# DESIGN, FABRICATION AND CHARACTERIZATION OF WEARABLE ENERGY HARVESTER USING POLYVINYLIDENE FLUORIDE

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**Abstract:** This paper describes the design, fabrication and characterization of Polyvinylidene Fluoride (PVDF) based piezoelectric energy harvester that scavenges energy from the movement of human limbs. It investigates the effect of a piezolaminated curvilinear shell structure on the power density of a wearable energy harvester through Finite Element Method (FEM) and experimental results. Curvilinear Shell structure with thin PVDF layers embedded on top and bottom surfaces showed higher output compared with a flat structure. The harvester attached with the fingergenerated a maximum output power of 10.02 µW against a 100 kΩ resistive load while the peak to peak voltage was 10.2 V.

**Keywords:** Energy harvesting, PVDF, Curvilinear structure, Finite element analysis

## INTRODUCTION

Various energy sources including light, heat and mechanical vibration are studied as MEMS energy sources to replace the existing batteries with a short lifetime. Among the various energy sources, the energy harvesting technology using piezoelectric converter is the most widely used because of simple configuration and high conversion efficiency [1].

Lead zirconatetitanate (PZT), zinc oxide (ZnO) and polyvinylidene fluoride (PVDF) are the representative piezoelectric materials used in the majority of MEMS piezoelectric transducer [2]. Most of the studies with piezoelectric materials have focused on PZT due to its high piezoelectric coefficient. The main problems of PZT come from its toxicity and brittleness [3]. On the other hand, PVDF films are flexible, lightweight, and provide a convenient foundation for electrode pattern shaping, which fosters their wide use as transducers.

In addition, various technologies including different geometrical designs and materials have been developed in order to harvest energy from human motion. For example, Kysmiss et al. presented a shoe-mounted generator consisting of a PVDF stave and PZT unimorph inserted into sneakers to generate electrical power [4]. Energy scavenging from outdoor activities using backpack was demonstrated [5]. In general most of the researches have been focused on the active vibration control of the structures using piezoelectric material. A tapered cantilever beam to ensure a constant strain in the piezoelectric film along its length for a given displacement was developed [6]. Additionally, the merits of both unimorph and bimorph cantilevers have been studied [7]. Yet, these beam and plate type structures depend on the specific vibration and frequency, whereas the human motion is relatively random.

Owing to the fast transition from the initial state to the folding state at the threshold point of the bending force, a curvilinear shell structure has been considered as a suitable alternative to solve the problem of random human motion.

In this work, we focus on the development of piezoelectric energy harvester based on PVDF using curvilinear shell structure to harness energy from each human movement even a slow finger motion. We develop and optimize a design method of the harvester using a curvilinear shell based on the finite element method.

## DESIGNANDFABRICATION

### Analytical modeling

When a piezoelectric material is mechanically stretched, electrical charges are induced on its surface according the following equation :

$$D = dT + \varepsilon_T E \quad (1)$$

where D is the charge density, d is the piezoelectric coefficient, T is the material stress, $\varepsilon_T$ is the relative permittivity and E is the electrical field. If the relationship, between stress and strain is linear, the total induced charge can be expressed as

$$Q = dYA\frac{\Delta l}{l_0} \quad (2)$$

From the above equation, it is clear that the strain applied to the material is converted into the electric energy.

Since higher strain is associated with higher electrical energy, this work considered the shell structure that produced the larger strain energy.Furthermore, it offers a remarkably fast transition which is decidedly much more suitable for slow human bending motion. The basic structure of shell with embedded PVDF is shown in Fig. 1.

