Characterization of composite piezoelectric materials for smart joint applications

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CHARACTERIZATION OF COMPOSITE PIEZOELECTRIC MATERIALS FOR SMART JOINT APPLICATIONS

A Thesis
submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for degree of
Master of Science in Mechanical Engineering
In
The Department of Mechanical Engineering

by
Hari Prasad Konka
B.Tech, Jawaharlal Nehru Technological University, 2007
August, 2010
This thesis is dedicated
to my parents
Shri. Konka Prakash
and
Shrimati. Konka Kalavathi
ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisors Dr. M. A. Wahab and Dr. Kun Lian for giving me constant guidance, motivation and research support throughout my Master’s program. Special thanks to NASA/EPSCoR, as this work is based upon work supported by the NASA/EPSCoR under grant number NASA/LEQSF (2007-10)-Phase3-01.

I would like to thank my committee member Dr. Shengmin Guo for evaluating my research work and providing valuable suggestions to improve the contents of the thesis. Special thanks to the faculty and staff members of Department of Mechanical Engineering, Louisiana State University who assisted me in my research and graduate studies.

Very special thanks to the staff at Center of Advanced Microstructures & Devices for helping me in conducting the various experiments for this research.

Thanks to fellow students, my dear friends and composite lab group for their constant support and help.
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ABSTRACT

Piezoelectric materials have the ability to provide desired transformation from mechanical to electrical energy and vice versa. When a mechanical force is applied to the piezoelectric material an electrical voltage is generated and when an electrical voltage is applied to the piezoelectric material it gets strained or deformed. Owing to these characteristics piezoelectric materials can be used as a sensor, an actuator, as well as a power generation unit.

The high brittleness of the original piezoelectric material is one of the major constraints in using them in the engineering applications. In order to overcome this difficulty the composite piezoelectric products were developed. The piezoelectric fiber composite products are highly flexible and can sustain the extensive deformation without being damaged, and is compatible with the composite structures’ processing procedure, which makes it an ideal material to be used as an embedded sensor, power harvesting device, and a force actuator within the composite structures.

The smart joint can be designed to have the piezoelectric materials embedded in them, the piezoelectric materials can detect the various loads that act on the composite joint and could provide the required counter-balancing force to the excitation forces acting on the joint; and thereby could reduce or even eliminate the effects of stress concentrations at the composite joint. A high stress concentration is one of the principal causes of structural failures for an adhesive bonded joint system.

The main objectives of this work are to study the sensing and force generation capabilities of various commercially available composite piezoelectric products through series of experimentations and to compare their performances in order to use them in the smart joint applications; and eventually, to reduce the detrimental effects of stress concentrations in the
structures. Firstly, the sensing capabilities of these products were investigated at various input frequencies and amplitudes of the dynamic loading conditions. Secondly, the tensile and bending force generation capabilities of these products were inspected with respect to various input excitation voltages. The results of these experiments depict that the voltage signals generated from these materials are proportional to amplitudes of mechanical movement, with good response at high frequency, even at micrometer deformation domain; but the force generation is relatively low under the current input conditions and configuration under study.
CHAPTER 1: INTRODUCTION TO PIEZOELECTRIC MATERIALS

1.1 HISTORY

In the year 1880 Pierre Curie and Jacques Curie discovered that some crystals when compressed in particular directions show positive and negative charges on certain positions of their surfaces. The amount of charges produced is proportional to the pressure applied and these charges were diminished when the pressure is withdrawn. They observed this phenomenon in the following crystals: zinc blende, sodium chlorate, boracites, tourmaline, quartz, calamine, topaz, tartaric acid, cane sugar, and Rochelle salt. Hankel proposed the name “piezoelectricity”. The word “piezo” is a Greek word which means “to press”, therefore piezoelectricity means electricity generated form pressure. The direct piezoelectric effect is defined as electric polarization produced by mechanical strain in crystals belonging to certain classes. In the converse piezoelectric effect a piezoelectric crystal gets strained, when electrically polarized, by an amount proportional to polarizing field [Curie et al., 1880, Walter., 1946, Moheimani & Fleming., 2006].

1.2 PIEZOELECTRIC DIRECT AND CONVERSE EFFECTS

The domains of the piezoelectric ceramic element are aligned by the poling process. In the poling process the piezoelectric ceramic element is subjected to a strong DC electric field, usually at temperature slightly below the Curie temperature. When a poled piezoelectric ceramic is mechanically strained it becomes electrically polarized, producing an electrical charge on the surface of the materials (direct piezoelectric effect), piezoelectric sensors work on the basis of this particular property. The electrodes attached on the surface of the piezoelectric material helps to collect electric charge generated and to apply the electric field to the piezoelectric element.
When an electric field is applied to the poled piezoelectric ceramic through electrodes on its surfaces, the piezoelectric material gets strained (converse effect). The converse effect property is used for actuator purposes. Figure 1.1 shows the converse piezoelectric effect.

Based on the converse and direct effects, a piezoelectric material can act as a transducer to convert mechanical to electrical or electrical to mechanical energy. When piezoelectric transducer converts the electrical energy to mechanical energy it is called as piezo-motor/actuator, and when it converts the mechanical energy to electrical energy it is called as piezo-generator/sensor. The sensing and the actuation capabilities of the piezoelectric materials depend mostly on the coupling coefficient, the direction of the polarization, and on the charge coefficients ($d_{31}$ and $d_{33}$). Figure 1.2 in the form of block diagrams shows the transducer characteristics of the piezoelectric materials.

![Piezoelectric material](http://academic.uprm.edu/paceres/Undergrad/SmartAlessandra/070ace60.jpg)

**Figure 1.1: Piezoelectric material.**

(Picture Source: http://academic.uprm.edu/paceres/Undergrad/SmartAlessandra/070ace60.jpg)
1.3 PIEZOELECTRIC MATERIALS

Some of the typical piezoelectric materials include quartz, barium titanate, lead titanate, cadmium sulphide, lead zirconate titanate (PZT), lead lanthanum zirconate titanate, lead magnesium niobate, piezoelectric polymer polyvinylidene fluoride (PVDF), polyvinyl fluoride (PVF). The piezoelectric ceramics are highly brittle and they have better electromechanical properties when compared to the piezoelectric polymers. This section gives in brief introduction about the various classes of piezoelectric materials: single crystal materials, piezo-ceramics, piezo-polymers, piezo-composites, and piezo-films.

1.3.1 Single Crystals

Quartz, lithium nihonate (LiNbO₃), and lithium tantalite (LiTaO₃) are some of the most popular single crystals materials. The single crystals are anisotropic in general and have different properties depending on the cut of the materials and direction of bulk or surface wave propagation. These materials are essential used for frequency stabilized oscillators and surface acoustic devices applications [Schwartz., 2009].
1.3.2 Piezoelectric Ceramics

Piezoelectric ceramics are widely used at present for a large number of applications. Most of the piezoelectric ceramics have perovskite structure. This ideal structure consists of a simple cubic cell that has a large cation “A” at the corner, a smaller cation “B” in the body center, and oxygen O in the centers of the faces. The structure is a network of corner-linked oxygen octahedral surroundings B cations.

![Figure 1.3: Crystalline structure of a Barium Titanate (Perovskite structure).](http://cst-www.nrl.navy.mil/lattice/struk/e2_1.html)

For the case of Barium Titanate ceramic, the large cation A is Ba\(^{+2}\), smaller cation B is Ti\(^{+4}\). The unit cell of perovskite cubic structure of Barium Titanate is shown in figure 1.3. The piezoelectric properties of the perovskite-structured materials can be easily tailored for applications by incorporating various cations in the perovskite structure. Barium Titanate (BaTiO\(_3\)) and Lead Titanate (PbTiO\(_3\)) are the common examples of the perovskite piezoelectric ceramic materials [Moheimani & Fleming., 2006, & Schwartz., 2009].
1.3.3 Polymers

The polymers like polypropylene, polystyrene, poly (methyl methacrylate), vinyl acetate, and odd numbernylons are known to possess piezoelectric properties. However, strong piezoelectric effects have been observed only in polyvinylidene fluoride (PVDF or PVF2) and PVDF copolymers. The molecular structure of PVDF consists of a repeated monomer unit (-CF₂-CH₂-)ₙ. The permanent dipole polarization of PVDF is obtained through a technological process that involves stretching and poling of extruded thin sheets of polymer. These piezoelectric polymers are mostly used for directional microphones and ultrasonic hydrophones applications [Schwartz., 2009].

