Predictions of Energy Content in Stretched Ribbons of Segmented Polymer Piezoelectrics

K. Prakash, S. Ramgopal1*, Sanjiv Sambandan1*

1. Department of Instrumentation and Applied Physics, Indian Institute of Science, Bangalore 560012, India

*Email address of corresponding author: sanjiv@iap.iisc.ernet.in

Abstract
Polymer piezoelectrics such as poly vinylidene fluoride (PVDF) offer advantages such as low temperature fabrication into large area flexible sheets. A primary advantage of this is that large sheets of PVDF can be stretched into membranes to build sensors and energy harvesters that have low resonant frequencies. A key result reported recently is that when polymer piezoelectrics membranes are provided non-uniform stress, the use of segmented electrodes helps improve energy content by reducing surface currents. Using this key result in conjunction with experiments performed on stretched ribbons of PVDF, we predict energy densities obtained via electrode segmentation in this paper.

Keywords: energy harvesting, polymer electronics, poly-vinyldene fluoride

1. Introduction
Polymer piezoelectrics such as poly vinylidene fluoride (PVDF) are easily fabricated into large sheets at low temperatures (Kawai, 1965). Stretching these large sheets of PVDF into large membranes allows for the design of sensors and energy harvesters that have a low resonant frequency (Erika, 2005; Sodano, 2004). Freely available source in nature is mechanical vibration; using these natural vibrations energy harvesting systems are proposed. Many applications have been developed and are proposed to use piezo-polymers as sensors in the research (Ottman, 2002; Meninger, 2001; Kaya, 2007). Considering the low weight of these materials compared to electromagnetic based systems (also used for low frequency), there are distinct advantages in using PVDF based piezoelectrics for wide area sensor networks.

The study of stretched membranes of polymer piezoelectrics for energy harvesting has been considered recently and two aspects of the study are of interest in this paper (Kodali, 2013; Kodali, 2014). First, when polymer piezoelectric PVDF was stretched into ribbons of various lengths and subject to periodic vibration, it was found that the open circuit voltage of the piezoelectric reduced with length. When the frequency of the incoming vibration equaled the resonant frequency of the ribbon, the amplitude of oscillations of the ribbon maximized and the energy output maximized. With such a setup it was shown that a power of 2 mW/gm could be delivered at resonance. This power was shown to be sufficient to power a CMOS ring oscillator at 10 kHz (Kodali, 2013). Second, it was shown the energy content and power delivery of piezoelectric ribbons improved when the contact electrodes were segmented. This was due to the reduction in the loss of energy due to surface currents (Kodali, 2014).

In this paper we use the above two pieces of information to make predictions on the energy content and power delivery in 1D-stretched ribbons with segmented electrodes, subject to periodic vibrations at resonant frequency.

2. Method
2.1 Experimental Setup
Experiments were performed on ribbon like membrane of PVDF, 9 cm long and 3 mm wide, stretched across two supports as shown in Fig. 1(a). Studies were performed using periodic pulse inputs that were provided with a stepper motor and a computer controlled audio speaker coupled to the shaft. Fig. 1(b)
illustrates the peak-peak voltage across the 9 cm ribbon as a function of frequency. The peak-peak voltage maximizes at around 700 Hz, which was resonance. The typical time domain response of the piezoelectric for 9 cm and 17 cm ribbon for a pulse like input is also shown figure 1(c), 1(d). In these experiments the typical amplitude of the vibrating ribbon was about 200μm.

Figure 1: Experimental setup, time domain response for the 17cm ribbon, frequency domain response for the 9cm ribbon.

Under loading the typical current voltage characteristics for the 9cm ribbon under resonance was found to be typically as shown in Fig. 2. The peak power deliver is about 80μW which translates to about 2 mW/gm of power density.

Figure 2: Current Voltage characteristics of the 9cm ribbon under loading and at resonance.

2.2 Theoretical Basis

Using this setup, the open circuit voltage for various lengths are obtained when the ribbon is provided periodic vibration at resonance. The theoretical variation of the peak open circuit voltage at is expected to be
Here $d_{31}$ is the piezoelectric coefficient in the 31 direction, $Y$ the modulus of elasticity, $l$ the length, $a_0$ the amplitude of vibration, $h$ the thickness of the ribbon, and $\varepsilon$ the permittivity of PVDF. However in reality the actual open circuit voltage may vary as

$$V_{oc} \sim \frac{d_{31} Y h a_0}{4 \varepsilon l} \gamma$$

(2)

Where $a_0$ is an exponent coefficient. This implies the energy content of the ribbon defined as the energy stored in the ribbon under open circuit condition varies as

$$E = \frac{CV_{oc}^2}{2} \sim \frac{d_{31}^2 Y^2 h l w h a_0}{32 \varepsilon ^2 l} \gamma$$

(3)

Hence the energy density varies as

$$E_{\gamma} \sim \frac{d_{31}^2 Y^2 h l w h a_0}{32 \varepsilon ^2 l} \gamma$$

(4)

Where $\rho$ is the mass density of PVDF.

