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Verification and Analysis of Characteristics of Polyvinylidene Fluoride Material

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Abstract: Piezoelectric materials possess a unique property of generation of electric charge when mechanical energy is applied to them. Piezoelectricity is a form of changing mechanical energy into electric energy. In other words they are transducers which are capable of converting mechanical energy into electrical energy. It is light weight and flexible. The proposed work discusses about the verification and analysis ofPolyvinylidene fluoride material (PVDF) film. A series of experiments have been performed by applying compressive force on the PVDF material at various frequencies. To record and analyze the output of the PVDF film, a Data Acquisition System (DAQ) running Labview software was used. The experiments were performed on single layer PVDF material. The observations of hysteresis loops in single layer PVDF film were successfully performed. The experiments were performed on 9 micron thickness of PVDF film and the changes in the output voltage generated were observed.

Keywords: Piezoelectric, Polyvinylidene fluoride material (PVDF), Compressive force, Single-layer PVDF material

I. INTRODUCTION

The Piezoelectricity is the ability of some materials (notably crystals and certain ceramics) to generate an electric potential in response to applied mechanical stress [2]. This may take the form of a separation of electric charge across the crystal lattice. If the material is not short-circuited, the applied charge induces a voltage across the material. The word is derived from the Greek piezein, which means to squeeze or press. It is an unusual phenomenon in which polarization is induced and electric field is established across a sample when it is mechanically stressed.Upon pressure, two opposite sides of the crystal create a potential difference (voltage). One side becomes positively charged, the other negatively charged. When a circuit is connected to both sides of the crystal, electrons from the negative side are discharged on the circuit. The crystals last indefinitely. Piezoelectric materials are used to transducer electrical and mechanical energy. Piezoelectric material technology has enabled a wide variety of commercially successful sensors and actuators. Transducer materials convert one form of energy into another, and are widely used in sensing applications. The tremendous growth in the use of microprocessors has propelled the demand for sensors in diverse applications. Today, PIEZOELECTRIC POLYMER SENSORS are among the fastest growing of the technologies within the $18 billion worldwide sensor market. Like any new technology, there have been an extraordinary number of applications where "PIEZO FILM" has been considered for the sensor solution. In the 20 years since the discovery of piezoelectric polymer, the technology has matured, practical applications have emerged from a long list of possibilities, and the rate of commercialization of the technology is accelerating.PVDF, Poly (vinylidene fluoride), is a polymer that has been studied for over four decades due to its good electromechanical properties, stability, and durability in various environments. Currently, PVDF is the only commercially available piezoelectric polymer.

II. PROPOSED METHOD FOR SINGLE LAYER PVDF MATERIAL

The various applications of the piezoelectric Polyvinylidene Fluoride (PVDF) film, particularly in sensory mode, are increasingly reported by numerous researchers. Due to thickness of the PVDF films, the only practical area to deposit electrodes is the film surface; hence the electrical charge can only be collected from the thickness direction. Although the application of the PVDF films in extensional modes is dominant, there are many situations in which the PVDF film must be placed between two surfaces as shown in Figure 2.1(a). For instance, in the traditional piezoelectric force sensors, it is customary to place the piezoelectric sensing element between two plates which also act as electrodes. These plates transmit the normal force to the surface of the piezoelectric films, so that they transform the applied point load to a distributed load over the piezoelectric surface. In this method, the longitudinal force direction is considered for sensory action. The film has sheet thickness of 9microns with leads as shown in Figure 2.1(b).