1.3.4 Composites

Piezo-composites comprised piezoelectric ceramics and polymers are promising materials because of excellent tailored properties. These materials have many advantages including high coupling factors, low acoustic impedance, mechanical flexibility, a broad bandwidth in combination with low mechanical quality factor. They are especially useful for underwater sonar and medical diagnostic ultrasonic transducers [Schwartz., 2009].

1.3.5 Thin Films

Both zinc oxide (ZnO) and aluminum nitride (AlN) are simple binary compounds that have Wurtzite type structure, which can sputter-deposited in a c-axis oriented thin films on variety of substrates. ZnO has reasonable piezoelectric coupling and its thin films are widely used in bulk acoustic and SAW devices [Schwartz., 2009].

1.4 PIEZOELECTRIC CONSTITUTIVE EQUATIONS

The constitutive equations describing the piezoelectric property are based on the assumption that the total strain in the piezoelectric material is the sum of mechanical strain induced by
mechanical stress and controllable actuation strain caused by the applied electric voltage. The electromechanical equations for a linear piezoelectric material can be written as [Moheimani., et al, 2006]:

\[ \epsilon_i = S_{ij}^{E} \sigma_j + d_{mi} E_m \]  \hspace{1cm} \text{Eq: 1.1}

\[ D_m = d_{mi} \sigma_i + \varepsilon_{ij}^{E} E_k \]  \hspace{1cm} \text{Eq: 1.2}

Rewriting the above equations in the following form, for sensor applications [4]:

\[ \epsilon_i = S_{ij}^{D} \sigma_j + g_{mi} D_m \]  \hspace{1cm} \text{Eq: 1.3}

\[ E_i = g_{mi} \sigma_i + \beta_{ij}^{D} D_k \]  \hspace{1cm} \text{Eq: 1.4}

where,

Indexes i, j =1,2,..,6

Indexes m, k=1,2,3 refer to different directions within the material coordinate system.

Superscripts D, E & \( \sigma \) represent measurements taken at constant electric displacement, constant electric field and constant stress.

\( \sigma \) = stress vector (N/m\(^2\))

\( \epsilon \) = strain vector (m/m)

E= vector of applied electric field (V/m)

\( \varepsilon \) = permittivity (F/m)

d=matrix of piezoelectric strain constants (m/V)

S=matrix of compliance coefficients (m\(^2\)/N)

D=vector of electric displacement (C/m\(^2\))

g=matrix of piezoelectric constants (m\(^2\)/N)

\( \beta \) = permittivity component (m/F)

The equations [1.1] & [1.2] express the converse piezoelectric effect (for actuator application), while the equations [1.3] & [1.4] express the direct piezoelectric effect (for sensor application).
1.5 PIEZOELECTRIC COEFFICIENTS

The physical meaning of various piezoelectric coefficients (d$_{ij}$, g$_{ij}$, S$_{ij}$, k$_{ij}$, and e$_{ij}$) will be discussed in this section. These coefficients play an important role in the performance of the piezoelectric materials [Moheimani., et al, 2006].

1.5.1 Piezoelectric Constant (d$_{ij}$)

It is defined as the ratio of the strain in j-axis to the electric field applied along the i-axis, when all external stresses are held constant. For example d$_{31}$ is the ratio of strain along axis 1 to the electric field applied along the axis 3.

1.5.2 Piezoelectric Constant (g$_{ij}$)

It is the ratio of strain developed along the j-axis to the charge (per unit area) deposited on electrodes perpendicular to the i-axis.

1.5.3 Elastic Compliance (E$_{ij}$)

It is the ratio of the strain in the i-direction to the stress in the j-direction, given that there is no charge of stress along the other two directions.

1.5.4 Dielectric Coefficient, (e$_{ij}$)

Determines the charge per unit area in the i-axis due to an electric field applied in the j-axis. The relative dielectric constant is defined as the ratio of the absolute permittivity of the material by permittivity of the free space.

1.5.5 Piezoelectric Coupling Coefficient (k$_{ij}$)

This coefficient represents the ability of a piezoelectric material to transform electrical energy to mechanical energy and vice versa. This transformation of energy between mechanical and electrical domains is employed in both sensors and actuators made from piezoelectric materials. The ij index indicates that the stress, or strain is in the direction j, and the electrodes are
perpendicular to the i-axis. The coupling coefficient in terms of piezoelectric constants written as:

\[ k_{ij}^2 = g_{ij} d_{ij} E_p \]  

Eq: 1.5

1.6 PIEZOELECTRIC SENSOR FORMULATIONS

The piezoelectric material has the properties of producing electrical charges when deformed mechanically; this is called direct piezoelectric effect. This characteristic makes piezoelectric transducers suitable for sensing applications. Some of the advantages of piezoelectric sensors are their superior signal to noise ratio, compactness, and easy to embed; and they require only moderate signal conditioning circuitry. This section explains the piezoelectric material’s sensor output voltage formulation [Moheimani., et al, 2006 & Preumont., 2002].

![Piezoelectric sensor diagram](image)

**Figure 1.4: Piezoelectric sensor.**

The resulting electric displacement vector, \( \mathbf{D} \) when a piezoelectric sensor is subjected to a stress field, \( \mathbf{S} \) can be written as shown below (Eq.1.6), assuming applied electric field is zero [Moheimani., et al, 2006 & Preumont., 2002].
\[ D = d \mathbf{S} \]

Eq: 1.6

where, \( d \) is coupling vector.

The displacement vector \( \mathbf{D} \), stress-field vector \( \mathbf{S} \), and the coupling vector \( d \) can be written as shown below:

\[
\mathbf{D} = \begin{bmatrix}
D_1 \\
D_2 \\
D_3
\end{bmatrix}
\]

\[
\mathbf{S} = \begin{bmatrix}
S_1 \\
S_2 \\
S_3 \\
S_{23} \\
S_{31} \\
S_{12}
\end{bmatrix}
\]

\[
d = \begin{bmatrix}
0 & 0 & 0 & 0 & d_{15} & 0 \\
0 & 0 & 0 & d_{15} & 0 & 0 \\
d_{31} & d_{31} & d_{33} & 0 & 0 & 0
\end{bmatrix}
\]

where,

\( D_1, D_2, \) and \( D_3 \) are the electric displacements in the directions 1, 2, and 3 respectively. The generated charge, \( q \) is given in Eq.1.7 [Moheimani., et al, 2006 & Preumont., 2002]:

\[
q = \iiint [D1 \quad D2 \quad D3] \begin{bmatrix}
dA1 \\
dA2 \\
dA3
\end{bmatrix}
\]

Eq: 1.7

where,

\( dA1, dA2, \) and \( dA3 \) are the areas of the differential electrodes in (2-3), (1-3), and (1-2) planes, respectively.

For the case when the strains/stress applied along the direction-1:
\[ D = E d_{31} \varepsilon_{11} \quad \text{Eq: 1.8} \]

\[ q = D dA \quad \text{Eq: 1.9} \]

The voltage generated, \( V \) is given by the expression [Preumont., 2002]:

\[ V = \frac{q}{c} \quad \text{Eq: 1.10} \]

where, \( C \) is the capacitance of the piezoelectric sensor.

Combining equations [1.8 to 1.10] gives:

\[ V = \frac{E d_{31} \varepsilon_{11} dA}{c} \quad \text{Eq: 1.11} \]

From equation [1.11] the following conclusions can be drawn: Sensor voltage output (\( V \)) is directly proportional to the applied strain (\( \varepsilon_1 \)); inversely proportional to the capacitance \( C \) of the piezoelectric sensor; and directly proportional to the material properties such as Young’s modulus and piezoelectric charge coefficient.