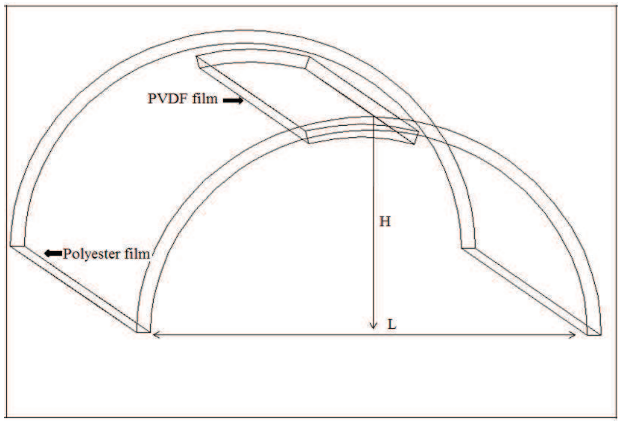


*Fig.1: Piezolaminated shell with unfolding state.*

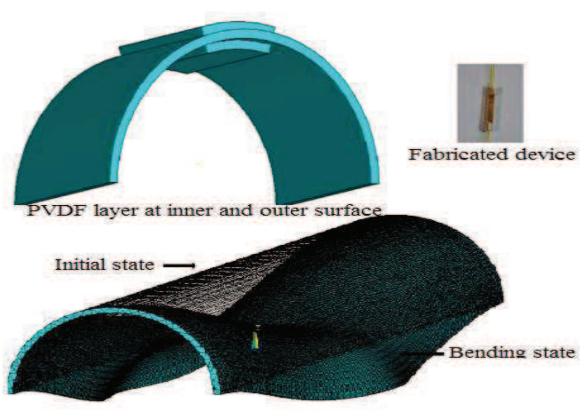


*Fig. 2: PVDF layers at inner and outer surface of shell and bending state of shell.*

When the bending force is applied, the shell structure makes a fast transition from its initial state to the folding state, thereby creating a higher strain. For the finite element method and the experimental result, the curvature of the laminate, k, was estimated using the following equation:

$$k = \frac{8H}{L^2 + 4H^2} \quad (3)$$

where L and H denote the length and height of the shell, respectively, as depicted in Fig.1. According to the Kirchhoff hypothesis, a fiber normal to the mid plane remains so after deformation. It follows that:

$$\{S\} = \{S_0\} + z\{k\} \quad (4)$$

where $\{S_0\}$ is the midplane deformation and z is the distance variable in a direction perpendicular to the film surface. The generated output voltage due to the folding state of the shell can be obtained from the following equation:

$$v_{out} = -\frac{Q}{C_r} = -\frac{1}{C_r}\int_{\Omega} D d\Omega \quad (5)$$

If the piezoelectric properties are isotropic in the plane ($d_{31}$=$d_{32}$), we have

$$D\{110\} = d_{31}\{110\}\{S\} \quad (6)$$

Combining, the Eq. 4 and Eq. 5, we find

$$v_{out} = -\frac{d_{31}}{C_r}[\int_{\Omega}(S^0x + S^0y)d\Omega + z_m\int_{\Omega}(k_x + k_y)d\Omega] \quad (7)$$

The first integral represents the contribution of the average membrane strains over the electrode and the second accounts for the contribution of the average bending motion.

## Fabrication

The proposed curvilinear shell structure device was fabricated using a polyester film and corona pooled PVDF commercial film. The thickness of the polyester film was 120 µm, and the PVDF film was 110 µm. Different thicknesses of a gold electrode were sputtered on the both side of PVDF film by using RF & DC magnetron Sputtering system (KBS-C4055). The wires on top and bottom electrode are attached to the film by silver paste. Then the film was cut to a length of 26 mm and a width of 2 mm.

A hollow cylindrical titanium rod with a diameter of 6 mm was used to hold the rounded polyester film. The polyester film was glued on one side to attach the film to the cylinder. The cylinder, embedded with polyester film, was kept in a furnace for 30 minutes at a temperature of 135°C. It was subsequently cooled at room temperature and detached from the rod. Different shell curvatures were fabricated using different diameters of cylindrical rods. After peeling the polyester film off from the metal rod, the film was cut to the desired size. The PVDF film with a gold layer was then attached to the shell by an elastic adhesive. Two layers embedded on the inner and outer surface of the shell was connected in parallel.Fabricated shells with embedded PVDF films are illustrated in Fig. 3 for different values of k.

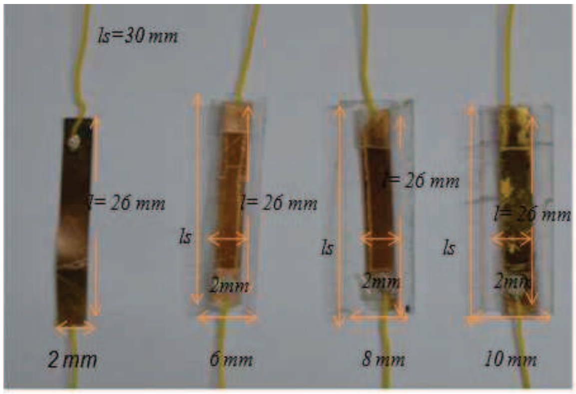


*Fig. 3: Fabricated shell with different values of k.*

## RESULTS AND DISCUSSIONS

The experimental setup for testing the proposed device is shown in Fig. 4.

