SMART STRUCTURES AND MATERIALS

SMART SYSTEMS/ STRUCTURES

Definition of Smart Systems/ Structures

The definition of smart structures was a topic of controversy from the late 1970's to the late 1980's. In order to arrive at a consensus for major terminology, a special workshop was organised by the US Army Research Office in 1988, in which '*sensors*', '*actuators*', '*control mechanism*' and '*timely response*' were recognised as the four qualifying features of any smart system or structure (Rogers, 1988). In this workshop, following definition of smart systems/ structures was formally adopted (Ahmad, 1988).

"A system or material which has built-in or intrinsic sensor(s), actuator(s) and control mechanism(s) whereby it is capable of ***sensing*** *a stimulus,* ***responding*** *to it in a predetermined manner and extent, in a* ***short/ appropriate*** *time, and reverting to its original state as soon as the stimulus is removed"*

According to Vardan and Vardan (2000), *smart system* refers to a device which can sense changes in its environment and can make an optimal response by changing its material properties, geometry, mechanical or electromagnetic response. Both the sensor and the actuator functions with their appropriate feedback must be properly integrated. It should also be noted that if the response is too slow or too fast, the system could lose its application or could be dangerous (Takagi, 1990).

Previously, the words 'intelligent', 'adaptive' and 'organic' were also used to characterize smart systems and materials. For example, Crawley and de Luis (1987) defined 'intelligent structures' as the structures possessing highly distributed actuators, sensors and processing networks. Similarly, Professor H. H. Robertshaw preferred the term 'organic' (Rogers, 1988) which suggests similarity to biological processes. The human arm, for example, is like a variable stiffness actuator with a control law (intelligence). However, many participants at the US Army Research Office Workshop (e.g. Rogers et al., 1988) sought to differentiate the terms 'intelligent', 'adaptive' and 'organic' from the term 'smart' by highlighting their subtle differences with the term 'smart'. The term 'intelligence', for example, is associated with abstract thought and learning, and till date has not been implemented in any form of adaptive and sensing material or structure. However, still many researchers use the terms 'smart' and 'intelligent' almost interchangeably (e.g. In the U.S.-Japan Workshop: Takagi, 1990; Rogers, 1990), though 'adaptive' and 'organic' have become less popular.

The idea of 'smart' or 'intelligent' structures has been adopted from nature, where all the living organisms possess stimulus-response capabilities (Rogers, 1990). The aim of the ongoing research in the field of smart systems/ structures is to enable such a structure or system mimic living organisms, which possess a system of distributed sensory neurons running all over the body, enabling the brain to monitor the condition of the various body parts. However, the smart systems are much inferior to the living beings since their level of intelligence is much primitive.

In conjunction with smart or intelligent structures, Rogers (1990) defined following additional terms, which are meant to classify the smart structures further, based on the level of sophistication. The relationship between these structure types is clearly explained in Fig. 1

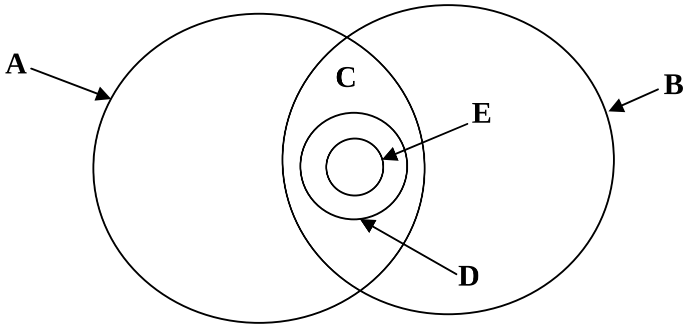
(a) Sensory Structures: These structures possess sensors that enable the determination or monitoring of system states/ characteristics.

(b) Adaptive Structures: These structures possess actuators that enable the alteration of system states or characteristics in a controlled manner.

(c) Controlled Structures: These result from the intersection of the sensory and the adaptive structures. These possess both sensors and actuators integrated in feedback architecture for the purpose of controlling the system states or characteristics.

(d) **Active Structures:** These structures possess both sensors and actuators that are highly integrated into the structure and exhibit structural functionality in addition to control functionality.

(e) **Intelligent Structures:** These structures are basically active structures possessing highly integrated control logic and electronics that provides the cognitive element of a distributed or hierarchic control architecture.



A: Sensory structures; **B:** Adaptive structures; **C:** Controlled structures;
D: Active structures; **E:** Intelligent structures.

Fig. 1 Classification of smart structures (Rogers, 1990).

It may be noted that the sensor-actuator-controller combination can be realised either at the macroscopic (structure) level or microscopic (material) level. Accordingly, we have smart structures and materials respectively. The concept of smart materials is introduced in the following section.

Smart Materials

Smart materials are new generation materials surpassing the conventional structural and functional materials. These materials possess adaptive capabilities to external stimuli, such as loads or environment, with inherent intelligence. In the US Army Research Office Workshop, Rogers et al. (1988) defined smart materials as *materials, which possess the ability to change their physical properties in a specific manner in response to specific stimulus input*. The stimuli could be pressure, temperature, electric and magnetic fields, chemicals or nuclear radiation. The associated changeable physical properties could be shape, stiffness, viscosity or damping. This kind of 'smartness' is generally programmed by material composition, special processing, introduction of defects or by modifying the micro-structure, so as to adapt to the various levels of stimuli in a controlled fashion. Like smart structures, the terms 'smart' and 'intelligent' are used interchangeably for smart materials. Takagi (1990) defined intelligent materials as the materials which respond to environmental changes at the most optimum conditions and manifest their own functions according to the environment. The feedback functions within the material are combined with properties and functions of the materials.

