the harvester designed in this paper, it works in 33-mode, so,

\[ D_3 = d_{33} T_3 \]  

Then,

\[ U = \frac{Q}{C} = \frac{d_{33} F_3}{C} \]  

Where \( F_3 \) is the force applied in the 3 direction, \( U \) is the output voltage, \( C \) is the capacitance of PVDF.

2.2. Connection Mode

Figure 1 shows a qualitative electrical circuit of the harvester, valid at frequencies below the first mechanical resonance. The unsegmented electrode (UE) harvester is represented as a current source in parallel with a capacitance (Norton equivalent) or a voltage source in series with a capacitance (Thevenin equivalent).[9] We resort to the voltage source to make a schematic of the segmented electrode in series (SES) harvester and the segmented electrode in parallel (SEP) harvester.
It can be seen that, for series connection mode,

\[ Q_S = \frac{qU}{2}, \quad U_S = 2U_U, \quad C_S = \frac{C_U}{4} \]  \hspace{1cm} (6)

For parallel connection mode,

\[ Q_P = Q_U, \quad U_P = U_U, \quad C_P = C_U \]  \hspace{1cm} (7)

Where \( Q_S, Q_P, Q_U \) denote the total charge of SES harvester, SEP harvester and UE harvester, respectively. \( U_S, U_P, U_U \) represent the open-circuit total voltage of SES harvester, SEP harvester and UE harvester, respectively. \( C_S, C_P, C_U \) are the total capacitance of SES harvester, SEP harvester and UE harvester, respectively. Obviously, parallel connection mode can generate more charges, proving that connecting the PVDF units in parallel is an effective approach to improving the harvesting performance [6].

2.3. Harvester design and fabrication

A simply sketch of PVDF energy harvesters studied in this paper is shown in figure 2. The active area of the segmented electrode harvester is the same with that of the unsegmented electrode harvester. Such a design does not change the active area or the mechanical response of the two harvesters. As an input force, a distributed pressure load is applied on the top surface and the PVDF experiences stress in the z (3) direction. Due to the electrodes are applied in the z (3) direction, the harvester is active in 33-mode[8].

The main structure of the harvester is a sandwich structure, where a layer PVDF thin film metalized on both sides is sandwiched by two insulation layers, then sandwiched by two stainless steel layers, each with a thickness of 200\( \mu \)m, a length of 20mm, a width of 20 mm. The dimensions of length, width, and thickness of the unsegmented electrode PVDF are 30, 20, and 0.03 mm, respectively. The segmented
electrode harvester is two equal area PVDF units separated by an insulation layer. The choose of the stainless steel layer is to render the 31 mode an inefficient element in the experiment. The other geometric and material parameters of PVDF are listed in Table 1.

Table 1. Material properties of the PVDF.

| Parameters                  | Value  |
|-----------------------------|--------|
| $d_{33}$ (PC/N)             | 21     |
| $d_{31}$ (PC/N)             | 17     |
| Coupling coefficient $k_{33}$ (%) | 10~14  |
| Density (kg/m$^3$)          | 1.78×10$^3$ |
| Relative permittivity       | 9.5±1.0 |
| Elastic modulus (MPa)       | 2500   |

3. Experimental Setups and Methods
To test the voltage of the three prototypes produced by the impulse force, the experiment were performed by a simple force excitation generator which can provide an impulse force at a frequency of 1Hz, as shown in Figure 3. During testing, the harvester was fixed to the buffer board and the impulse force was set to 500N. The capacitances of the unsegmented PVDF film and the segmented PVDF film are 2.2 nF and 1.12 nF respectively. The output voltage of the three prototypes was measured by an oscilloscope and processed on a personal computer.

Figure 3. Scheme of the simple force excitation generator. (a) structure; (b) schematic.

4. Results and Discussion
Figure 4 compares the experimental results of the peak output voltage of the three harvesters. The peak output voltage of the UE harvester, SEP harvester and SES harvester are 1.75V, 1.59V and 3.22V respectively. As expected, the output voltage of SES harvester is 2 times as large as UE harvester and the output voltage of SEP harvester is about the same with the UE harvester. The trend of the experimental results are consist with the theoretical investigation derived from (6) and (7).
Figure 4. Comparison of the experimental voltage of the three harvesters.

The coefficient of variation (CV) of the output voltage reflects the structural stability of the harvester. The bigger of the CV, the worse of the fabrication of the harvester, which means it needing a better fabrication process. Figure 5 shows the CV of the three harvesters, it can be seen that the unsegmented electrode harvester work well under the same fabrication process among these three harvesters.

Figure 5. The CV of the peak output voltage of the three prototypes.

5. Conclusion
This paper introduces three 33-mode energy harvesters, the qualitative electrical circuit of which are represented and the relationship of the open-circuit total voltage among the three harvesters are derived. We perform the experiment under 500N impulse force at 1Hz and find that all the harvesters can be used to scavenging energy and can serve as a wearable power supply for low power wearable sensors. The PVDF energy harvester units wired in parallel can generate more charges and the PVDF energy harvester units wired in series can improve the voltage output.
Acknowledgments
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