Piezoelectric PVDF-TrFE/PET Energy Harvesters for Structural Health Monitoring (SHM) Applications

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ABSTRACT
This study presents a piezoelectric energy harvester made of poly(vinylidene fluoride-trifluoroethylene)/polyethylene terephthalate for use in structural health monitoring applications. The piezoelectric energy harvester was made of a layer of polyvinylidene fluoride-trifluoroethylene (PVDF/TrFE). In addition, PET sheets, double-sided micron-thick tapes, and PVDF-TrFE sheets were utilized in the fabrication of the device. The proposed device was characterized by measuring its output voltage and current. The output power of the harvester was sufficient to operate a MEMS pressure sensor under wind pressure, with a maximum current of 291.34 mA and a maximum voltage of 937.01 mV. The power value obtained was 272.99 μW.

1. Introduction
The field of microelectronics has made tremendous advancements, resulting in the emergence of various electronic devices that have become commonplace in our daily lives. The continuous advancement of energy harvesting technologies has led to a reduction in the cost, size, weight, and power requirements of these devices. As a result, the creation of distributed environments has become feasible. The current energy storage capacity remains the primary factor in determining the size, mass, and cost of modern electronic devices. Batteries often raise concerns about their impact on the environment when disposed of, as well as the practicality of replacing them in various systems.

Due to this issue, there appears to be an increase in interest in the advancement of energy harvesting technologies. These technologies are expected to address the problems caused by the use of traditional energy sources in electronic devices [1]. Sensors, actuators, transmitters, receivers, and processors are all highly integrated intelligent electronic devices that have paved the way for various new life-improving applications. The development of microelectromechanical systems (MEMS) technology has led to significant improvements in the functionality of electronics, as well as reductions in size, cost, and power consumption [2]. Distributed systems have become possible due to the ongoing trend toward smaller and less expensive equipment, as well as advancements in wireless communication [3]. These networks have the potential to be used for various purposes.
Examples of potential applications include detecting hazardous chemical compounds in high-traffic areas and measuring tire acceleration and pressure [4, 5]. Various industry professionals believe that low-wattage embedded electrical equipment will soon become an essential component of our daily lives. These devices will perform a wide range of activities, from automating factories to meeting our entertainment needs [6]. The effectiveness of these emerging technologies depends on the availability of reliable sources of energy. Cost, size, and duration are significant concerns for energy sources with fixed capacities, such as batteries. This research is focused on energy harvesting, which is an alternative approach to addressing these challenges.

The most recent iteration of structural health monitoring (SHM) systems incorporates low-power sensors and wireless communication components powered by energy harvesters’ outputs [7]. Energy can be harvested from the surrounding environment to fuel self-sufficient sensor systems [8]. Integrating Structural Health Monitoring (SHM) technology into wind energy systems is a lucrative application that showcases the effectiveness of SHM technology in general [9]. The components that require inspection are large and challenging to examine. For example, during operation, wind turbines are subjected to intense and complex wind loads. Therefore, evaluating their dynamic responses to wind loads is desirable due to the possibility of fatigue and the need to better understand the turbine’s response [10]. In addition to assessing the fundamental condition, monitoring can also contribute to more efficient turbine operation. Wind energy harvesting is subject to a limitation known as the “Betz Limit.” In practice, the maximum deliverable power is multiplied by a factor of 0.593 (16/27) to account for this limitation. SHM can be performed using Vibration-activated transducers because vibration is a ubiquitous phenomenon in nature. In recent years, there has been significant interest in vibration energy harvesters that use piezoelectric transduction mechanisms. This is because they have a higher power density, are easy to apply, and can be scaled up easily [11]. In situations where there is no fixed vibration, piezoelectric harvesters are powered by wind-induced vibrations. This thesis describes a piezoelectric energy harvester device designed for Structural Health Monitoring (SHM) applications. The device is capable of generating power from vibrational wind energy, which can be used to power electronic devices.