Optical fibres, piezo-electric polymers and ceramics, electro-rheological (ER) fluids, magneto-strictive materials and shape memory alloys (SMAs) are some of the smart materials. Fig. 2 shows the associated 'stimulus' and 'response' of common smart materials. Because of their special ability to respond to stimuli, they are finding numerous applications in the field of sensors and actuators. A very detailed description of smart materials is covered by Gandhi and Thompson (1992).

Active and Passive Smart Materials

Smart materials can be either *active* or *passive*. Fairweather (1998) defined active smart materials as those materials which possess the capacity to modify their geometric or material properties under the application of electric, thermal or magnetic fields, thereby acquiring an inherent capacity to transduce energy. Piezoelectric materials, SMAs, ER fluids and magneto-strictive materials are active smart materials. Being active, they can be used as force transducers and actuators. For example, the SMA has large recovery force, of the order of 700 MPa (10^5 psi) (Kumar, 1991), which can be utilized for actuation. Similarly piezoelectric materials, which convert electric energy into mechanical force, are also 'active'.

The smart materials, which are not active, are called passive smart materials. Although smart, these lack the inherent capability to transduce energy. Fibre optic material is a good example of a passive smart material. Such materials can act as sensors but not as actuators or transducers.

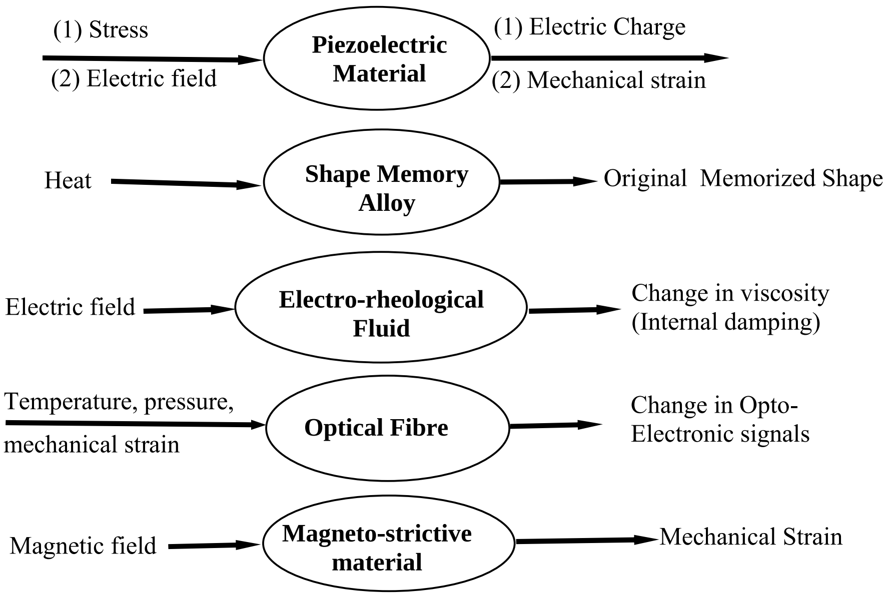


Fig. 2 Common smart materials and associated stimulus-response.

Applications of Piezoelectric Materials

Since this thesis is primarily concerned with piezoelectric materials, some typical applications of these materials are briefly described here. Traditionally, piezoelectric materials have been well-known for their use in accelerometers, strain sensors (Sirohi and Chopra, 2000b), emitters and receptors of stress waves (Giurgiutiu et al., 2000; Boller, 2002), distributed vibration sensors (Choi and Chang, 1996; Kawiecki, 1998), actuators (Sirohi and Chopra, 2000a) and pressure transducers (Zhu, 2003). However, since the last decade, the piezoelectric materials, their derivative devices and structures have been increasingly employed in turbo-machinery actuators, vibration dampers and active vibration control of stationary/ moving structures (e.g. helicopter blades, Chopra, 2000). They have been shown to be very promising in active structural control of lab-sized structures and machines (e.g. Manning et al., 2000; Song et al., 2002). Structural control of large structures has also been attempted (e.g. Kamada et al., 1997). Other new applications include underwater acoustic absorption, robotics, precision positioning and smart skins for submarines (Kumar, 1991). Skin-like tactile sensors utilizing piezoelectric effect for sensing temperatures and pressures have been reported (Rogers, 1990). Very recently, the piezoelectric materials have been employed to produce micro and nano scale systems and wireless inter digital transducers (IDT) using advanced embedded system technologies, which are set to find numerous applications in micro-electronics, bio-medical and SHM (Varadan, 2002; Lynch et al., 2003b). Recent research is also exploring the development of versatile piezo-fibres, which can be integrated with composite structures for actuation and SHM (Boller, 2002).

The most striking application of the piezoelectric materials in SHM has been in the form of EMI technique. This is the main focus of the present thesis and details will be covered in the subsequent sections.

Smart Materials: Future Applications

Seasoned researchers often share visionary ideas about the future of smart materials in conferences and seminars. According to Prof. Rogers (Rogers, 1990), following advancements could be possible in the field of smart materials and structures.

- Materials which can restrain the propagation of cracks by automatically producing compressive stresses around them (Damage arrest).
- Materials, which can discriminate whether the loading is static or shock and can generate a large force against shock stresses (Shock absorbers).
- Materials possessing self-repairing capabilities, which can heal damages in due course of time (Self-healing materials).
- Materials which are usable up to ultra-high temperatures (such as those encountered by space shuttles when they re-enter the earth’s atmosphere from outer space), by suitably changing composition through transformation (thermal mitigation).