1.7 PIEZOELECTRIC ACTUATION

Many configurations have been developed in order to utilize the actuation capability of the piezoelectric material effectively. Piezoelectric bimorph configuration is one of the most widely used transducer configuration to convert mechanical to electrical and electrical to mechanical energy. The piezoelectric bimorphs can be classified into two heterogeneous bimorphs and homogeneous bimorphs. In heterogeneous bimorph one element serves only an elastic function and the other serves two functions electric and elastic where as in the homogeneous bimorphs both the elements serve both functions, electric and elastic. In this section the formulations for heterogeneous bimorph configuration is discussed.
The effective bending moment produced by the heterogeneous bimorph configuration is a function of the thickness ratio of the piezoelectric layer and elastic layer [Cunningham et al., 1997]. With the following assumptions Cunningham et al. derived the equation for the effective bending moment and interfacial stress for a heterogeneous piezoelectric bimorph configuration:

(i) The composite structure is assumed to be very thin
(ii) A linear strain distribution is assumed across the thickness of the composite structure
(iii) The elastic layer is fully covered by piezoelectric layer
(iv) The electric field strength is held constant
(v) The bonding layer thickness is assumed zero (i.e. perfect bonding)

Figure 3 shows a schematic of a heterogeneous piezoelectric bimorph configuration. In the figure D is the distance of neutral axis from the lower edge of the elastic layer.

![Figure 1.5: Piezoelectric layer bonded to the elastic layer](image)

Expression for the D is given by [Cunningham et al., 1997]

$$D = \frac{T_e(1+2ET+ET^2)}{2(1+ET)}$$  

Eq: 1.12

Where, $T = T_p/T_e$ (thickness ratio)
The stress strain relationship for a piezoactuator is given by the equation [Cunningham et al., 1997]

\[
\sigma_p = E_p (\epsilon_p - \Lambda)
\]

Eq: 1.13

\[
= E \frac{\sigma}{T_e} (Y + D) - E_p \Lambda
\]

Eq: 1.14

Where,

\[
\Lambda = \left( \frac{V}{T_p} \right) * d_{31} & \ E = E_p/E_e
\]

The stress strain expression for the elastic layer is given by the following expression [Cunningham et al., 1997]

\[
\sigma_e = E_e \epsilon_e
\]

Eq: 1.15

\[
= \sigma (Y+D) / T_e
\]

The interface stress \( \sigma \) expression can be determined by use of moment equilibrium condition about neutral axis [Cunningham et al., 1997]

\[
\int_{\text{elastic}} \sigma_e \ dA + \int_{\text{piezo}} \sigma_p \ dA = 0
\]

Eq: 1.16

The interface stress [Cunningham et al., 1997], \( \sigma \)

\[
\sigma = E_p \frac{\left[ \frac{\Delta}{2} - T^2 - 2T + 2\frac{D}{T_e} \right]}{\frac{Te}{3} \left[ 1 - 3\frac{D}{T_e} + 3\left( \frac{D}{T_e} \right)^2 + E \left( \frac{T^3 + 3T^2 \left( 1 - \frac{D}{T_e} \right)}{3T^2 \left( 1 - \frac{2D}{tb + \frac{D^2}{T_e^2}} \right)} \right) \right]} + \frac{D}{2} \left[ BT \left( \frac{2D}{T_e} - T - 2 \right) + \left( \frac{3D}{T_e} - 1 \right) \right]
\]

Eq: 1.17

The effective bending moment \( M \) applied to the elastic layer by piezoelectric layer can be expressed as [Cunningham et al., 1997]:
M= \frac{W}{6} \cdot \frac{T_e^2 \varphi}{4}

= \frac{W}{4} \cdot \frac{T_e^2 \varphi}{E_p} \cdot \left[ 1 - 3 \left( \frac{D}{T_e} \right)^2 + 3 \left( \frac{D}{T_e} \right)^4 \right] \left[ \frac{T^3 + 3T^2 \left( 1 - \frac{D}{T_e} \right) + \frac{D^2}{T^2} \left( 1 - \frac{D}{T_e} \right)}{3T^2 \left( 1 - \frac{D}{T_e} \right)^4 + \frac{D^2}{T_e}} \right] + 6D \left[ ET \left( \frac{2D}{T_e} - T - 2 \right) + \left( \frac{2D}{T_e} - 1 \right) \right]

From the equations [1.17 & 1.18] we can conclude that the interface stress and the effective bending moment are the function of the parameters D, the thickness ratio T (T_p/T_e) and also the young’s modulus ratio E (E_p/E_e). D is again the function of T and E. Hence by controlling the value of the parameters T & E one can control the upper value of effective bending moment and interface stress. With an optimum value of the T & E we can achieve maximum effective bending moment and interface stress. This optimum piezoelectric heterogeneous bimorph configuration can be used as an embedded actuator in a smart joint to control the bending stress and forces acting on the joint.

1.8 APPLICATIONS OF PIEZOELECTRIC MATERIALS

The discovery of piezoelectricity generated significant interest within the European scientific community. Subsequently, roughly within 30 years of its discovery, and prior to World War I, the study of piezoelectricity was viewed as a credible scientific activity. The first serious application for piezoelectric materials an ultrasonic submarine detector appeared during World War I was built by Paul Langevin and his co-workers in France. This device was used to transmit a high-frequency chirp signal into the water and to measure the depth by timing the return echo. Since then piezoelectric crystals were employed in many classic applications such as sonar applications, frequency stabilizers, ultrasonic transducers, microphones, accelerometers, microphones, piezo-ignition systems, sensitive hydrophones and ceramic phono cartridges etc [Moheimani., et al, 2006].
Piezoelectric vibration control has shown promise in a variety of applications ranging from consumer/sporting products/satellite/fighter aircraft vibration control systems. Some of the companies like HEAD and K2 have invested in high-performance and novelty items such as composite piezoelectric tennis racquets, skis, and snowboards. These products typically involve the use of a shunted piezoelectric transducer to decrease vibration, which will increase the user comfort, better handling and performance. The next generation hard disk drives may also incorporate piezoelectric vibration control systems in a number of ways [Moheimani & Fleming., 2006].

The piezoelectric materials have been extensively used in the aerospace devices, structural health monitoring, vibration control, and energy harvesting applications. In the aircraft structures application the piezoelectric materials are used in the jet tailfins, helicopter rotor blades, morphing wings and telecommunication satellites. A considerable research effort has been undertaken on the structural control of military aircraft. Piezoelectric materials are also used in the noise control applications which include: suppression of acoustic radiation form underwater submersibles, launch vehicle structural and acoustic noise mitigation, acoustic transmission reduction panels, and active antenna structures. A primary consideration in the design of space structures is the vibration experienced during launch. In future, structures incorporating piezoelectric transducers may form the basis of lightweight, high performance mechanical components for use in space applications. Energy harvesting is another important application area of these materials [Moheimani & Fleming., 2006].

The piezoelectric actuators are also being studied as a potential means of reducing the buffeting loads on twin tail fighter aircraft flying at high angle of attack. The activated piezoelectric actuators will counteract to the torsional and bending stresses induced by the
buffeting loads. In the Figure 1.6 we can see the 1/6\textsuperscript{th} scale active vertical tail model containing the embedded LaRC-MFC \textsuperscript{TM} (Macro Fiber Composite) actuators built at NASA-Langley [Wilkie \textit{et al.}, 2000].

![Image of a model](image1)

Figure 1.6 : 1/6th scale LaRC-MFCTM buffet load alleviation wind tunnel model [Wilkie \textit{et al.}, 2000].

The figure 1.7 shows the design of the shoe energy harvester system, which contains the polyvinylidene fluoride (PVDF) piezoelectric film insert and metal spring with coupled generator system. This PVDF insert in the shoe is used to recover some of the power in the process of walking. The natural flexing of the shoe when walking provides the necessary deflection for generating power from the piezoelectric film insert. The figure 1.8 shows the magic back up, the straps of this back pack are made using a special piezoelectric material called polyvinylidene fluoride (PVDF), generating electrical charges when stress is applied. These nylon-like straps convert that mechanical strain into electrical energy, and researchers have
figured out that if you carry a 100-pound pack and walk at 2-3 mph you can generate 45.6 mW of power. That's enough to the power an iPod, or maybe a head-mounted flashlight. This magic back up can be effectively used for the military applications [Sodano et al., 2007].