2. Modeling of the Harvester Device

In the electrical domain, there is a capacitor; in the mechanical domain, there are spring and mass elements. Ideal transformer elements are used to indicate domain coupling. The damping in the mechanical domain caused by anchor loss and other factors is insignificant. Therefore, it is not included in the model. Table 1 contains the parameters of the model. The capacitance, $C$, is described in the electrical domain as a conventional parallel plate capacitor, with its capacitance defined by equation [12]:

$$C = \frac{\varepsilon \pi r_{pm}^2}{t_{pvdf}}$$  \hspace{1cm} (1)

where $\varepsilon$ the proportion of relative permittivity of PVDF to the permittivity of a vacuum, $t_{pvdf}$ represents the PVDF thickness, and $r_{pm}$ represents the radius of the top electrode.
With a normal plate deflection shape function of $\varphi(x)$ [13]:

$$\varphi(x_0) = \left(1 - x_0^2\right)^2$$  \hspace{1cm} (2)

where $x_0$ is the radial coordinate in its normalized form. The axisymmetric plate deflection is $w(x_0) = w_0\varphi(x)$, where $w_0$ is the static plate deflection at the clamped plate’s center. One can calculate $I_m$, the piezoelectric coupling integral, and $I_e$, strain energy integral which are specified as [12]:

$$I_m = \frac{1}{1-v} \int_0^{\pi/2} \left( x_0 \frac{d^2 \varphi(x_0)}{dx_0^2} + \frac{d\varphi(x_0)}{dx_0} \right) dx_0$$  \hspace{1cm} (3)

$$I_e = \int_0^{1} \left( x_0 \frac{d^2 \varphi(x_0)}{dx_0^2} \right)^2 + 2v \left( \frac{d\varphi(x_0)}{dx_0} \right) \left( \frac{d^2 \varphi(x_0)}{dx_0^2} \right) + \left( \frac{d\varphi(x_0)}{dx_0} \right) \right) dx_0$$  \hspace{1cm} (4)

where $v$ is the composite plate’s effective Poisson’s ratio, and $M$ is the piezoelectric bending moment provided by [14]:

$$M = -e_{31,f}V_{in}z$$  \hspace{1cm} (5)

The transverse piezoelectric coefficient is $e_{31,f}$. The applied voltage is $V_{in}$. The distance, denoted as $z$, between the mid-plane of the active PVDF-TrFE layer and the neutral plane. It is worth noting that the piezoelectric coupling integral $I_m$ is calculated exclusively within the electrode region, but the strain energy integral $I_e$ is calculated across the entire radius. The location of the neutral plane $z$ in a composite plate structure is defined by:

$$z = \frac{\sum_{k=1}^{3} \frac{t_kE_k}{1-\nu_k^2}}{\sum_{k=1}^{3} \frac{t_kE_k}{1-\nu_k^2}}$$  \hspace{1cm} (6)

**Table 1. Values for the equivalent circuit of PEH**

| Symbol | Description | Units |
|--------|-------------|-------|
| $C$    | Electrical capacitance | F     |
| $r_{pm}$ | Radius of the top electrode | m     |
| $t_{pvdf}$ | PVDF-TrFE thickness | m     |
| $\varphi(x_0)$ | Normal plate deflection shape function |       |
| $I_m$ | Piezoelectric coupling integral |       |
| $I_e$ | Strain energy integral |       |
| $M$ | Piezoelectric bending moment | $CV^2/kg$ |
| $e_{31,f}$ | Transverse piezoelectric coefficient | C/N   |
| $V_{in}$ | Applied voltage | V     |
| $z$ | Neutral plane | m     |
| $t_x, t_z, E_k$ | Layer thickness, the center axis of each layer, Young’s modulus | m, m, Pa |
| $\nu_k$ | Poisson’s ratio |       |
| $D, h_k$ | Flexural rigidity, the distance to the top of each layer | $Pam^4, m$ |
| $\mu_{eff}$ | Effective mass per unit |       |
| $\rho_k$ | Area, density | $m^2, kg/m^3$ |
| $k_m$ | Stiffness | $kg/m^2$ |
| $\eta$ | Electromechanical coupling | C/N   |
| $f_n$ | Resonance frequency | Hz    |
| $\lambda_{01}$ | Eigenvalue for the first mode vibration |       |
| $m_m$ | Total mass | kg    |
| $m_d$ | Modal mass | kg    |
Counting from the bottom, the subscripts indicate the layers of thin plates. The Young’s modulus is $E_k$, the Poisson’s ratio is $v_k$, and the center axis of each layer is $z_k$. Similarly, the flexural rigidity, $D$ [15], and effective mass per unit area, $\mu_{\text{eff}}$:

$$D = \sum_{k=1}^{3} \frac{1}{3} \frac{(h_k - z)^3 - (h_{k-1} - z)^3}{1 - v_k^2} \frac{1}{k}$$

$$\mu_{\text{eff}} = \left( \frac{1}{D} \right) \sum_{k=1}^{3} \rho_k t_k$$

(7) (8)

$\rho_k$ is the density and $h_k$ represents the height of each layer. $z$ is the distance to the top of each layer. One gets when solving Eq. 11 for the mechanical compliance $1/k_m$:

$$\frac{1}{k_m} = \frac{r^2}{2\pi DL}$$

(9)