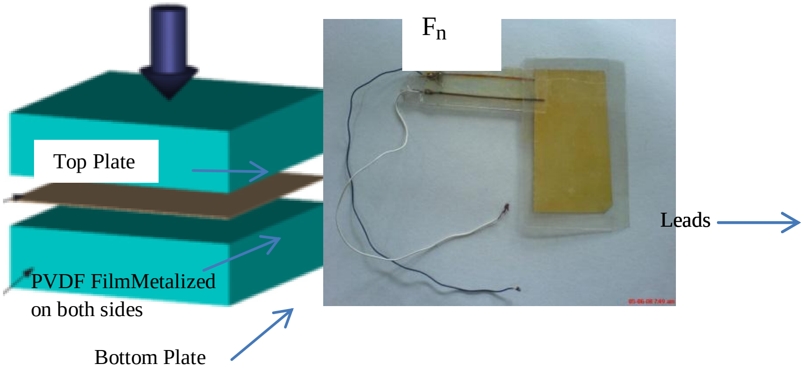


Fig 2.1 **(a)** **(b)**

Fig 2.1(a)The geometry of the problem in which a PVDF film is sandwiched between two aluminum plates and a load is applied in the normal direction. (b) PVDF material with 9 micron thickness.

The various components of the setup for calibration are electro-dynamic shaker, force transducer, piezoelectric sensor, blowerand support for the transducer. The shaker is made to vibrate at a certain frequency controlled electronically. The force transducer is used to measure the force acting on the sensor surface. The voltage output of the sensor is measured by connecting its leads to Data Acquisition system (DAQ). The blower is used to remove heat from the Electrodynamic shaker.

The layout of the experimental setup for a single layer PVDF used in this work. To apply a repetitive load, a signal generator which is used for the increasing and decreasing the frequency with sinusoidal output was used. Before connecting this signal to the shaker, the signals were amplified using a power amplifier (TECHRON 5507). To characterize the output voltage of the PVDF film sandwiched between two surfaces, a calibrated load sensor (Kistler 9712B50) was used to record the amplitude of the applied load. A 50 mm square shape 9 microns thickness uniaxial PVDF film used. The shaker is made to vibrate (sinusoidally) at different frequencies. At each frequency, voltage output was measured for different forces at particular amplitude. The loads are applied from 7N to 17N in steps of 2N at the frequency of 10Hz to 60Hz was applied to the PVDF film. To record and analyze the output of the PVDF film, data acquisition system DAQ (National Instrument, NI PXI-1050) runningLabview software (Version 8.0) was used. To connect the piezoelectric charge output to the DAQ as well as force transducer, a charge amplifier was used. The peak-to-peak of the PVDF output and the corresponding input was recorded.

Data acquisition is the sampling of the real world to generate data that can be manipulated by a computer. Sometimes abbreviated DAQ or DAS, data acquisition typically involves acquisition of signals and waveforms and processing the signals to obtain desired information. The components of data acquisition systems include appropriate sensors that convert any measurement parameter to an electrical signal, which is acquired by data acquisition hardware.

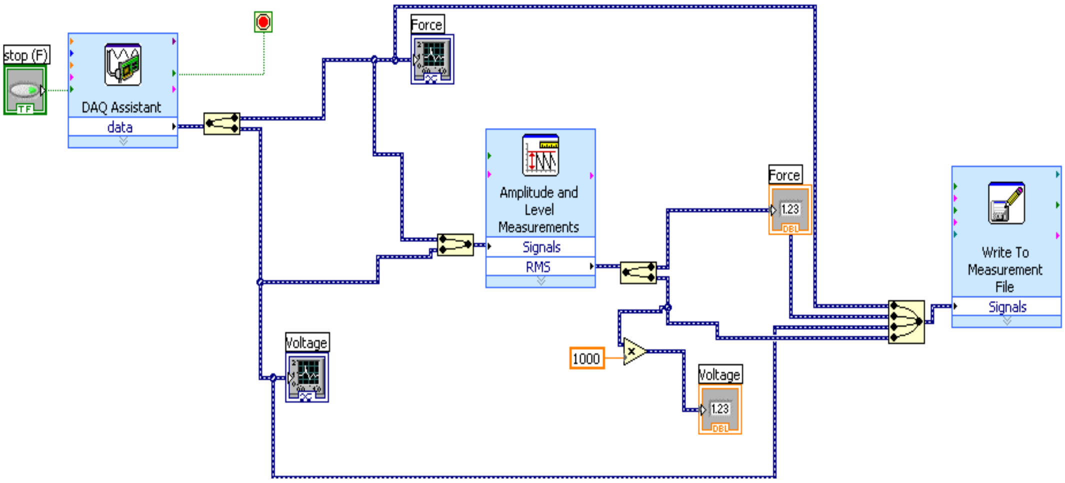
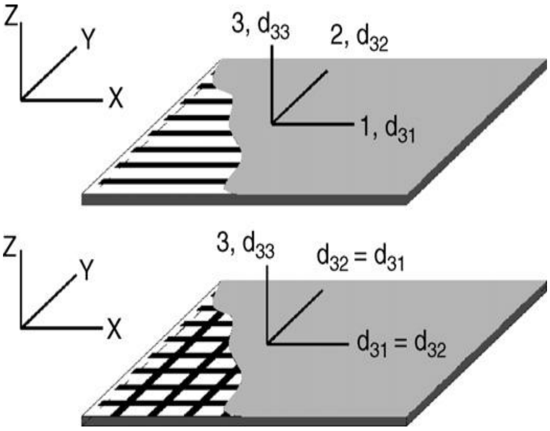