Figure 1.7: Shoe energy harvesting system [Starner., 1996]

Figure 1.8: Magic backpack straps power generator [Sodano et al., 2007].
The figure 1.9 shows the piezoelectric linear motor/actuator and piezoelectric Z-axis nano-positioning stage from Pyhsik Instruments. The figure 1.10 illustrates one of the applications where the piezoelectric materials have been used for the structural health monitoring. In this application piezoelectric materials have been used to assess the wear status of the wheel.

Figure 1.9: (a) N 215 Linear piezoelectric motor (Pyhsik Instruments), (b) P-611 piezoelectric Z-axis nano-positioning stage (Pyhsik Instruments).

Figure 1.10: The proposed method for the assessment of the roughness of the wheel. A piezoelectric sensor detects the vibrations of the wheel, leading to an assessment of its wear status [Nuffer & Bein, 2006].
1.7 CONCLUSION

In this chapter emphasis has been made to introduce the readers to the basics of the piezoelectric materials and the various applications of these materials. The wide range applications shown in this chapter gives us an idea about the growing popularity of these materials in various fields. The next chapter gives a brief introduction about the smart structures and the function of piezoelectric materials in smart structures.
CHAPTER 2: SMART JOINT

2.1 INTRODUCTION TO SMART STRUCTURES

A structure is an assembly that serves an engineering function. Smart structures are those which possess characteristics close to, and, if possible, exceeding, those found in biological structures. A smart structure has the ability to respond adaptively in a pre-designed useful and efficient manner to changes in the environmental conditions, as also any changes in its own condition [Vinod., 2007 & Schwartz., 2009].

A smart configuration would be that in which normal loads are taken care of in normal conditions, and the abnormal loads are tackled by activating suitable actuation systems. Even the normal loads, corrosion and other aging effects can render the original passive design unsuitable (even unsafe) with the passage of time. If continuous monitoring can be built into the design through distributed, embedded, smart sensors, timely repairs can be taken up, thus saving costs and ensuring higher degrees of safety. In brief smart structures can monitor their own health and can activate their actuation system depending upon the external loading situations [Vinod., 2007].

Smart structures are gaining the importance in many current and future structural applications, as these structures which can monitor and detect their own integrity and can act as per the surrounding environment situations. These smart structures are capable of sensing and reacting to their environment in a predictable and desired manner, through the integration of various elements, such as sensors, actuators, power sources, signal processors, and communications network. Smart structures may alleviate vibration, reduce acoustic noise, monitor their own condition and environment, automatically perform precision alignments, or
change their shape or mechanical properties on command in a more controlled fashion. Smart structures use the smart materials as their major functional element.

2.2 SMART MATERIALS

Smart materials are the materials which have one or more properties which alter significantly in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields etc. Many smart materials were invented more than 30 years ago, but their development and improvement over the past three decades has led to new, more varied uses of these adaptable materials. Some of the common smart materials are piezoelectric materials, shape memory polymers & alloys, magnetic shape memory alloys, temperature responsive polymers, pH sensitive polymers etc. The property of the smart materials to change their properties in a controlled fashion is used to monitor the health of the structures and detect the various loads acting on the structure. These smart materials have been employed in many important applications, such as aerospace applications, automobile applications, civil engineering structures such as dams, bridges, highways and buildings, health monitoring systems, nondestructive evaluation technologies etc [Schwartz., 2009].

Piezoelectric materials are the most popular smart material, which have been used for many self adaptive smart structures. In general, smart structures are designed in the form of laminated composites and the piezoelectric materials are embedded on these structures.

2.3 SMART JOINT

The piezoelectric materials have been widely used in many important engineering applications including structural health monitoring, sensing, actuation, and energy harvesting. Cheng et al, 2006 used the piezoelectric materials to develop the smart joint systems. The smart joint is a structure which has the piezoelectric materials embedded in them, the integration of piezoelectric
layers with an adjustable electric field can smartly control the peel/shear stress distribution at the bond-line and the stress concentration can be dramatically reduced. By adjusting the applied electric field on the piezoelectric layer in the developed smart joint system, one can produce the additional forces and moments which would act oppositely to those developed internally, thereby alleviating the stress concentration in the joint edges. This would in turn, improve the performance of the adhesively bonded joint [Konka., et al, 2009].

Figure 2.1 gives the details about the position of the high stress concentration regions (highlighted with the circle) in the conventional adhesive bonding joint systems. The high level of stress concentrations in the joint edges (critical locations) is the main reason for the failure of the adhesively bonded joint system. Figure 2.2 illustrates the details of the newly developed smart adhesively bonded joint systems. The newly developed joint system has the piezoelectric materials embedded on them at the critical locations of the joint. By adjusting the applied electric field on the embedded piezoelectric layer in this new joint system, one can produce additional forces and moments which would act oppositely to those developed internally, thereby alleviating stress concentration in the joint edges [Cheng., et al, 2006].

Figure 2.3 illustrates the details of smart joint control system. The main functions of the piezoelectric materials in the smart joint are threefold: (i) to detect the various loads that act on the composite joint; (ii) to produce the force in order to provide counter balancing force to the force acting on the joint and thereby to reduce the stress concentrations in the joint; and (iii) to convert impact energy acting on the joint to electrical power. The plot in the figure 2.3 illustrates reduction in the stress concentration level in the joint by adaptively using the piezoelectric materials [Konka., et al, 2009].
Figure 2.1: The conventional adhesive bonding joint systems (a) Single-lap joint (b) Single-strap joint [Cheng., et al, 2006].

Figure 2.2: Illustrations of the smart adhesive bonding joint systems: (a) Smart single-lap joint (b) Smart single-strap joint [Cheng., et al, 2006].
Figure 2.3: A smart strap joint with piezoelectric materials embedded inside the joint.

2.4 CONCLUSION

In this chapter a brief introduction to the smart structures and smart materials is discussed. Section 2.3 gives the details of the smart joint, which is the main motivation behind this work. Chapter 3 discusses gives the various details of the experiments performed to test the sensing and force generation capabilities of the piezoelectric materials.
CHAPTER 3: EXPERIMENTATION

The sensing and the force generation capabilities of the piezoelectric materials play an important role in the proper functioning of the smart adhesive joint system. Piezoelectric materials should be able to provide the strain amplitude and dynamic information (such as frequency and waveform) at the various points on the structure. By obtaining this kind of information from piezoelectric materials we can monitor the health of the structure continuously and detect the various loads acting on the structure. The main aim of this study is to investigate and compare the sensing and force generation capabilities of the various composite piezoelectric materials in order to use them as an embedded sensor and actuator in the smart joint system. A brief description of the experiments performed is given in this chapter. In the first set of experiments the sensing capability of the piezoelectric materials under various dynamic loading conditions has been investigated. In the second set of experiment the force generation capabilities of the piezoelectric materials were investigated with respect to various input voltages.

3.1 PIEZOELECTRIC COMPOSITES MATERIALS USED FOR EXPERIMENTS

Experiments were performed on three different types of piezoelectric composite products mentioned above. This section discusses the various details & configuration of the piezoelectric composite products used for the experiments. The MFC and the PFC are basically composed of the piezoelectric fibers, whereas the QP is composed of piezoelectric sheets.

3.1.1 MACRO FIBER COMPOSITE (MFC)

MFC was first developed by NASA’s Langley Research Center in 2003. The major advantages of MFC are their high strain energy density, controlled directional actuation, relatively high performance in achieving in controlled actuation, flexibility, conformability, and durability. Due
to the MFC’s construction using PZT fibers, the overall strength of the material is greatly increased when compared to that of the base material [Wilkie., et al, 2000].