Takagi (1990) similarly projected the development of more functional and higher grade materials with recognition, discrimination, adjustability, self-diagnostics and self-learning capabilities.

PIEZOELECTRICITY AND PIEZOELECTRIC MATERIALS

The word 'piezo' is derived from a Greek word meaning pressure. The phenomenon of piezoelectricity was discovered in 1880 by Pierre and Paul-Jacques Curie. It occurs in non-centro symmetric crystals, such as quartz (SiO_2), Lithium Niobate ($LiNbO_3$), PZT [$Pb(Zr_{1-x}Ti_x)O_3$)] and PLZT [$(Pb_{1-x}La_x)(Zr_{1-y}Ti_y)O_3$)], in which electric dipoles (and hence surface charges) are generated when the crystals are loaded with mechanical deformations. The same crystals also exhibit the converse effect; that is, they undergo mechanical deformations when subjected to electric fields.

In centro-symmetric crystals, the act of deformation does not induce any dipole moment, as shown in Fig. 3. However, in non-centro symmetric crystals, this leads to a net dipole moment, as illustrated in Fig. 4. Similarly, the act of applying an electric field induces mechanical strains in the non-centro symmetric crystals.

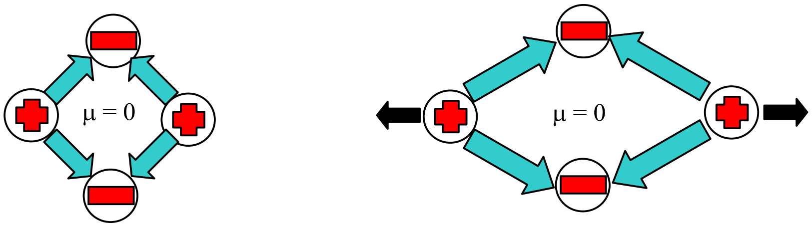


Fig. 3 Centro-symmetric crystals: the act of stretching does not cause any dipole moment (μ = Dipole moment).

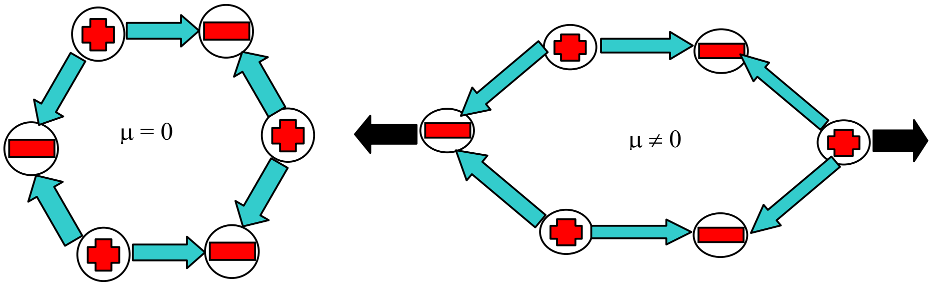


Fig. 4 Noncentro-symmetric crystals: the act of stretching causes dipole moment in the crystal (μ = Dipole moment).

Constitutive Relations

The constitutive relations for piezoelectric materials, under small field condition are (IEEE standard, 1987)

$$D_i = \overline{\varepsilon_{ij}^T} E_j + d_{im}^d T_m \tag{1}$$

$$S_k = d_{jk}^c E_j + \overline{s_{km}^E} T_m \tag{1}$$

Eq. (1) represents the so called *direct effect* (that is stress induced electrical charge) whereas Eq. (2) represents the *converse effect* (that is electric field induced mechanical strain). Sensor applications are based on the direct effect, and actuator applications are based on the converse effect. When the sensor is exposed to a stress field, it generates proportional charge in response, which can be measured. On the other hand, the actuator is bonded to the structure and an external field is applied to it, which results in an induced strain field. In more general terms, Eqs. (2.1) and (2.2) can be rewritten in the tensor form as (Sirohi and Chopra, 2000b)

$$\begin{bmatrix} D \\ S \end{bmatrix} = \begin{bmatrix} \overline{\varepsilon^T} & d^d \\ d^c & \overline{s^E} \end{bmatrix} \begin{bmatrix} E \\ T \end{bmatrix} \tag{3}$$

where [D] (3x1) (C/m^2) is the electric displacement vector, [S] (3x3) the second order strain tensor, [E] (3x1) (V/m) the applied external electric field vector and [T] (3x3) (N/m^2) the stress tensor. Accordingly, [$\overline{\varepsilon^T}$] (F/m) is the second order dielelectric permittivity tensor under constant stress, [d^d] (C/N) and [d^c] (m/V) the third order piezoelectric strain coefficient tensors, and [$\overline{s^E}$] (m^2/N) the fourth order elastic compliance tensor under constant electric field.