Fig 2.2 LABVIEW Setup for single layer PVDF material

III. INDENTATIONS AND EQUATIONS

The By machining the material in one or two perpendicular directions prior to the polarization process, different piezoelectric behaviors can be obtained as shown in Figure.



The constitutive equations read

Stress - Charge Form

$$\begin{aligned} \{T\} &= \left[c^E\right]\{S\} - [e]^T\{E\} \\ \{D\} &= [e]\ \{S\} + \left[\varepsilon^S\right]\{E\} \end{aligned} \qquad (3.1)$$

Strain - Charge Form

$$\begin{aligned} \{S\} &= \left[s^E\right]\{T\} + [d]^T\{E\} \\ \{D\} &= [d]\ \{T\} + \left[\varepsilon^T\right]\{E\} \end{aligned} \qquad (3.2)$$

Strain - Voltage Form

$$\begin{aligned} \{S\} &= \left[s^D\right]\{T\} + [g]^T\ \{D\} \\ \{E\} &= -[g]\{T\} + \left[\varepsilon^T\right]^{-1}\{D\} \end{aligned} \qquad (3.3)$$

Stress - Voltage Form

$$\begin{aligned} \{T\} &= \left[c^D\right]\{S\} - [h]^T\ \{D\} \\ \{E\} &= -[h]\{S\} + \left[\varepsilon^S\right]^{-1}\{D\} \end{aligned} \qquad (3.4)$$

Where

$\{T\} = \{T_{11} \quad T_{22} \quad T_{33} \quad T_{23} \quad T_{13} \quad T_{12}\}^T$ is the stress vector. (N/m^2)

{S}, the deformation vector. (m/m)
{E}, the electric field vector. (V/m) or (N/C)
{D}, the electric displacement vector. (N/Vm) or (C/m^2)
[c] and [s], the elasticity constants matrices. (N/m^2) and (m^2/N)
[ε] , the dielectric constants matrix. (F/m)
[d], [e], [g] and [h], the piezoelectric constants matrix

The generalized strain charge form for piezoelectric material relation in matrix form is represented in terms of

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & s_{14}^E & s_{15}^E & s_{16}^E \\ s_{21}^E & s_{22}^E & s_{23}^E & s_{24}^E & s_{25}^E & s_{26}^E \\ s_{31}^E & s_{32}^E & s_{33}^E & s_{34}^E & s_{35}^E & s_{36}^E \\ s_{41}^E & s_{42}^E & s_{43}^E & s_{44}^E & s_{45}^E & s_{46}^E \\ s_{51}^E & s_{52}^E & s_{53}^E & s_{54}^E & s_{55}^E & s_{56}^E \\ s_{61}^E & s_{62}^E & s_{63}^E & s_{64}^E & s_{65}^E & s_{66}^E \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} d_{11} & d_{21} & d_{31} \\ d_{12} & d_{22} & d_{32} \\ d_{13} & d_{23} & d_{33} \\ d_{14} & d_{24} & d_{34} \\ d_{15} & d_{25} & d_{35} \\ d_{16} & d_{26} & d_{36} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \qquad (3.5)$$