Figure 3.1 illustrates the construction details of the MFC. The MFC contains PZT fibers of rectangular cross-section, which gives the maximum contact area between the PZT fibers and the interdigitated electrodes due to the larger surface area when compared to the PZT fibers of circular cross-section, that results in more efficient transfer of electric field to the PZT fibers [Wilkie., et al, 2000]. The MFC piezoelectric module used in our experiments is type M2807 P2 (Smart Materials Corp.). This module contains one layer of PZT fibers, as mentioned above the fibers are of rectangular cross-section (width=350 µm, thickness=175µm). They are of PZT-5A1-Navy- II type material and the properties are shown in the Table 1.

![Figure 3.1: Construction Details of Macro Fiber Composite [Ref: Smart materials corp].](image)
3.1.2 PIEZOELECTRIC FIBER COMPOSITE (PFC)

The PFC has high degree of structural flexibility and comprises of uni-directionally aligned piezoelectric fibers of circular cross-section. The fibers are surrounded by a resin matrix system which provides damage tolerance through load transfer mechanisms. Electrical inputs/outputs are delivered through a separate interdigitated electrode layer [Advanced Cerametrics, Inc.]. The advantages of the PFC are its high strength, conformability, high performance, high flexibility, cost effective, and highly damage tolerant. The PFC module used in our experiments is PFC-W14 type from Advanced Cerametrics, Inc. They are, 250 microns in diameter. The properties of the PFC fibers are shown in Table 1.

![Image: Piezoelectric Fiber Composite (PFC)]

**Figure 3.2: Piezoelectric Fiber Composite (PFC).**

3.1.3 QUICK PACK (QP)

Quick Pack contains two layers of piezoelectric layers, 250 microns of thickness (bimorph configuration). They are surrounded with the Kapton and Epoxy matrix system as a protective layer and this matrix system adds to the flexibility of the overall product [Mide technological corp.]. The Quick Pack modules used are QP22b and QPV22bL (fig: 3.4) from Mide Technological corp. The product QP22b is specially designed for the actuator applications and
QPV22bL is designed for the energy harvesting and sensing applications. The thickness of the piezoelectric sheets is about 250 microns. The base piezoelectric material used for this product is PZT-5H-Navy II type and the properties are shown in Table 1. Figure 3.3 gives the construction details of the Quick pack modules.

![Figure 3.3: Construction detail of Quick packs](image)

![Figure 3.4: Quick Pack modules used for experiment](image)
Table 1: Properties of base piezoelectric material for PFC, QP, and MFC

<table>
<thead>
<tr>
<th>Properties</th>
<th>Units</th>
<th>PFC</th>
<th>QP</th>
<th>MFC</th>
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<tr>
<td>(d_{31}) (strain constant)</td>
<td>m/V or Coul/N</td>
<td>-1.73E-10</td>
<td>-1.75E-10</td>
<td>-1.85E-10</td>
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<tr>
<td>(d_{33}) (strain constant)</td>
<td>m/V or Coul/N</td>
<td>3.80E-10</td>
<td>3.50E-10</td>
<td>4.40E-10</td>
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<tr>
<td>(g_{33}) (voltage constant)</td>
<td>Vm/N</td>
<td>2.50E-02</td>
<td>2.42E-02</td>
<td>2.55E-02</td>
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<tr>
<td>(k_{33}) (coupling factor)</td>
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<td>0.7</td>
<td>0.72</td>
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<tr>
<td>(k_{31}) (coupling factor)</td>
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<td>0.35</td>
<td>0.33</td>
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<tr>
<td>(K) (dielectric constant-1kHz)</td>
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<td>1850</td>
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<tr>
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<td>%</td>
<td>2</td>
<td>1.8</td>
<td>0.012</td>
</tr>
<tr>
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<td>g/cm(^3)</td>
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<td>7.7</td>
<td>7.7</td>
</tr>
<tr>
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<td>350</td>
<td>335</td>
</tr>
<tr>
<td>(C_{11}) (compliance)</td>
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<td>1.44E-11</td>
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<td>(C_{33}) (compliance)</td>
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<td>1.80E-11</td>
<td>2.07E-11</td>
</tr>
</tbody>
</table>

3.2 SENSING CAPABILITY

In this experiment the sensing capabilities of the piezoelectric materials were investigated at three different dynamic loading conditions (tensile, bending, and compression). The most common types of loads that act on joints are usually tensile, compression, and bending. Since the piezoelectric materials will be embedded in a joint in order to detect the loads acting on the joint, hence the responses of these products with respect to these types of loads were required to be investigated.
A Dynamic Mechanical Analyzer (DMA- TA Instruments 2980) was used to provide controlled input dynamic loading. The DMA machine can provide/measure the displacements of micro-level amplitudes, forces of milli-newton level. Piezoelectric products are mounted on the DMA clamps, one end of the piezoelectric material is fixed with one of the clamps and the other end is screwed on to the top of the movable shaft, which is located at the center of the clamps.

Figure 3.5: Block diagram of experimental setup

The movable shaft of the DMA is used to provide the required excitation frequency and input amplitude of dynamic loading case. The output voltage response from the piezoelectric materials is recorded in the computer using the DAQ interface. The details of the experimental setup are shown in Figs. 3.5 & 3.6. Figure 3.7 shows various types of loading conditions imposed on piezoelectric beam configuration. Three different types of loads (bending, tensile, and
compressive) were imposed on the piezoelectric materials by using the dual cantilever (Fig. 3.8), tensile (Fig. 3.9) and compression clamps (Fig. 3.10) of the DMA machine respectively. 

The frequencies are varied from 5.0 Hz to 60 Hz and amplitudes varied from 10µm to 300µm for bending; 1.0 µm to 10µm for longitudinal vibrations; and 5 µm to 15µm for compressive loading. Low amplitude ranges (1.0 µm to 10µm) are selected for longitudinal vibration because inputting amplitudes above these ranges exceeded the maximum permissible strain of the products. The corresponding output voltages from the piezoelectric materials are recorded using a DAQ interface on the computer. By investigating the voltage output response from the piezoelectric material with respect to a certain input loading provides a clear picture
about the capabilities of these piezoelectric materials to sense the above mentioned loading conditions. By following the procedure and experimental setup mentioned above we investigated the sensing capabilities of the piezoelectric materials at various types of dynamic loading conditions. Two kinds of characteristic curves have been obtained (i) constant frequency curves (ii) constant strain curves, from the above experiments. Constant frequency curves are obtained by keeping the frequency of dynamic loading vibration constant and varying the strain levels, where as the constant strain curves are obtained by keeping the strain levels constant and by varying the frequency of dynamic load vibration. The experimental procedure for testing the force generation capability is explained in the next section.

Figure 3.7: Loading conditions (a) Transverse, (b) Longitudinal, (c) Compressive
Figure 3.8: Dual Cantilever Clamp with sample [Ref: DMA user manual]

Figure 3.9: Tensile Clamp [Ref: DMA user manual]
3.3 FORCE GENERATION CAPABILITY

The main aim of this experiment is to measure the amount of force that the piezoelectric materials can generate with various input voltages. In this experiment we investigated the amount of tensile and bending forces produced by these piezoelectric materials. The reason for not using the strain gauges is because the force generation from the piezoelectric material is small and the strain gauges cannot be used for measuring such small forces.

In this experiment the stress relaxation mode of DMA machine is used. A pre-strain is applied initially on the piezoelectric material by using DMA machine and the force required to maintain that initial pre-strain before and after applying the voltage is observed with respect to various input voltage ranging from 1.0 V to 30V. The difference in the values of the force from both cases gives the amount of force produced by the piezoelectric materials by actuation.
Figures 3.11 & 3.12 shows the tensile and dual cantilever clamps of the DMA machine which were used for measuring tensile and bending forces produced by the piezoelectric material.

**Figure 3.11: Tensile Clamp.**

**Figure 3.12: Dual Cantilever Clamp.**
By following the procedure and experimental setup above, we investigated the force generation capabilities of the piezoelectric materials with respect to the change in the electric field applied.