Taking advantage of the symmetry of the stress and the strain tensors, these can be reduced from a second order (3x3) tensor form to equivalent vector forms, (6x1) in size. Thus, $[S] = [S_{11}, S_{22}, S_{33}, S_{23}, S_{31}, S_{12}]^T$ and similarly, $[T] = [T_{11}, T_{22}, T_{33}, T_{23}, T_{31}, T_{12}]^T$. Accordingly, the piezoelectric strain coefficients can be reduced to second order tensors (from third order tensors), as [d^d] (3x6) and [d^c] (6x3). The superscripts ‘d’ and ‘c’ indicate the *direct* and the *converse* effects respectively. Similarly, the fourth order elastic compliance tensor [$\overline{s^E}$] can be reduced to (6x6) second order tensor. The superscripts ‘T’ and ‘E’ indicate that the parameter has been measured at constant stress (free mechanical boundary) and constant electric field (short-circuited) respectively. A bar above any parameter signifies that it is complex in nature (i.e. measured under dynamic conditions). The piezoelectric strain coefficient d_{jk}^{c} defines mechanical strain per unit electric field under constant (zero) mechanical stress and d_{im}^{d} defines electric displacement per unit stress under constant (zero) electric field. In practice, the two coefficients are numerically equal. In d_{jk}^{c} or d_{im}^{d}, the first subscript denotes the direction of the electric field and second the direction of the associated mechanical strain. For example, the term d_{31} signifies that the electric field is applied in the direction ‘3’ and the strain is measured in direction ‘1’.

If static electric field is applied under the boundary condition that the crystal is free to deform, no mechanical stresses will develop. Similarly, if the stress is applied under the condition that the electrodes are short-circuited, no electric field (or surface charges) will develop. For a sheet of piezoelectric material, as shown in Fig. 5, the poling direction is usually along the thickness and is denoted as 3-axis. The 1-axis and 2-axis are in the plane of the sheet.

The matrix [d^c] depends on crystal structure. For example, it is different for PZT and quartz, as given by (Zhu, 2003)

$$d^{c} = \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \textbf{(PZT)} \quad \textbf{,} \quad \begin{bmatrix} d_{11} & 0 & 0 \\ -d_{11} & 0 & 0 \\ 0 & 0 & 0 \\ d_{14} & 0 & 0 \\ 0 & -d_{14} & 0 \\ 0 & -2d_{11} & 0 \end{bmatrix} \textbf{(quartz)} \qquad (4)$$

where the coefficients d_{31}, d_{32} and d_{33} relate the normal strain in the 1, 2 and 3 directions respectively to an electric field along the poling direction 3. For PZT crystals, the coefficient d_{15} relates the shear strain in the 1-3 plane to the field E_1 and d_{24} relates the shear strain in the 2-3 plane to the electric field E_2. It is not possible to produce shear in the 1-2 plane purely by the application of an electric field, since all terms in the last row of the matrix [d^c] are zero (see Eq. 2.4). Similarly, shear stress in the 1-2 plane does not generate any electric response. In all poled piezoelectric materials, d_{31} is negative and d_{33} is positive. For a good sensor, the algebraic sum of d_{31} and d_{33} should be the maximum and at the same time, ε_{33} and the mechanical loss factor should be minimum (Kumar, 1991).

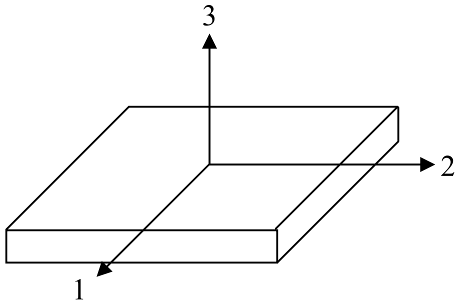


Fig. 5 A piezoelectric material sheet with conventional 1, 2 and 3 axes.

The compliance matrix has the form

$$\overline{s^E} = \begin{bmatrix} \overline{s^E_{11}} & \overline{s^E_{12}} & \overline{s^E_{13}} & \overline{s^E_{14}} & \overline{s^E_{15}} & \overline{s^E_{16}} \\ \overline{s^E_{21}} & \overline{s^E_{22}} & \overline{s^E_{23}} & \overline{s^E_{24}} & \overline{s^E_{25}} & \overline{s^E_{26}} \\ \overline{s^E_{31}} & \overline{s^E_{32}} & \overline{s^E_{33}} & \overline{s^E_{34}} & \overline{s^E_{35}} & \overline{s^E_{36}} \\ \overline{s^E_{41}} & \overline{s^E_{42}} & \overline{s^E_{43}} & \overline{s^E_{44}} & \overline{s^E_{45}} & \overline{s^E_{46}} \\ \overline{s^E_{51}} & \overline{s^E_{52}} & \overline{s^E_{53}} & \overline{s^E_{54}} & \overline{s^E_{55}} & \overline{s^E_{56}} \\ \overline{s^E_{61}} & \overline{s^E_{62}} & \overline{s^E_{63}} & \overline{s^E_{64}} & \overline{s^E_{65}} & \overline{s^E_{66}} \end{bmatrix} \tag{5}$$

From energy considerations, the compliance matrix is symmetric, which leaves only 21 independent coefficients. Further, for isotropic materials, there are only two independent coefficients, as expressed below (remaining terms are zero)

$$\overline{s^E_{11}} = \overline{s^E_{22}} = \overline{s^E_{33}} = \frac{1}{\overline{Y^E}} \tag{6}$$

$$\overline{s^E_{12}} = \overline{s^E_{13}} = \overline{s^E_{21}} = \overline{s^E_{23}} = \overline{s^E_{31}} = \overline{s^E_{32}} = \frac{-\nu}{\overline{Y^E}} \tag{7}$$

$$\overline{s^E_{44}} = \overline{s^E_{55}} = \overline{s^E_{66}} = \frac{1}{\overline{G^E}} \tag{8}$$

where $\overline{Y^E}$ is the complex Young's modulus of elasticity (at constant electric field), $\overline{G^E}$ the complex shear modulus (at constant electric field) and ν the Poisson's ratio. It may be noted that the static moduli, Y^E and G^E, are related by

$$G^E = \frac{Y^E}{2(1+\nu)} \tag{9}$$

The electric permittivity matrix can be written as

$$[\overline{\varepsilon^T}] = \begin{bmatrix} \overline{\varepsilon_{11}^T} & \overline{\varepsilon_{12}^T} & \overline{\varepsilon_{13}^T} \\ \overline{\varepsilon_{21}^T} & \overline{\varepsilon_{22}^T} & \overline{\varepsilon_{23}^T} \\ \overline{\varepsilon_{31}^T} & \overline{\varepsilon_{32}^T} & \overline{\varepsilon_{33}^T} \end{bmatrix} \tag{10}$$