Direct piezoelectric equation in matrix form

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \qquad (3.6)$$

The strain - charge form for PVDF thin film is

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\ s_{12}^E & s_{11}^E & s_{13}^E & 0 & 0 & 0 \\ s_{13}^E & s_{13}^E & s_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{44}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(s_{11}^E - s_{12}^E) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{31} \\ 0 & 0 & d_{33} \\ 0 & d_{15} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \qquad (3.7)$$

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{11} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \qquad (3.8)$$

The relationship between voltage and stress for a piezoelectric coefficient
For PVDF as a sensor, the two piezoelectric coefficients are defined as follows,

$$d_{ij} = \frac{\mathit{charge\ density\ produced\ in\ direction\ i}}{\mathit{mechanical\ stress\ applied\ direction\ j}} \qquad (3.9)$$

and

$$g_{ij} = \frac{\mathit{electric\ field\ produced\ in\ direction\ i}}{\mathit{mechanical\ stress\ applied\ in\ direction\ j}} \qquad (3.10)$$

These two coefficients have a linear dependence given by

$$g_{ij} = \frac{d_{ij}}{C}$$

Piezoelectric charge coefficient

$$d_{33} = \frac{Q}{F} \quad (3.11)$$

Where $Q = C * V$

$$C = \frac{\varepsilon_0 \varepsilon_r A}{t} \quad (3.12)$$

ε_0 is dielectric constant of air = 8.85*10-12 farads/ meter, ε_r is Relative dielectric constant 13
d_{ij} is Piezoelectric charge coefficient and C is Capacitance.

The first subscript (i) indicates the direction perpendicular to the electrodes and the second subscript (j) indicates the direction of applied stress or deformation. Then the relation between the voltage and piezoelectric coefficient are as given below.

$$V = g_{33} * \sigma_3 * t \quad (3.13)$$

Where g_{33}= Piezoelectric coefficient,

$$\sigma_{33} = \frac{F}{A}$$

t = Thickness ofthe PVDF material.
By using equation (3.11) the output of the PVDF voltage and the piezoelectric coefficient (d_{33}) easily we can calculate.

IV. RESULT AND DISCUSSION

The experiments are conducted on commercially available PVDF film. The film was purchased from M/s. Precision Engineering Co. United Kingdom. It is a uniaxial PVDF film, having three microns gold coating on either side. The film is polarized across its thickness and the gold coating is required to tap the voltage generated. The polarity on the film is indicated and this used for the connection to the DAQ card using crocodile pins. The thickness of the PVDF film that was commercially bought is 9 microns, 28 microns, 52 microns, and 110 microns.

The experiments conducted were as follows.

1. Single layer PVDF film under compressive loading, considering different thickness of the film.
2. Experiments on multi-layer PVDF film, starting from double layer to four layers of the film.
3. Time interval was considered in taking the readings between each load applied.
4. Experiments on Hysteresis of load versus voltage output of the PVDF film were conducted.
5. Experiments on the PVDF film stacked between different materials such as transparency sheet, glass paper and without any material were conducted and the variation in the voltage output of the film observed.

In all the above cases the excitation frequency of the exciter is varied from 10 Hz to 50 Hz.

A. Single Layer PVDF Film under Compressive Loading, Considering Different Thickness of The Film.

Experiments were conducted on different thickness of PVDF film. The film is placed between two transparency sheets as packaging. The force is varied from 7N to 17N with steps of 2N. The variation in the voltage output of the PVDF film with respect to change in force and frequency is tabulated in the Table 5.1. It can be observed from the table the voltage varies from 2.877mV to 9.658mV for a constant force of 7N and varying frequency. Figure 5.1 shows the plot of force with voltage output of the PVDF film. From the graph it can be inferred that the voltage variation is linear with increase in force. The area of the PVDF film considered 40*40 mm^2.