3.4 CONCLUSIONS

This chapter gives the details of experimental setup and the procedure used for the experiments. The experiments were designed to test the sensing and force generation capabilities of the piezoelectric materials. The details of the products (MFC, PFC, & QP) used for the experiments is also illustrated briefly in this section. By following the experimental procedure mentioned in the section 3.2 & 3.3 the sensing and the force generation capabilities of the piezoelectric materials were investigated and compared. A brief discussion on the results of the experiments performed is illustrated in the chapter 4.
CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 RESULTS FROM SENSING CAPABILITIES

As a sensor the following things are required from the piezoelectric sensors: (i) high sensitivity to the low level stress/strains, (ii) linear response, (iii) wide operating frequency. The procedure mentioned in the previous chapter is followed to investigate the presence of required sensor qualities in the piezoelectric sensors. The peak to peak voltage output was recorded with respect to change in the frequency and amplitude of vibration of various modes. The obtained voltage output has been divided by the volume of the original piezoelectric material present in each product, so that the output voltage for each product can be compared with each other.

4.1.1 RESULTS FROM TRANSVERSE / BENDING VIBRATION LOADING

The plots in Figs. 4.1, 4.2, & 4.3 depict the voltage output (millivolts/mm$^3$) response of the PFC, MFC, & QP-V22BL respectively under transverse vibration loading. MFC, PFC, & QP behaved almost linearly to this type of input loading case. The plots 4.4 & 4.5 compare the voltage output (milli volts/mm$^3$) of MFC, PFC, and QP at 5 and 60 Hz frequency of transverse vibration.

From plots in Figs. 4.4 & 4.5 it is evident that QPV22BL has better performance when compared to the other two products, MFC and PFC. Both PFC and MFC show almost similar type of voltage output behavior, linearly increasing with small slope at low frequencies of vibrations; but at higher frequencies PFC performed slightly better than MFC. All these products produced detectable output voltage signals in response to this type of dynamic loading condition without any pre-amplification even at the displacement amplitudes of micrometer level and the voltage output signal were better at higher frequencies when compared to low frequencies of vibrations. The output voltage behavior of the PFC, MFC, and QP has almost linear response with the increase in the displacement amplitude level.
Figure 4.1: Output voltage/volume of piezoelectric material vs. Displacement Amplitude at different frequencies of transverse vibrations of PFC-W14.

Figure 4.2: Output voltage/volume of piezoelectric material vs. Displacement Amplitude at different frequencies of transverse vibrations of MFC-2807-P2.
Figure 4.3: Output voltage/volume of piezoelectric material vs. Displacement Amplitude at different frequencies of transverse vibrations of QPV22BL.

Figure 4.4: Comparison of output voltage response of PFC, MFC & QPV22BL with respect to input displacement amplitude at 5Hz.
This linear behavior & high sensitivity to low domain displacement amplitudes shows their effectiveness as a sensor to detect the bending type of dynamic loading of various frequencies and amplitudes.

4.1.2 RESULTS FROM LONGITUDINAL VIBRATION LOADING

The Figs. 4.6, 4.7, & 4.8 depict voltage output (milli volts/mm$^3$) response of the PFC, MFC, and QP-V22BL respectively under longitudinal vibration at various frequencies. The plots in Figs. 4.9 & 4.10 compare the voltage output (milli volts/mm$^3$) of MFC, PFC and QP at 5 and 60 Hz frequency of longitudinal vibration. The plots in both the figures illustrate the better performance of QP in comparison to both MFC & PFC at 5 Hz, whereas PFC performed slightly better than QP at 60 Hz. And MFC showed significantly lower levels of voltage output.
All these products produced good quality detectable output voltage signals in response to this type loading condition without any pre-amplification even at μm level displacement amplitudes; and the voltage output signal was better at higher frequencies when compared to low frequencies of vibrations. The output voltage behavior of the PFC, MFC, and QPs for various input displacement amplitudes was found to be linear. This linear behavior with respect to the displacement amplitude shows their effectiveness as a sensor to detect the longitudinal type of dynamic loading of various frequencies and amplitudes.

![Figure 4.6: Output voltage/volume of piezoelectric material vs. Displacement Amplitude at different frequencies of longitudinal vibrations (PFC-W14).](image-url)
Figure 4.7: Output voltage/volume of piezoelectric material vs. Displacement Amplitude at different frequencies of longitudinal vibrations (MFC).

Figure 4.8: Output voltage/volume of piezoelectric material vs. Displacement amplitude for different frequencies of longitudinal vibrations (QPV22BL).
Figure 4.9: Comparison of Output Voltage response of MFC, PFC & QPV22BL with respect to input displacement amplitude at 5Hz.

Figure 4.10: Comparison of Output Voltage response of MFC, PFC & QPV22BL with respect to input displacement amplitude at 60Hz.
4.1.3 RESULTS FROM COMPRESSION MODE VIBRATION

The plots in Figs. 4.11, 4.12, & 4.13 depict the voltage output (millivolts/mm\(^3\)) response of the PFC, MFC, and QP-V22BL respectively under compression vibration loading. The plots in 4.14 & 4.15 compare the voltage output (milli volts/mm\(^3\)) of MFC, PFC and QP at 5 Hz and 60 Hz under compression vibration mode. From Fig. 4.14 it is evident that the QP performed better at low frequencies (5 Hz) than both MFC and PFC; and MFC performed slightly better than PFC. MFC’s performance improved slightly at larger displacement amplitudes. QP performed almost two folds at 5Hz frequency. From Fig. 4.15 it can be seen that QP performed better at the beginning and up to a displacement level of 10x10\(^{-3}\) mm and MFC performed better than QP beyond this level at 60Hz. At higher frequencies MFC performed better than PFC.

![Figure 4.11 Output voltage/volume of piezoelectric material vs. Displacement amplitude at different frequencies under Compression mode vibrations for MFC.](image)

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Figure 4.12: Output voltage/volume of piezoelectric material vs. Displacement amplitude for different frequencies of Compression mode vibrations for PFC.

Figure 4.13: Output voltage/volume of piezoelectric material vs. Displacement amplitude for different frequencies of Compression mode vibrations for QPV22BL.
Figure 4.14: Comparison of Output Voltage response of MFC, PFC & QPV22BL with respect to input displacement amplitude at 5Hz.

Figure 4.15: Comparison of Output Voltage response of MFC, PFC & QPV22BL with respect to input displacement amplitude at 60Hz.
It was observed that these composite piezoelectric materials respond well for all three types of vibration modes (transverse, longitudinal, and compression) for all the given input displacement amplitudes. The high sensitivity of these materials to such low micrometer level displacement amplitudes gives an indication about their effectiveness as a sensor. From the above experimental results two types of characteristic curves have been obtained for each piezoelectric material (constant frequency curves and constant strain curves).

4.2 CONSTANT FREQUENCY CURVES

Constant frequency curves are obtained by keeping the frequency of the vibration constant and by changing the strain levels continuously. The voltage o/p due to the change in the strain levels is recorded and voltage o/p vs. strain (%) for a particular frequency is plotted. Constant frequency curves illustrate the sensitivity of the piezoelectric materials to the change in strain levels at constant frequency level.

4.2.1 CONSTANT FREQUENCY CURVES (BENDING STRAIN)

The plots in Figs. 4.16, 4.17, & 4.18 shows the constant frequency curves for PFC, MFC, & QP-V22BL respectively. The r.m.s voltage output (volts/mm³) has been recorded at various bending strain levels while maintaining a constant frequency. From these plots the following conclusions can be drawn: the voltage o/p has almost linear relationship with the applied strain; as the frequency of input vibration is increased the slope of the voltage vs. strain curve increases. These curves show the credibility of these materials to detect the changes in the strain levels when the frequency of i/p dynamic loading is constant.
Figure 4.16: Output voltage/volume of piezoelectric material vs. Strain (%) at different frequencies of transverse vibrations of PFC-W14 (Constant Frequency Curves).

Figure 4.17: Output voltage/volume of piezoelectric material vs. Strain (%) at different frequencies of transverse vibrations of MFC-2807-P2 (Constant Frequency Curves).
Figure 4.18: Output voltage/volume of piezoelectric material vs. Strain (%) at different frequencies of transverse vibrations of QPV22BL (Constant Frequency Curves).