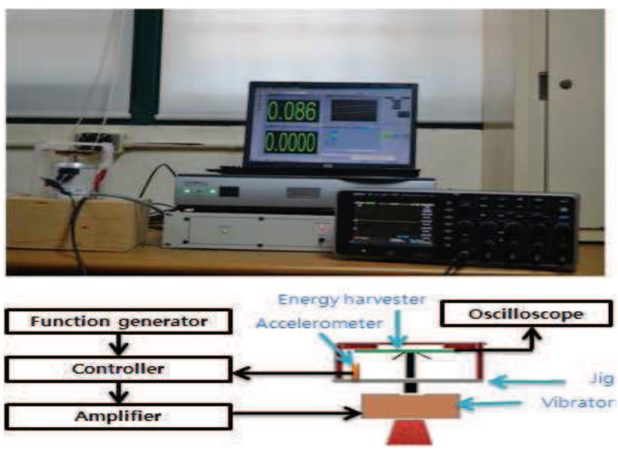


*Fig. 4: Experimental setup for testing the device.*

Fig. 5 clearly shows that the strain due to the shell structure is proportional to the displacement.

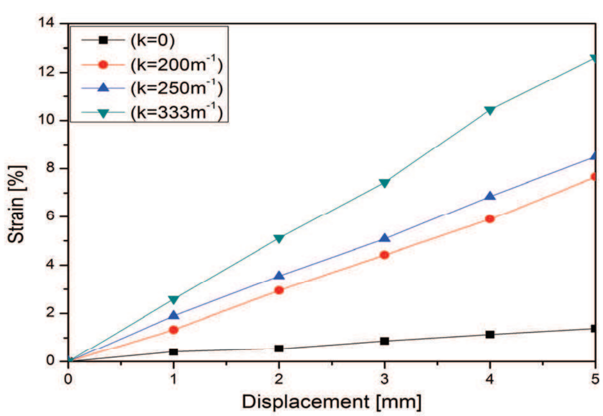


*Fig. 5: Variation of strain with different displacements.*

It also reveals that the strain is totally dependent on the curvature k. Although the strain is slightly increased for flat structure (k=0), the increment is comparatively lower than that of the shell. The FEMsimulation has been performed to investigate the effect of curvature on the strain.

Fig. 6 shows the variation of output voltage for different values of k. The maximum peak-peak voltage was 3.2 V when the value of k is 333 $m^{-1}$. The other peak-peak voltages are 2.5 V and 2 V for 250 $m^{-1}$ and 200 $m^{-1}$, respectively. The results agree with the output voltage equation and the simulation data.

Note that, as the polyester film heated up from room temperature $20^0$c to $135^0$c, an additional prestress was induced. This prestress was caused by a thermal expansion mismatch between the titanium housing and the stretched polyester film. Therefore, the total prestrain was composed of both mechanical and thermal prestrain. As the curvature rose, however, the strain increased. The effect of both K and the displacement on the output voltage (root mean square) is represented in Fig. 7.

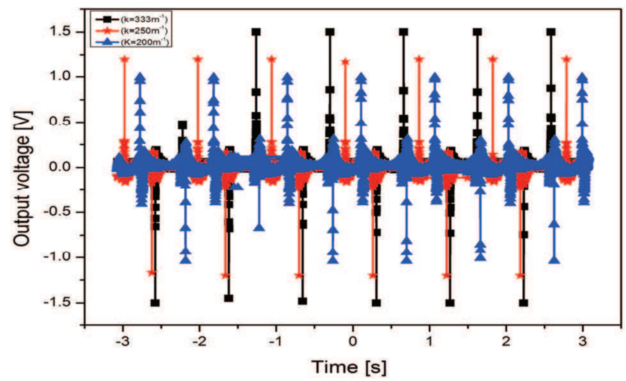


*Fig.6: Comparison of output voltage with different values of k for single layered shell.*