A.1 Single layer PVDF film- Thickness 9 microns:

Single layer PVDF film 9 microns, load is applied on the PVDF film which is placed in between two transparency sheets and the area of the aluminum plate is 40*40mm2 and is as shown in Table 4.1.

Load In N	PVDF voltage output at 10Hz (mV)	PVDF voltage output at 20Hz (mV)	PVDF voltage output at 30Hz (mV)	PVDF voltage output at 40Hz (mV)	PVDF voltage output at 50Hz (mV)
7	2.877	4.761	6.540	8.703	9.658
9	3.792	4.932	6.441	8.952	10.847
11	4.619	6.677	9.017	11.031	13.146
15	8.312	10.482	12.693	15.716	18.612
17	12.764	14.053	17.266	20.053	22.911

Table 4.1 Results for 9 μm thickness PVDF film subjected to compressive load

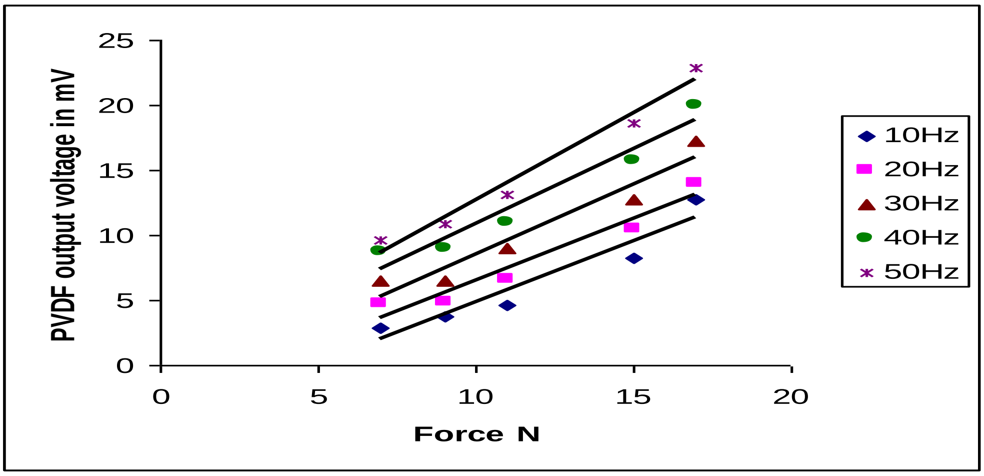


Fig 4.1 Load versus voltage output of the PVDF for 9 microns.

Load in N at 40Hz	Piezoelectric coefficient d_{33} (pC/ N)	Piezoelectric coefficient g_{33}(Vm/ N)
7	25.429	0.211
9	24.402	0.212
11	20.510	0.178
15	21.429	0.186
17	24.126	0.209

$(d_{33})_{avg}$ = 23.1792 pC/ N g_{33} = 0.199 Vm/ N

Table 4.2 The piezoelectric coefficients of thickness-9 microns

V. CONCLUSION

In the present research work an attempt has been made to study the characteristics of PVDF film used as single layers for longitudinal loads.It is clear from the method about the piezoelectric property of the PVDF film material. It was observed from the results, that the voltage output produced by the PVDF film increases linearly for the corresponding longitudinal force applied. It was also observed that the frequency with which force is applied also has influence on the voltage output of the PVDF film.It is found that the voltage generation increases with the increase in thickness of the PVDF material. The percentage increment of output voltage is not uniform for the variation in the input force as well as frequency. It is also observed that the percentage of increased in voltage is more for higher force as well as higher frequency. It can also be inferred from the above study that PVDF material can be tailored to any sensitivity by appropriate number of layer based on the load ranges to be sensed.

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