From energy arguments, the permittivity matrix can also be shown to be symmetric, which reduces the number of independent coefficients to 6. Further, taking advantage of crystal configurations, more simplifications can be achieved. For example, it takes following simple forms for monoclinic, cubic and orthorhombic crystals (Zhu, 2003)

$$[\overline{\varepsilon^T}] \quad = \quad \underset{\textbf{monoclinic}}{\begin{bmatrix} \overline{\varepsilon_{11}^T} & 0 & \overline{\varepsilon_{31}^T} \\ 0 & \overline{\varepsilon_{22}^T} & 0 \\ \overline{\varepsilon_{13}^T} & 0 & \overline{\varepsilon_{33}^T} \end{bmatrix}} \;, \; \underset{\substack{\textbf{orthorhombic} \\ \textbf{(e.g. PZT)}}}{\begin{bmatrix} \overline{\varepsilon_{11}^T} & 0 & 0 \\ 0 & \overline{\varepsilon_{22}^T} & 0 \\ 0 & 0 & \overline{\varepsilon_{33}^T} \end{bmatrix}} \;, \; \underset{\textbf{cubic}}{\begin{bmatrix} \overline{\varepsilon_{11}^T} & 0 & 0 \\ 0 & \overline{\varepsilon_{11}^T} & 0 \\ 0 & 0 & \overline{\varepsilon_{11}^T} \end{bmatrix}} \tag{11}$$

Commercial Piezoelectric Materials

Previously, piezoelectric crystals, which used to be brittle and of large weight, were used in practice. However, now the commercial piezoelectric materials are available as ceramics or polymers, which can be cut into a variety of convenient shapes and sizes and can be easily bonded.

(a) Piezoceramics

Lead zirconate titanate oxide or PZT, which has a chemical composition $[\mathrm{Pb}(\mathrm{Zr}_{1-x}\mathrm{Ti}_x)\mathrm{O}_3)]$, is the most widely used type piezoceramic. It is a solid solution of lead zirconate and lead titanate, often doped with other materials to obtain specific properties. It is manufactured by heating a mixture of lead, zirconium and titanium oxide powders to around 800-1000°C first to obtain a perovskite PZT powder, which is mixed with a binder and sintered into the desired shape. The resulting unit cell is elongated in one direction and exhibits a permanent dipole moment along this axis. However, since the ceramic consists of many such randomly oriented domains, it has no net polarization. Application of high electric field aligns the polar axes of the unit cells along the applied electric field, thereby reorienting most of the domains. This process is called ***poling*** and it imparts a permanent net polarization to the crystal. This also creates a permanent mechanical distortion, since the polar axis of the unit cell is longer than other two axes. Due to this process, the material becomes piezoelectrically transversely isotropic in the plane normal to the poling direction i.e. $d_{31} = d_{32} \neq d_{33}$; $d_{15} = d_{24}$, but remains mechanically isotropic (Sirohi and Chopra, 2000b).

PZT is a very versatile smart material. It is chemically inert and exhibits high sensitivity of about 3μV/Pa, that warrants nothing more sophisticated than a charge amplifier to buffer the extremely high source impedance of this largely capacitive transducer. It demonstrates competitive characteristics such as light weight, low-cost, small size and good dynamic performance. Besides, it exhibits large range of linearity (up to electric field of 2kV/cm, Sirohi and Chopra, 2000a), fast response, long term stability and high energy conversion efficiency. The PZT patches can be manufactured in any shape, size and thickness (finite rectangular shapes to complicated MEMS shapes) at relatively low-cost as compared to other smart materials and can be easily used over a wide range of pressures without serious non-linearity. The PZT material is characterized by a high elastic modulus (comparable to that of aluminum). However, PZT is somewhat fragile due to brittleness and low tensile strength. Tensile strength measured under dynamic loading is much lower (about one-third) than that measured under static conditions. This is because under dynamic loads, cracks propagate much faster, resulting in much lower yield stress. Typically, G1195 (Piezo Systems Inc., 2003) has a compressive strength of 520 MPa and a tensile strength of 76 MPa (static) and 21 MPa (dynamic) (Zhou et al., 1995). The PZT materials have negative d_{31}, which implies that a positive electric field (in the direction of polarization) results in compressive strain on the PZT sheet. If heated above a critical temperature, called the *Curie temperature*, the crystals lose their piezoelectric effect. The Curie temperature typically varies from 150^{o}C to 350^{o}C for most commercial PZT crystals. When exposed to high electric fields (>12 kV/cm), opposite to the poling direction, the PZT loses most of its piezoelectric capability. This is called *deploing* and is accompanied by a permanent change in the dimensions of the sample.