From experiments on segmented piezoelectric ribbons, it was seen that the energy content of the ribbon varied as $1 + A(n-1)/n$ where $n$ is the number of segments, and ‘A’ a coefficient defining the properties of the piezoelectric (Kodali, 2014). We approximately implement this information with the above relation for energy density by stating that the energy density of the piezoelectric for $n$ segmented electrodes is

$$E_{\gamma}(n) \sim \frac{d_{31}^2 Y^2 h l w h a_0}{32 \varepsilon ^2 l} \gamma + \frac{n}{l} \frac{1}{n}$$

(5)

When the piezoelectric ribbon is subject to non uniform stress, the charge stored in each region of the piezoelectric is different. This charge flows across a continuous electrode till the entire electrode surface reaches equipotential. This movement of charge (surface current) results in a loss in energy content due to Joule heating. As the electrode is segmented, the surface currents are reduced and the energy content improves.

We now perform experiments to determine $\gamma$ so as to derive a complete relation for energy density and number of segments.

3. Results

Extracting the open circuit voltage for different lengths at their respective resonant frequencies, it was found that the open circuit voltage decreases as $l^{0.83}$ as described in Figure 3, with $l$ being the length of the ribbon.
The energy content improvement for segmented electrodes is shown in Fig. 4. The saturative behavior in energy content fits the definition of the dependence on \( n \) as shown in Eq. 5 reasonably well.

4. Discussions

Based on the results observed in Fig. 3 and Fig. 4, and using the value of \( \rho = 0.83 \) in Eq. 5 we obtain the complete model for predicted energy content of the piezoelectric ribbon under tension and non uniform stress with \( n \) electrode segments as,

\[
E_c(n) \sim \frac{d_{31}^2 Y^2 \varepsilon_0 a_0^{1.64}}{32 \varepsilon_0 l} - \left[ \frac{n \varepsilon_0 1}{n} \right]^{1.8} 
\]  \hspace{1cm} (6)

For poled PVDF \( d_{31} \sim 10 \text{ pC/N}, \ Y \sim 2 \text{ GPa}, \ \varepsilon_0 \sim 8.854 \times 10^{-12} \text{ F/m} \) and \( \rho \sim 1780 \text{ kg/m}^3 \). Using these parameters in Eq. 6, Fig. 5 shows the predicted variation in energy content in with \( a_0/l \) and \( n \).
Conclusion
The study of segmented PVDF piezo effect on the efficiency of energy harvesting was carried out. The experimental setup to arrange energy scavengers of different lengths with different segments were studied to realize the energy efficiency. Responses of desired segments of selected strips were simulated by means of the pulsed tapping with stepper motor and its driving unit. Thus it concludes that energy content is improved and maximized with optimum number of segments.

Acknowledgements
The authors acknowledge the Department of Science and Technology for the funding received Grant No. DST/TSG/PT/2012/26.

References
Erika, M. (2005). Energy harvesting from vibration using a piezoelectric membrane, J. Physique, 128, 187-193.

Kawai, H. (1965). The piezoelectricity of Poly (vinylidene Flouride). Jpn. J. of Appl. Phys., 8, 975-976.

Ottman, G. K. (2002). Adaptive piezoelectric energy harvesting circuit for wireless remote power supply. Power Electronics, IEEE Transactions on, 17(5), 669-676.

Meninger, S. (2001). Vibration-to-electric energy conversion. Very Large Scale Integration (VLSI) Systems, IEEE Transactions on, 9(1), 64-76.

Kaya, T. (2007, September). A new batteryless active RFID system: smart RFID. In RFID Eurasia, 2007 1st Annual (pp. 1-4). IEEE.

Kodali, P. (2013). Harvesting energy at resonance from standing waves on polymer piezoelectric ribbon-like membrane. Electronic Letters, 49 (20), 1294-1296.

Kodali, P. (2014). Segmented Electrodes for Piezoelectric Energy Harvesters. IEEE Electron Device Letters, 35 (4), 485,487.

Sodano, H. A. (2004). A review of power harvesting from vibration using piezoelectric materials. Shock and Vibration Digest 36, 197-205.