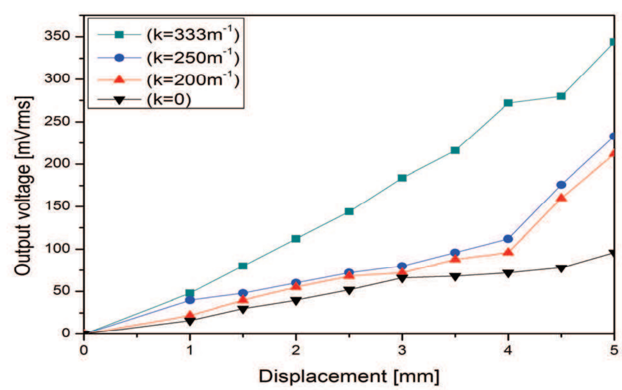


*Fig. 7: Comparison of output voltage with respect to displacement and k.*

The output voltage did not increase linearly due to the loose bonding between the Piezo layer and Polyester shell. The adhesion between gold layers and PVDF film might also have contributed to these unexpected increments. Fig. 8 illustrates the peak-peak output voltage due to the bending and stretching movement of a finger. It clearly shows that the output voltage is very higher compared to the experimental result. The experimental set up was embedded with only one PVDF layer. But in case of practical application, two PVDF layers were embedded on the top and bottom surface of the shell structure. Moreover,the mid plane displacement due to the finger movement was much higher than the displacement provided by our instrument. Note that the shell was attached to the hand glove with an elastic adhesive.

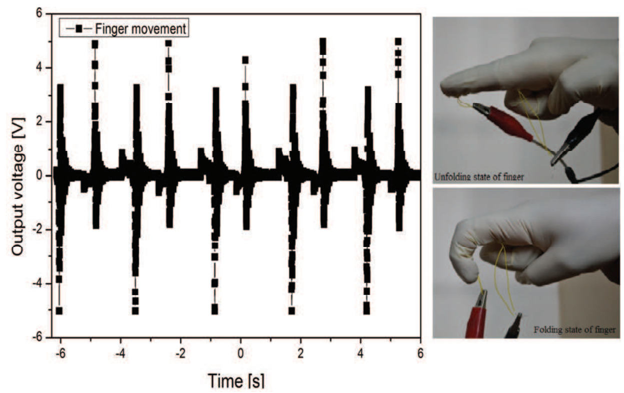


*Fig. 8: Output voltage from the finger movement.*

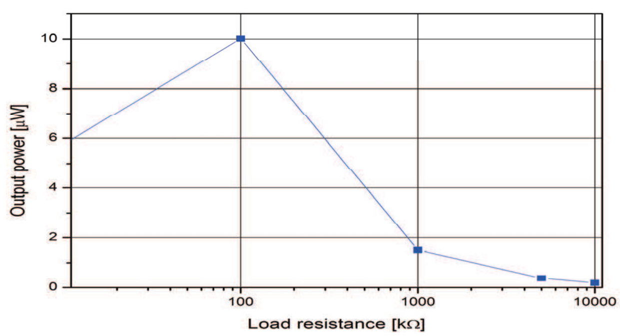


*Fig. 9: Output power due to finger movement.*

The output power of bimorph against various loads is presented in Fig. 9. Voltage doubler rectifier circuit was used instead of conventional rectifier circuit. The maximum output power (10.02 µW) is achieved against a load resistance of 100 kΩ, with a power density of 23.63 µW/cm$^3$.

## CONCLUSIONS

This paper presents an analysis of scavenging energy from the movement of human limbs by using a curvilinear structure. The system successfully harvested energy from the bending and stretching movement of a finger. The outputs are illustrated by theoretical derivations, simulation results and experimental measurements. The fabricated device showed rectified maximum output power of 10.02 µW against a load resistance of 100 kΩ with a power density of 23.63 µW/cm$^3$. Consequently, we have demonstrated that a storage capacitor can be efficiently charged; even in case of very slow movements. It is also possible to harvest the energy from elbow and knee movement by using the curvilinear shell, which offers remarkably fast transition from the stretching to bending position and vice versa. Future work will be focused on using other piezoelectric composite polymer and improving the effectiveness of the AC/DC and DC/ DC converters to charge micro batteries or super capacitors.

## ACKNOWLEDGEMENTS

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