From plots 4.19 & 4.20 it is evident that QPV22BL has better voltage output response when compared to the other two products, MFC and PFC. MFC and PFC have similar voltage output response because both are the piezoelectric fiber composites. At 5 Hz frequency and 0.0467% strain level the voltage o/p from the QP is about 4 times greater than the o/p from the MFC & PFC. Even at higher frequency 60 Hz and the same strain level 0.0467% the voltage o/p from the QP is again about 4 times greater than the o/p from the MFC & PFC. It is observed from the plots 4.16, 4.17, & 4.18 that the QP produces more voltage output response than MFC and PFC at all the frequencies and strain levels of this type of loading condition. This behavior gives us an understanding about the effectiveness of the QP as a sensor. All these products PFC, MFC & QP produced detectable output voltage signals in response to this type of dynamic loading condition without any pre-amplification even at such a low strain level domain (0.003 % to 0.05 %).
Figure 4.19: Performance comparison of PFC, MFC & QP at 5Hz frequency of input vibration and various strain levels.

Figure 4.20: Performance comparison of PFC, MFC & QP at 60Hz frequency of input vibration and at various strain levels.
Figure 4.21: Slope of the constant frequency curves vs. Frequency (Hz) for MFC, PFC and QP.

The plots in the fig.4.21 give us the idea about the sensitivity (Volts/Strain) of the piezoelectric material to the frequency changes. It is evident from these plots is that the slope of the constant frequency curves was increasing with the increase in the frequency. MFC and PFC show the similar kind of slope behavior, as MFC and PFC are the piezoelectric fiber composite products. The slopes of constant frequency curves for QP increases at a constant rate up to 30 Hz frequency and after 30 Hz the slopes increase rate changes. This kind of QP-V22BL’s behavior tells us that the QP-V22BL can distinguish the changes quite effectively up to 30 Hz frequency.

4.2.2 CONSTANT FREQUENCY CURVES (TENSILE STRAIN)

The tensile clamp of the DMA machine is used to apply the tensile strain on the piezoelectric materials. The plots in the figs.4.22, 4.23 & 4.24 shows the constant frequency curves in response to tensile strains. All the products show the linear behavior with respect to change in strains at all the frequency levels. The plots in figs. 4.25 & 4.26 compare the performance of the
MFC, PFC, & QP at 5 & 60 Hz frequency of input vibration and in the strain domain (0.006% to 0.05%). At 5 Hz frequency of input vibration QP produces more voltage o/p in response to the various input strain levels when compared to the other two products, MFC and PFC. Both QP & MFC has almost similar slopes for voltage o/p response at 5 Hz frequency. At 60 Hz frequency of input vibration PFC has more voltage o/p response when compared to the QP & MFC in this type of loading condition.

The plots in the fig. 4.27 illustrate the changes in the sensitivity (Volts/Strain) behavior w.r.t changes in the input frequency of the dynamic loading. It can be observed clearly that for PFC the sensitivity (Volts/Strain) increases at a constant rate with the increase in the input frequency of dynamic loading.

![Diagram](image)

Figure 4.22: Output voltage/volume of piezoelectric material vs. Strain (%) at different frequencies of longitudinal vibrations (Constant Frequency Curves) (PFC-W14).
Figure 4.23: Output voltage/volume of piezoelectric material vs. Strain (%) at different frequencies of longitudinal vibrations (Constant Frequency Curves) (MFC).

Figure 4.24: Output voltage/volume of piezoelectric material vs. Strain (%) for different frequencies of longitudinal vibrations (Constant Frequency Curves) (QPV22BL).
Figure 4.25: Performance comparison of PFC, MFC, & QP at 5Hz frequency of input vibration and various strain levels.

Figure 4.26: Performance comparison of PFC, MFC & QP at 60Hz frequency of input vibration and various strain levels.
QP & MFC shows the similar kind of slope trend behavior. The sensitivity of QP & MFC increases at a constant rate up to 30 Hz frequency and after 30 Hz the sensitivity increase rate changes. This kind of behavior of both of these materials tells us that they can distinguish the changes in frequency quite effectively up to 30 Hz frequency. The use of the same kind of base piezoelectric material is the main reason for observing the same kind of trend behavior in both of these products. The voltage o/p response behavior of MFC, PFC, and QP is linear with respect to the various increases in the strain levels.

4.3 CONSTANT STRAIN CURVES

Constant strain curves are obtained by keeping the strain level constant and increasing the frequency of the vibration continuously. The voltage o/p is recorded with the change in the

Figure 4.27: Slope of the constant frequency curves vs. Frequency (Hz) for MFC, PFC, and QP.
frequency of vibration loading and the voltage o/p vs. frequency has been plotted for each strain level. The constant strain curves illustrate the sensitivity of the piezoelectric materials to the changes in the frequency for a constant strain level.

4.3.1 CONSTANT STRAIN CURVES (BENDING STRAIN)

The plots in figs. 4.28, 4.29, & 4.30 shows the constant strain curves in response to the various frequencies of input vibrations. From these plots it was observed that the slope of the constant strain increases with the increase in the strain levels. The voltage output response of the PFC & QP has almost a linear relationship with frequency change and at all the strain levels. MFC has linear relationship with the frequency change only up to 30Hz of input frequency and after 30Hz the slope of the constant strain curve changes and curve tends to flatten out. This kind of MFC behavior is observed in case of all the strain levels.

Figure 4.28: Output voltage/volume of piezoelectric material vs. Frequency (Hz) at various transverse strain levels (Constant Strain Curves) for PFC.
Figure 4.29: Output voltage/volume of piezoelectric material vs. Frequency (Hz) at transverse strain levels (Constant Strain Curves) for MFC.

Figure 4.30: Output voltage/volume of piezoelectric material vs. Frequency (Hz) at transverse Strain levels (Constant Strain Curves) for Quick Pack-QPV22BL.
The plots in the figs. 4.31 & 4.32 compare the performance of the MFC, PFC, & QP at two different strain levels (0.00659% and 0.0467 %). From these plots it is evident that QPV22BL has the higher sensing voltage output at all the frequencies and strain levels, when compared to the MFC & PFC. Figure 4.33 gives the details about the sensitivity(Volts/Hz) behavior of the MFC, PFC, & QP to detect the changes in the frequency levels with the increase in strain levels. From the plots in the fig. 4.33, it can be observed clearly that for MFC, PFC, & QP the sensitivity(Volts/Hz) increases at a constant rate with the increase in the strain levels, this behavior indicates their effectiveness to detect the changes in the strain levels.

Figure 4.31: Performance comparison of PFC, MFC & QP at 0.00659% Strain level at various frequencies of input vibration.
Figure 4.32: Performance comparison of PFC, MFC & QP at 0.0467127 % Strain level at various frequencies of input vibration.

Figure 4.33: Slope of the constant strain curves vs. Strain (%) for MFC, PFC and QP.
4.3.2 CONSTANT STRAIN CURVES (TENSILE STRAIN)

The plots in the figs. 4.34, 4.35 & 4.36 shows the constant strain curves in response to the various frequencies of input vibrations. From these plots the following conclusions can be drawn: the voltage o/p increases with the increase in the frequency level; increase in the strain levels increases the slope of the voltage vs. frequency curve. These curves show the capability of these materials to detect the changes in the frequency of i/p dynamic loading when input strain levels are maintained constant. The slope of constant strain curves for various strain levels for QP & MFC increases at a constant rate up to 30 Hz frequency and after 30 Hz the slope increase rate changes for all the strain levels. This kind of behavior of both of these materials tells us that they can distinguish the changes quite effectively up to 30 Hz frequency. The use of the same kind of base piezoelectric material is the main reason for observing the same kind of trend behavior in both of these products.