Due to high stiffness, the PZT sheets are good actuators. They also exhibit high strain coefficients, due to which they can act as good sensors also. These features make the PZT materials very suitable for use as collocated actuators and sensors. They are used in deformable mirrors, mechanical micropositioners, impact devices and ultrasonic motors (Kumar, 1991), sonic and ultrasonic sensors, filters and resonators, signal processing devices, igniters and voltage transformers (Zhu, 2003), to name only a few. For achieving large displacements, multi layered PZT systems can be manufactured, such as stack, moonie and bimorph actuators.

However, due to their brittleness, the PZT sheets cannot withstand bending and also exhibit poor conformability to curved surfaces. This is the main limitation with PZT materials. In addition, the PZT materials show considerable fluctuation of their electric properties with temperature. Also, soldering wires to the electroded piezoceramics requires special skill and often results in broken elements, unreliable connections or localized thermal depoling of the elements. As a solution to these problems, active piezoceramic composite actuators (Smart Materials Corporation), active fibre composites (Massachusetts Institute of Technology) and macro fibre composites, MFCs (NASA, Langley Centre) have been developed recently (Park et al., 2003a). The MFCs have been commercially available since 2003. These new types of PZTs are low-cost, damage tolerant, can conform to curved surface and are embeddable. In addition, Active Control eXperts, Inc. (ACX), now owned by Mide Technology Corporation, has developed a packaging technology in which one or more PZT elements are laminated between sheets of polymer flexible printed circuitry. This provides the much robustness, reliability and ease of use. The packaged sensors are commercially called QuickPack® actuators (Mide Technology Corporation, 2004). These are now widely used as vibration dampers in sporting goods, buzzer alerts, drivers for flat speakers and more recently in automotive and aerospace components (Pretorius et al., 2004). However, these are presently many times expensive than raw PZT patches.

(b) Piezopolymers

The most common commercial piezopolymer is the Polyvinvylidene Fluoride (PVDF). It is made up of long chains of the repeating monomer ($-CH_2-CF_2-$) each of which has an inherent dipole moment. PVDF film is manufactured by solidification from the molten phase, which is then stretched in a particular direction and poled. The stretching process aligns the chains in one direction. Combined with poling, this imparts a permanent dipole moment to the film. Because of stretching, the material is rendered piezoelectrically orthotropic, that is $d_{31} \neq d_{32}$, where '1' is the stretching direction. However, it still remains mechanically isotropic.

The PVDF material is characterized by low stiffness (Young's modulus is 1/12th that of aluminum). Hence, the PVDF sensors are not likely to modify the stiffness of the host structure due to their own stiffness. Also, PVDF films can be shaped as desired according to the intended application. Being polymer, it can be formed into very thin sheets and adhered to curved surfaces also due to its flexibility. These characteristics make PVDF films more attractive for sensor applications, in spite of their low piezoelectric coefficients (approximately 1/10th of PZT). It has been shown by Sirohi and Chopra (2000b) that shear lag effect is negligible in PVDF sensors.

Piezo-rubber, which consists of fine particles of PZT material embedded in synthetic rubber (Rogers, 1990), has appeared as an alternative for PVDF. The piezo-rubber shows much higher electrical output due to larger thickness, which is not possible in PVDF. The piezo-rubber is used in piezoelectric coaxial cable as a vehicle sensor. It has much longer life and is immune to rain water.

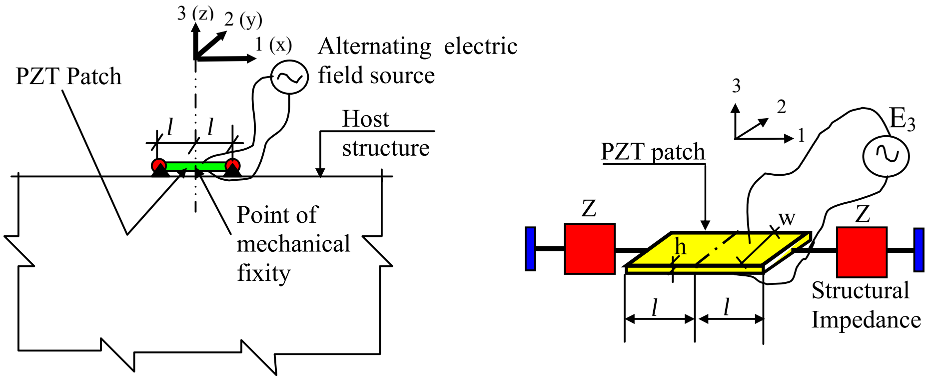
PIEZOELECTRIC MATERIALS AS MECHATRONIC IMPEDANCE TRANSDUCERS (MITs) FOR SHM

The term *mechatronic impedance transducer* (MIT) was coined by Park (2000). A mechatronic transducer is defined as a transducer which can convert electrical energy into mechanical energy and vice versa. The piezoceramic (PZT) materials, because of the direct (sensor) and converse (actuator) capabilities, are mechatronic transducers. When used as MIT, their electromechanical impedance characteristics are utilized for diagnosing the condition of the structures and the same patch plays the dual roles, as an actuator as well as a sensor. The technique utilizing the PZT based MIT for SHM/ NDE has evolved during the last nine years and is called as the *electro-mechanical impedance* (EMI) technique in the literature. The following sections describe the various aspects of this technique in detail.

Physical Principles

The EMI technique is very similar to the conventional global dynamic response techniques described previously. The major difference is with respect to the frequency range employed, which is typically 30-400kHz in EMI technique, against less than 100Hz in the case of the global dynamic methods.

In the EMI technique, a PZT patch is bonded to the surface of the monitored structure using a high strength epoxy adhesive, and electrically excited via an impedance analyzer. In this configuration, the PZT patch essentially behaves as a



(a) (b)

Fig. 6 Modelling PZT-structure interaction.