The following equation for the electromechanical coupling ratio is found by solving:

$$\eta = 2\pi I_m e_{31,t} z$$

(10)

The circular plate formula is utilized [13] to get the natural frequency:

$$f_n = \left( \frac{\lambda_{01}}{r} \right)^2 \sqrt{\frac{D}{\mu_{\text{eff}}}}$$

(11)

where $\lambda_{01}$ corresponds to the (01) vibration mode eigenvalue. As the plates will be vibrating in their first eigenfrequencies, $\lambda_{01}$ was used throughout the equations. The total mass of the composite disk, $m_d$, and the shape function is used to determine the modal mass:

$$m_d = (\rho_{pp} t_{pp} + \rho_{be} t_{be} + \rho_{ap} t_{ap}) \pi r^2 + \rho_{te} t_{te} \pi (r_{te})^2$$

$$m_m = m_d * 2 \int_0^1 \varphi(x_\theta)^2 x_\theta \, dx_\theta$$

(12) (13)

where the densities of the distinct layers are $\rho_{pp}$, $\rho_{be}$, $\rho_{ap}$ and $\rho_{te}$, respectively. The finite element model (FEM) was developed to measure the voltage output of the device.

3. Experiments

PVDF-TrFE was selected as the actuation material for the piezoelectric harvester. Table 2 demonstrates the superior voltage output KPI of PVDF-TrFE in comparison to other commonly utilized piezoelectric materials. PVDF-TrFE material was characterized in terms of thickness, pyroelectricity, and ferroelectricity measurements.

In order to characterize the material, it is necessary to first use a solvent such as acetone with 2 wt% PVDF-TrFE (Piezotech FC25). The specimen is then placed on a magnetic stirrer at 80 °C for 1h. The solution was then filtered to make it more homogeneous. The filtered solution was spin-coated onto glass substrates, with the speed ranging from 750 RPM to 5000 RPM. After the operation, the solution was annealed at 140 °C for one hour. Figure 1 displays the thickness of the deposited layer at various RPMs.
The relationship between RPMs and the thickness of the deposited layer may not be linear, since the thickness of the deposited layer depends on a number of factors, including the viscosity of the solution, the surface tension, and the centrifugal force generated by the spin coating process. Because the centrifugal force is insufficient at lower RPMs to disperse the solution equally, a narrower layer may result. The solution spreads more evenly and forms a thicker layer as the RPM rises, increasing the centrifugal force. At higher RPMs, however, the solution can become overly thin and reduce the thickness of the deposited layer. As a result, the correlation between RPMs and the thickness of the deposited layer may not be simple and linear, but complex and dependent on a number of factors.

Film formation was not desirable in the film spin-coated at 5000 RPM, as short circuit tests for this specimen failed in most regions when it was applied on ITO glass. This indicates a high level of non-uniformity or porosity on the surface. Film formation was better when spin-coated at 2000 RPM compared to 5000 RPM. However, the short circuit test failed at the edges of the ITO glass. The 33 wt% PVDF-TrFE solution (FC25 Arkema Piezotech) was too viscous to be dispensed using pipettes. In conclusion, operating at lower RPMs (less than 2000) led to improved film uniformity. However, it appears that acetone is not a suitable solvent for PVDF-TrFE due to its high volatility. Poling was performed using a high-voltage DC power supply. An additional 100 V was applied for a thickness of 1 μm. A Sawyer-Tower circuit was constructed to conduct ferroelectric measurements on the specimens. Figure 2 displays the results of the ferroelectric measurements conducted using the circuit.

PVDF-TrFE exhibits a dual-phase microstructure comprising alpha and beta phases, with the stiffness and crystallinity of the film being determined by the percentage of the beta phase. Figure 3 shows the test setup used to plot the stress-strain curve and displays the curve in the elastic region for the semi-crystalline PVDF-TrFE copolymer.

According to Fig. 3(c), the polymer exhibits Young’s modulus of 0.87 GPa, demonstrating its robustness. In addition to its high stiffness, PVDF-TrFE is a suitable candidate for energy harvesting applications that require flexibility and mechanical
robustness [25]. According to Eq. (1), where “d” represents thickness, “s” represents applied stress, and “piezoelectric voltage coefficient” is a constant, the voltage output of a piezoelectric film is directly proportional to the applied stress on the film. Figure 4
demonstrates the flexibility of the film under a microscope, while Fig. 5 displays an optical image of a harvester prototype.