The plots in figs. 4.37 & 4.38 compare the performance of the MFC, PFC, & QP at 0.019% & 0.0519 % strain levels at various frequencies of input vibrations. From these plots it is evident that PFC has better voltage o/p response when compared to the other two products, MFC and QP at both the strain levels (0.019% & 0.0519 % ) and at all frequencies of input vibration. MFC has the lowest voltage output range when compared with PFC and QP. QP & MFC show the similar kind of slope trends i.e. the slopes of the constant strain curves increases continuously up to 30 Hz at a constant rate and after that the slopes increase rate changes. For PFC the slope rate increases continuously at a constant rate with the increase in the frequency of the vibration. From the plots in the fig. 4.39, it can observed clearly that for MFC, PFC, & QP the sensitivity (Volts/Hz) increases at a constant rate with the increase in the strain levels, this behavior indicates their effectiveness to detect the changes in the strain levels.
Figure 4.34: Output voltage/volume of piezoelectric material vs. Frequency (Hz) at different Strain levels of longitudinal type (Constant Strain Curves) PFC.

Figure 4.35: Output voltage/volume of piezoelectric material vs. Frequency (Hz) at different Strain levels of transverse type (Constant Strain Curves) MFC.
Figure 4.36: Output voltage/volume of piezoelectric material vs. Frequency (Hz) at different Strain levels of longitudinal type (Constant Strain Curves) QP.

Figure 4.37: Performance comparison of PFC, MFC & QP at 0.019% strain level.
Figure 4.38: Performance comparison of PFC, MFC & QP at 0.0519% strain level.

Figure 4.39: Slope of constant bending strain curves vs. strain (%) for MFC, PFC and QP.
4.4 RESULTS FROM FORCE GENERATION

The results from the force generation experiments are explained in details in this section. Sections 4.4.1 & 4.4.2 illustrate the bending and tensile force generation capabilities of the piezoelectric materials respectively.

4.4.1 BENDING FORCE GENERATION CAPABILITY

An initial pre-strain of 0.01% is applied on the piezoelectric materials and the force required in maintaining the initial pre-strain is measured with the time, with applying the voltage and without applying the voltage, i.e. with no electric field and with applied electric field. The first 10 minutes in the plots (Figs. 4.40 - 4.42) corresponds to the case when no voltage is applied to the piezoelectric material; and after that, the change in force levels are because of the actuation properties of the piezoelectric materials with the given input voltage. The electric field applied to the piezoelectric material is calculated by dividing the input voltage with the spacing between the electrodes present on the piezoelectric materials. The clamp used for this experiment is the dual cantilever clamp. From Figs. 4.40 to 4.42 it can be seen that the force decreases linearly after 10 min with the application of electric field. This experiment gives the indication of the bending force generation capabilities and the sensitivity of these materials with respect to the applied input voltage. The plots in Figs. 4.40, 4.41, and 4.42 show the bending force generation capabilities of the MFC, PFC, and QP respectively. The bending force produced by the MFC, PFC and QP at a typical value of 30V input electric field are: 6 mN (Fig: 4.40), 4 mN (Fig: 4.41), and 6 mN (Fig: 4.42) respectively. The plots in the figure 4.43 give the details about the bending force generation behavior of the three products with respect to the various input voltages. The bending force produced from MFC, PFC, & QP has almost a linear relationship
with the input voltage applied. Hence the bending force generation capability of the three products is almost at the same level.

Figure 4.40: Bending force vs. Time response of MFC subjected to change in electric field.

Figure 4.41: Bending force vs. Time response of PFC subjected to change in electric field.
Figure 4.42: Bending force vs. Time response of QP22B subjected to change in electric field.

Figure 4.43: The bending force produced vs. Input Voltage.
4.4.2 TENSILE FORCE GENERATION CAPABILITY

For tensile force generation an initial pre-strain of 0.1% is applied on the piezoelectric beam and the force required in maintaining this initial pre-strain is measured with time, with applying the voltage and without applying the voltage. The clamp used for this experiment is the tensile clamp of DMA machine. The first 10 minutes in the plots corresponds to the case when no voltage is applied to the piezoelectric material (hence the curve is flat in that region); and after that flat period, the change in force levels takes place and are due to the applied voltages to the piezoelectric materials. The difference of both these force values with the applied voltage and without the applied voltage gives the amount of the force produced by piezoelectric materials. The plots in figs. 4.44, 4.45, and 4.46 show the tensile force generation capabilities of the MFC, QP, and PFC respectively. In all three figures the slope of the force generated vs. time is linearly decreasing slope. The slope in Fig. 4.44 is almost bimodal type with a larger slope from 10 min to 35 minutes and the slope changes significantly from 35 min to 60 min.

![MFC- Tensile Force](image)

**Figure 4.44**: Tensile force vs. Time response of MFC subjected to the change in the electric field.
Figure 4.45: Tensile force vs. Time response of QP22B subjected to change in the electric field.

Figure 4.46: Tensile force vs. Time response of PFC-W14 subjected to change in the electric field.
The typical values of the tensile forces produced by MFC, PFC, and QP at 30V input are 0.36 (Fig. 4.44), 1 (Fig. 4.45), and 0.5 N (Fig. 4.46) respectively. The plots in the figure 4.47 give the details about the tensile force generation behavior of the three products with respect to the various input voltages. The force produced for all these products have almost linear relationship with the input voltage. Therefore, from the above experiments it is evident that these products produce significant tensile forces when compared to the bending forces; and these could be used effectively as counter-balancing forces at higher input voltages.

![Figure 4.47: Tensile force produced vs. Input voltage.](image)

4.5 CONCLUSIONS

In this chapter emphasis has been made to explain the results obtained from the various experiments performed. The sensing capabilities of all these products were tested for various kinds of dynamic loads of different frequencies and displacement amplitudes. The results of
these experiments confirm that the voltage signals generated from these materials are proportional to the input mechanical strain, with good response to high frequencies, even at micrometer deformation domain. Two kinds of characteristic curves were obtained constant strain and constant frequency curves. The tensile and bending force generation capabilities of these products were tested with respect to the various input electric fields.
CHAPTER 5: CONCLUSIONS AND FUTURE WORK

5.1 CONCLUSIONS

Piezoelectric materials are important functioning elements in the smart joint. The two major functions of the piezoelectric materials in the smart joint are: to act as a sensor to detect the various loads acting on the joint, and to act as an actuator to provide counter balancing force/moments to the external/internal forces acting on the joint. In the present study an experimental characterization of the piezoelectric materials has been done in order to investigate the sensing and force generation capabilities of the piezoelectric materials in order to use them for the smart joint/ smart structure applications.

5.1.1 SENSING CAPABILITIES

The sensing capabilities of all these products were tested for various kinds of dynamic loads of different frequencies and displacement amplitudes. The results of these experiments confirm that the voltage signals generated from these materials are proportional to the amplitudes of mechanical movement, with good response to high frequencies, even at micrometer deformation domain. Two kinds of characteristic curves were obtained constant strain and constant frequency curves. Constant strain curves illustrate the sensitivity of the piezoelectric materials to detect the change in the frequency of the vibration when the input strain level is constant. Constant frequency curves give the details about the sensitivity of the piezoelectric materials to the strain changes when the frequency of the input vibration is constant. All these products have the linear voltage o/p behavior with respect to the input strains. The results of these experiments give us an idea about the applicability of these products in different dynamic loading domains. QP & MFC shows the similar kind voltage output trend behavior in response to the various kinds of dynamic
loading conditions, because of the same kind of the base piezoelectric used for both of these products.

5.1.2 FORCE GENERATION CAPABILITIES

Force generation capability of piezoelectric material is another important feature that is required for reducing the stress concentrations levels inside a joint. The force produced by these materials is used to produce counter balancing force to the external/internal forces produced inside a joint. The bending and the tensile force generation capabilities of the products QP, MFC, and PFC were tested with respect to the various input electric fields. The force generation was observed to be low under the current input conditions.

5.2 FUTURE WORK

The results of these experiments will be used to develop a smart joint system with embedded piezoelectric materials. The smart joint is a high performance joint which will be able to monitor its health continuously and can adaptively reduce the high stress concentrations developed in joint.

5.3 RECOMMENDATIONS

A more elaborated study is required to be conducted in order to investigate the force generation capabilities of these piezoelectric materials. A parametric study is required to be conducted on the various parameters which affect the sensing and the force generation capabilities of these materials. Various configurations of the piezoelectric materials which improve the force generation capabilities are to be studied in detail.
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VITA

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