(a) A PZT patch bonded to structure under electric excitation.

(b) Interaction model of PZT patch and host structure.

thin bar undergoing axial vibrations and interacting with the host structure, as shown in Fig. 6 (a). The PZT patch-host structure system can be modelled as a mechanical impedance (due the host structure) connected to an axially vibrating thin bar (the patch), as shown in Fig. 6(b). The patch in this figure expands and contracts dynamically in direction '1' when an alternating electric field E_3 (which is spatially uniform i.e. $\partial E_3/\partial x = \partial E_3/\partial y = 0$) is applied in the direction '3'. The patch has half-length '*l*', width 'w' and thickness 'h'. The host structure is assumed to be a skeletal structure, that is, composed of one-dimensional members with their sectional properties (area and moment of inertia) lumped along their neutral axes. Therefore, the vibrations of the PZT patch in direction '2' can be ignored. At the same time, the PZT loading in direction '3' is neglected by assuming the frequencies involved to be much less than the first resonant frequency for thickness vibrations. The vibrating patch is assumed infinitesimally small and to possess negligible mass and stiffness as compared to the host structure. The structure can therefore be assumed to possess uniform dynamic stiffness over the entire bonded area. The two end points of the patch can thus be assumed to encounter equal mechanical impedance, Z, from the structure, as shown in Fig. 2.8 (b). Under this condition, the PZT patch has zero displacement at the mid-point (x= 0), irrespective of the location of the patch on the host structure. Under these assumptions, the constitutive relations (Eqs. 1 and 2) can be simplified as (Ikeda, 1990)

$$D_3 = \overline{\varepsilon_{33}^T} E_3 + d_{31} T_1 \qquad (13)$$

$$S_1 = \frac{T_1}{\overline{Y^E}} + d_{31} E_3 \qquad (14)$$

where S_1 is the strain in direction '1', D_3 the electric displacement over the PZT patch, d_{31} the piezoelectric strain coefficient and T_1 the axial stress in direction '1'. $\overline{Y^E} = Y^E(1+\eta j)$ is the complex Young's modulus of elasticity of the PZT patch at constant electric field and $\overline{\varepsilon_{33}^T} = \varepsilon_{33}^T(1-\delta j)$ is the complex electric permittivity (in direction '3') of the PZT material at constant stress, where $j = \sqrt{-1}$. Here, η and δ denote respectively the mechanical loss factor and the dielectric loss factor of the PZT material.

The one-dimensional vibrations of the PZT patch are governed by the following differential equation (Liang et al., 1994), derived based on dynamic equilibrium of the PZT patch.

$$\overline{Y^E}\frac{\partial^2 u}{\partial x^2} = \rho\frac{\partial^2 u}{\partial t^2} \tag{15}$$

where 'u' is the displacement at any point on the patch in direction '1'. Solution of the governing differential equation by the method of separation of variables yields

$$u = (A\sin\kappa x + B\cos\kappa x)e^{j\omega t} \tag{16}$$

where κ is the wave number, related to the angular frequency of excitation ω, the density ρ and the complex Young's modulus of elasticity of the patch by

$$\kappa = \omega\sqrt{\frac{\rho}{\overline{Y^E}}} \tag{17}$$

Application of the mechanical boundary condition that at x = 0 (mid point of the PZT patch), u = 0 yields B = 0.

Hence, strain in PZT patch $$S_1(x) = \frac{\partial u}{\partial x} = Ae^{j\omega t}\kappa\cos\kappa x \tag{18}$$

and velocity $$\dot{u}(x) = \frac{\partial u}{\partial t} = Aj\omega e^{j\omega t}\sin\kappa x \tag{19}$$

Further, by definition, the mechanical impedance Z of the structure is related to the axial force F in the PZT patch by

$$F_{(x=l)} = whT_{1(x=l)} = -Z\dot{u}_{(x=l)} \tag{20}$$

where the negative sign signifies the fact that a positive displacement (or velocity) causes compressive force in the PZT patch (Liang et al., 1993, 1994). Making use of Eq. (2.14) and substituting the expressions for strain and velocity from Eqs. (2.18) and (2.19) respectively, we can derive

$$A = \frac{Z_a V_o d_{31}}{h\kappa\cos(\kappa l)(Z + Z_a)} \tag{21}$$

where Z_a is the short-circuited mechanical impedance of the PZT patch, given by

$$Z_a = \frac{\kappa wh\overline{Y^E}}{(j\omega)\tan(\kappa l)} \tag{22}$$

Z_a is defined as the force required to produce unit velocity in the PZT patch in short circuited condition (i.e. ignoring the piezoelectric effect) and ignoring the host structure.

The electric current, which is the time rate of change of charge, can be obtained as

$$\bar{I} = \iint_A \dot{D}_3 dxdy = j\omega \iint_A D_3 dxdy \tag{23}$$

Making use of the PZT constitutive relation (Eq. 13), and integrating over the entire surface of the PZT patch (*-l* to *+l*), we can obtain an expression for the electromechanical admittance (the inverse of electro-mechanical impedance) as

$$\bar{Y} = 2\omega j \frac{wl}{h}\left[(\overline{\varepsilon_{33}^T} - d_{31}^2 \overline{Y^E}) + \left(\frac{Z_a}{Z + Z_a}\right) d_{31}^2 \overline{Y^E}\left(\frac{\tan \kappa l}{\kappa l}\right)\right] \tag{24}$$

This equation is same as that derived by Liang et al. (1994), except that an additional factor of 2 comes into picture. This is due to the fact that Liang et al. (1993, 1994) considered only one-half of the patch in their derivation.