Also, based on the stress correlation with strain, which is realized by the Young Modulus (Eq. (2)), the higher magnitude for $E$ results in higher voltage output, which is crucial for energy harvesters.

\begin{align}
V &= g_{33} \Delta s \\
V &= g_{33} dE \epsilon
\end{align}

Figure 4. (a) Optical image representing the flexibility of the harvester. (b) PET layer was used as a substrate for the piezoelectric layer to bend without going into a tear, permanent deformation. (c) Optical image of the fabricated harvester from the top view (first design). (d) Bottom view of the same design.

Figure 5. (a) Optical image of the second design for the harvester. (b) Bottom view of the same design.
The tunability of the $\beta$ phase percentage through chemical methods or electrical poling of the film can result in higher crystallinity, which in turn determines Young’s modulus of PVDF-TrFE films. Thus, we used FC20 polymer powders containing 20% mol of TrFE ($\beta$ phase) to achieve the desired balance of flexibility and stiffness. In this way, a range of PVDF-TrFE films with elastic moduli between 0.7 and 3 GPa can be chosen, depending on the desired balance between flexibility and voltage output for a given energy harvesting application.

### 3.1. Fabrication Process

To validate the fabrication process, a 3 mm diameter hole was created on a 10 $\times$ 10 mm PET sheet using a mechanical cutter. A thin double-sided tape was placed on top of a supportive PET material that had been cut into a 7 $\times$ 10 mm rectangle. Another PET sheet, which will later be replaced by PVDF-TrFE, was then cut according to the design constraints. This layer also included contact pads with dimensions of 3 $\times$ 3 mm, which were attached to the double-sided tape. To fabricate the device, the first step involved cutting plain PET sheets into 10 $\times$ 10 mm sizes using a mechanical cutter device (step 1). The sheets were 140 $\mu$m thick and were cut using a laser to create circular cavities with a diameter of 1.5 mm (step 2). A 65 $\mu$m thick double-sided tape was then placed on top of the PET (step 3). The tape was used to secure the PolyK PVDF-TrFE film onto the sheet. In addition, the tape was utilized as the structural layer for the harvester, thereby shifting the piezoelectric layers away from the neutral axis. Figure 6 displays a 3D image of the harvester, while Fig. 7 illustrates the fabrication steps utilized to create the PEH prototypes. Before conducting functionality tests, voltage output tests were performed under a high-impact force.

An 18 $\mu$m layer of PVDF-TrFE was placed onto the double-sided tape in step 4. Two 3 $\times$ 3 mm electrode pads were cut out of the PVDF-TrFE film to facilitate bonding and establish connections with the device. Connections are made using flat-tip connectors (Step 5). The sheet was coated with metal on both sides. Circular plate energy harvesters with a diameter of 1.5 mm were fabricated using the described process. The length of the acoustic resonator tube was fixed at 140 $\mu$m in all prototypes.

![Figure 6. PVDF-TrFE sheets vibrating within circular cavities.](image-url)
3.2. Tests

The experimental platform was constructed as depicted in Fig. 8. The setup comprised a 4-wire fan with pulse width modulation (PWM), an Arduino Uno, a dry air supply, and a BMP280 pressure sensor breakout board from Adafruit. The output properties of the piezoelectric energy harvester with a resonant cavity were studied experimentally. A code was developed to dynamically measure pressure from serial pins. The Serial Peripheral Interface (SPI) protocol was used for communication. A unique testing setup was constructed using 3D-printed components. Dry air was directed toward the rotating propeller of the fan, which created pressure fluctuations by generating intervals. The frequency of these intervals was adjusted by modifying the PWM frequency of the fan and

Figure 7. (a) Plain PET sheets were cut in 10 × 10 mm size with a mechanical cutter device. (b) Sheets were cut with a laser to form 1.5 mm diameter circular cavities. (c) A thin double-sided tape was put on top of the PET. (d) The tape was used to fix the piezoelectric film on the sheet. (e) Bonding connections were realized.
the operating voltage, as illustrated in Fig. 9. The maximum wind frequency for the experiments was selected in order to achieve the highest electric output [26]. The PEH was fixed near the fan to vibrate with the fluctuations, generating alternating voltage. The maximum wind speed measured was 20 m/s. The rotational speed of the fan was verified using a tachometer. The current output of the harvester was measured with an oscilloscope. The output voltage was converted to current by dividing the peak-to-peak output of CH2 on the oscilloscope by the resistance value of 1.5 kΩ. The procedure was applied to both designs of the harvester.