In the EMI technique, this electro-mechanical coupling between the mechanical impedance Z of the host structure and the electro-mechanical admittance $\bar{Y}$ is utilized in damage detection. Z is a function of the structural parameters- the stiffness, the damping and the mass distribution. Any damage to the structure will cause these structural parameters to change, and hence alter the drive point mechanical impedance Z. Assuming that the PZT parameters remain unchanged, the electromechanical admittance $\bar{Y}$ will undergo a change and this serves as an indicator of the state of health of the structure. Measuring Z directly may not be feasible, but $\bar{Y}$ can be easily measured using any commercial electrical impedance analyzer. Common damage types altering local structural impedance Z are cracks, debondings, corrosion and loose connections (Esteban, 1996), to which the PZT admittance signatures show high sensitivity. Contrary to low-frequency vibration techniques, damping plays much more significant role in the EMI technique due to the involvement of ultrasonic frequencies. Most conventional damage detection algorithms (in low-frequency dynamic techniques), on the other hand are based on damage related changes in structural stiffness and inertia, but rarely in damping (Kawiecki, 2001).

It is worthwhile to mention here that traditionally, in order to achieve self-sensing, a complicated circuit was warranted (Dosch et al., 1992). This was so because in the traditional approach, an actuating signal was first applied and the sensing signal was then picked up and separated from the actuating signal. But due to the high voltage, and also due to the strong dependence of the capacitance on temperature, the signal was mixed with the input voltage as well as noise and was therefore not very accurate. The EMI technique, on the other hand, offers a much hassle free, simplified, and more accurate self-sensing approach.

At low frequencies (<1/5 th of the first resonant frequency of the PZT patch), the term (tanκl/κl) → 1. This is called as 'quasi-static sensor approximation' (Giurgiutiu and Zagrai, 2002), and for this condition, Eq. (24) can be simplified as

$$\overline{Y} = 2\omega j \frac{wl}{h}\left[\overline{\varepsilon_{33}^{T}} - d_{31}^{2}\overline{Y_{11}^{E}}\left(\frac{Z}{Z + Z_a}\right)\right] \tag{25}$$

The electromechanical admittance $\overline{Y}$ (unit Siemens or ohm^{-1}) consists of real and imaginary parts, the *conductance* (G) and *susceptance* (B), respectively. A plot of G over a sufficiently wide band of frequency serves as a diagnosis signature of the structure and is called the *conductance signature* or simply *signature*. Fig. (7) shows the typical conductance and susceptance plots for a PZT patch bonded on to the bottom flange of a steel beam (Bhalla et al., 2001). The sharp peaks in the conductance signature correspond to structural modes of vibration. This is how the conductance signature identifies the local structural system (in the vicinity of the patch) and hence constitutes a unique health-signature of the structure at the point of attachment.

Since the real part actively interacts with the structure, it is traditionally preferred over the imaginary part in the SHM applications. It is believed that the imaginary part (susceptance) has very weak interaction with the structure (Sun et al., 1995).

Therefore, all investigators have so far considered it redundant and have solely utilized the real part (conductance) alone in the SHM applications.

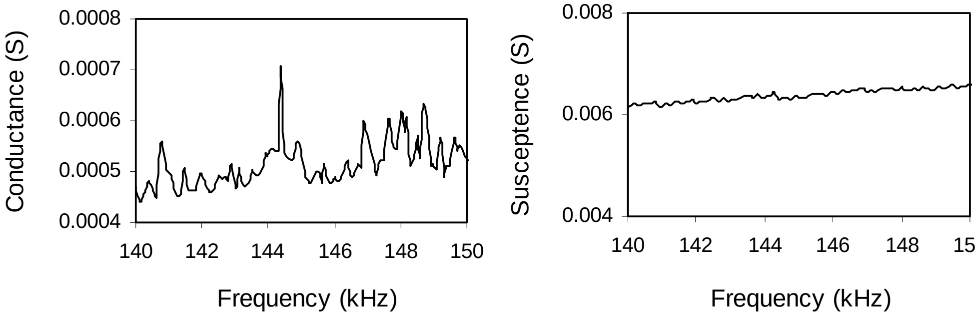


Fig. 7 Conductance and susceptance plots of a PZT patch bonded to bottom flange of a steel beam.

Method of Application

In the EMI technique, a PZT actuator/ sensor patch is bonded to the surface of the structure (whose health is to be monitored) using high strength epoxy adhesive. The conductance signature of the patch is acquired over a high frequency range (30-400 kHz). This signature forms the benchmark for assessing the structural health. At any future point of time, when it is desired to assess the health of the structure, the signature is extracted again and compared with the benchmark signature.

The signature of the bonded PZT patch is usually acquired by means of commercially available impedance analyzers, such as HP 4192A impedance analyzer (Hewlett Packard, 1996). The impedance analyzer imposes an alternating voltage signal of 1 volts rms (root mean square) to the bonded PZT transducer over the user specified preset frequency range (for example 140-150 kHz in Fig. 7). The magnitude and the phase of the steady state current are directly recorded in the form of conductance and susceptance signatures in the frequency domain, thereby eliminating the requirements of domain transforms. Besides, no amplifying device is necessary. In fact, Sun et al. (1995) reported that higher excitation voltage has no influence on the conductance signature, but might only be helpful in amplifying weak structural modes.

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