4. Discussion

The research presents two transducers, each measuring 10 × 10 mm, that are built on the PET layer. The neutral axis and its distance from the midplanes of the piezoelectric layers were determined by utilizing the measured layer thicknesses. The value of z was calculated to be 74 μm. Figures 10 and 11 represent the voltage output of the harvester with the first design and the electrical outputs from the experiments, respectively.
The second harvester design, which had a higher power output, was evaluated using a wind test setup (Fig. 12). Figure 13 (a–c) demonstrates the voltage, current, and power output of the harvester on the same time scale. The difference in power output between the two designs is primarily due to the effective area of the piezoelectric layer. The second design has a 36.2% larger piezoelectric layer area than the first design. The impact was applied to the harvester to measure the capacitor’s charge-discharge curve. A full-bridge rectifier circuit was used to convert the AC output and charge the capacitor. The ceramic capacitor was charged to 585 mV. The maximum voltage measured across the capacitor was 760 mV. The voltage increase for a single impulse was 174 mV.

Figure 9. (a) Pressure fluctuation spikes were plotted for 1680 RPM measurement showing peak-to-peak 45 Pa pressure changes per hit. (b) Using the dry air supply, 400 Pa of pressure could apply to the piezoelectric plates. (c) Sweeping through 720 RPM to 1680 RPM tests using the PWM fan, FFT was done to each test data extracting the dominant fluctuation frequencies. 1680 RPM was chosen for the application for having the highest fluctuation frequency having dominant peaks at 72 Hz and 84 Hz. (d) Testing data was filtered through the moving median filter by taking the average of last five values. The 0 Hz noise in the FFT plots was eliminated using filtering.

Figure 10. The maximum peak-to-peak value seen was 1.4 V under impulse (first design).
Figure 11. (a) The maximum current was 136.9 μA under impulse when taking the average of the peak values (first design). (b) The output current from the harvester under impulse current of $I_{\text{max}} = 273$ μA (second design). (c) The output voltage measured from the harvester (second design) plotted by taking average values of five different impulse tests reporting in error bars. The results are not time-dependent. It is worth noting that the output voltage produced is 6.61 $V_{\text{max}}$.

Figure 12. Two flat-tip crocodile wires were used to get contacts from the bottom and top electrodes.
Figure 13. (a) The maximum voltage obtained from the wind setup was $v_{\text{max}} = 937.01 \text{ mV}$ while the harvester was connected to the current measurement circuit. (b) The maximum current obtained from the wind setup was $I_{\text{max}} = 291.34 \mu \text{A}$. (c) The maximum power obtained from the wind setup was $P_{\text{max}} = 272.99 \mu \text{W}$.

Figure 14. (a) Charge in the capacitor was periodically changed due to impulses on the piezoelectric element. (b) The 104 nF capacitor had a stable charge during the acquisition. (c) Harvester’s voltage output under wind load without any external circuit connection to validate the values taken from the current measurement circuit. $V_{pp} = 1.74 \text{ V}$ was measured from the wind tests.
The data for capacitor charging is presented in Fig. 14(a). After the force was released from the piezoelectric element, the charge on the capacitor was discharged because of the 1 MΩ input impedance of the oscilloscope. This experiment runs for 10,000 s to demonstrate the stability of the capacitor charge (see Fig. 14(b)). As the rest of the measurements demonstrate the instantaneous output or power, the measurement in Fig. 14(b) is a measure of the device’s capability of producing a significant average power output. Figure 14(c) displays the open circuit voltage output during wind tests.

The PVDF-TrFe energy harvester can power a MEMS BMP280 pressure sensor, which is commonly used in structural health monitoring applications for wind turbines. The BMP280 sensor can be powered using the PVDF-TrFe energy harvester, requiring an input of 2.7 μA current and 1.20 V voltage. Figure 15 shows the power and current requirements of two additional commercial pressure sensors that operate at a maximum voltage of 1.5 V, along with the BMP280. The figure demonstrates that the PVDF-TrFe piezoelectric harvester is capable of powering these devices with a suitable step-up converter circuit.

5. Conclusion

The PVDF-TrFe energy harvester can power a MEMS BMP280 pressure sensor, which is commonly used in structural health monitoring applications for wind turbines. The BMP280 sensor can be powered using the PVDF-TrFe energy harvester, requiring an input of 2.7 μA current and 1.20 V voltage. Figure 15 shows the power and current requirements of two additional commercial pressure sensors that operate at a maximum voltage of 1.5 V, along with the BMP280. The figure demonstrates that the PVDF-TrFe piezoelectric harvester is capable of powering these devices.

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Disclosure Statement

No potential conflict of interest was reported by the author(s).

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