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Research on Smart Materials & Structures

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ABSTRACT

Piezoelectric materials appealing for use in smart structures as sensors and actuators instantaneously transform mechanical energy to electrical energy and contrariwise. They remember configurations and guarantee them when subject to stimulus, have superb electromechanical coupling characteristics and outstanding frequency response .Innumerous utilization of smart structures technology to diverse physical systems have progressed to actively control shape, aeroelastic stability, noise, damping, vibration and stress distribution. In this article the research activities of piezoelectric materials for smart structures is grouped into characterization, formulation, analysis, applications & debonding in aid in future research activities in any of the grouped class.

INTRODUCTION

The beauty of Smart materials is such that the very same material can act as a sensor and actuator as well. Whereas the sensor by piezoelectric or electrostrictive effect does involve the transformation of mechanical variable force or displacement into quantifiable electrical quantity, alternatively the actuator via converse or indirect piezoelectric effect involves a conversion of the electrical signal into force or useful displacement The qualities of performing both actuation and sensing are uniquely being exhibited by ferroelectric materials.

Ferroelectricity: An impetuous electric polarization exhibited by certain materials and that polarization is revertible under execution of an electric field, traditionally the characteristic of dielectric crystals. When electric field is applied, the charged particles of crystal tend to dislocate being loaded by the electrostatic forces. The direction of polarization can be reverted with a change in dimensions when being subjected to the coercive level of an electric field opposite to the polarized orientation, during this instability phase abrupt shape changes occur with changes from one crystal state to another and electrostatic forces rearranging the location of negative and positive charges. The cluster polycrystalline is composed of several fundamental crystals in a way that polarized direction of each and every crystal differ from the other that constitute the aggregate, resulting in a polycrystalline which is not polarized at the global level. On subjecting the material to an electric field at the coercive level each individual crystal switches its polarized direction along the applied field and material gets polarized, on withdrawing the electric field the material retains a degree of polarization and remains polarized with individual crystal poling orientations mostly aligned along the coercive field direction. For electric field variation in a cyclic fashion, the polarization manifest hysteresis loop implying a loss of energy.

Ferroelectricity is thus an electrical property wherein a material gets polarized upon experiencing a nearby electric field. Polarization is displacement of certain ions in a structure in response to an external field. In dielectrics (insulators) all charges are attached to a specific atom or molecule in a tight leash all they can do is move a bit within the atoms/molecules. Ferroelectric materials retain this state even after the removal of an electric field, they own the average dipole moment per unit cell (spontaneous and abrupt polarization).The direction of polarization is reversible as a result of the reason that ferroelectric polar structure is, in fact, a slightly distorted nonpolar structure.

This distortion leads to nonlinear dielectric behaviour. These crystals though do not have an inversion Centre, yet they have a specific polar axis. They belong to a group of polar dielectrics. Their spontaneous polarization can be toggled upon application of an electric field and is exhibited in an explicit manner in P-E hysteresis loop. These undergo a phase transition from paraelectric phase at high temperature into ferroelectric phase a low temperature through Curie temperature. Above the Curie temperature ferroelectric crystals lose their ferroelectric properties and tend to become paraelectric materials with centrosymmetric crystallography and with barely any spontaneous polarization. Ferroelectrics have very high dielectric constants at relatively low applied electric field frequencies. In order to improve properties of ferroelectric ceramics we chemically modify them by doping which can be either addition of donor dopants to create cation vacancies with impurities like in a PZT the replacement of Pb2+ with higher valence dopants like Bi3+ or La3+ and Ti4+(Zr4+) with Nb5+ or Ta5+,which lead to reducing aging ,lower coercive fields, increased dielectric constant, high piezoelectric coupling etc., there crystals after being doped with higher valence dopants are known as soft ferroelectrics. On the contrary when being doped with lower valence dopants or addition of acceptor dopants to create anion vacancies known as hard ferroelectrics like Pb2+ with Na+ or K+ and Ti4+ (Zr4+) with Mg2+ or Fe3+ for PZT, which would exhibit lower electrical resistivity, lower dielectric

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constants, lower dielectric losses and higher coercive fields. The soft ferroelectrics result with having low melting or decomposition temperatures, water soluble and mechanically soft. The hard ferroelectrics developed at high temperatures are water-insoluble and mechanically hard. Another classification of ferroelectrics is uniaxial ferroelectrics and multiaxial ferroelectrics, uniaxial ferroelectrics crystals polarize along one axis only and multi-axial ferroelectrics polarize along various axes. In general, hard ferroelectrics are multiaxial and soft are uniaxial.

Soft ferroelectrics normally have a complex molecular structure and include Sodium potassium tartrate tetrahydrate (NaKC4H4O64H2O) or Rochelle salt, Potassium dihydrogen phosphate (KH2PO4 or H2KO4P) and Guanidine aluminum sulphate hexahydrate (CN3H6)Al(SO4)2•6H2O) or GASH. The structural characteristics of hard (oxide) ferroelectrics are well-organized and crystallize usually into perovskite structure, labelled after the mineral (Calcium Titanate).

PYROELECTRICITY

In some crystals, temporary voltage appears upon being cooled or heated. The change in temperature changes the positions of atoms to some degree within the crystal leading to polarization which results in generating a potential across the crystal. It is found in crystals like Gallium nitride (GaN), Cesium nitrite (CSNo3), polyvinyflourides (PVF), tourmaline etc. First reference of pyroelectricity comes from writings of Theophrastus in 314 BC. However properties of tourmaline were re-described by Johann George Schmidt in 1707.David Brewster bestowed the effect in 1824, the name it is known by today. Woldemar Voigt in 1897 and subsequently William Thomson in 1878 developed theories for explaining the phenomenon of pyroelectricity. Every ferroelectric material is pyroelectric but the converse is not true.

ELECTROSTRICTION AND PIEZOELECTRICITY

Electrostriction: - A second order effect that occurs in dielectric materials and produces a change in shape (deformation) of the material on application of an electrical field. The relation between Electrostrictive strain and vector field being quadratic. This process is irreversible, occurs in all dielectric materials, spawned by electrical domains that are randomly oriented, the electrical domains get aligned by applied electric field ensuring elongation in the field direction and reducing the thickness of materials orthogonal to the direction of an electric field as unlike ends of the domains pull each other. There is a centrosymmetric relation between field and deformation.

Technically valuable qualities of materials are piezoelectric and electrostrictive ceramics, which comprise of haphazardly positioned grains partitioned by grain boundaries. These are cost effective and offer comparable piezoelectric and electrostrictive properties. A piezoelectric material on deformation develops electric dipoles resulting in a potential difference. The reason for developing dipoles is lack of Centre of symmetry (anisotropy).This effect is reversible, if a potential difference is applied to such a material it gets deformed. An important point to note is piezoelectric strains are much higher than electrostrictive strains. Piezoelectric crystals being brittle and slightly have larger weight paved way for available piezoceramics which can be sliced into a variety of desirable sizes and shapes and is effortlessly bondable. A piezoelectric system is converted into an intelligent system wherein a sensor and actuator are mutually secured via integrated electronics with intellect capabilities. In order to express piezoelectric properties, the crystal should belong to one of 20 non centrosymmetric crystallographic class.

Piezoelectricity was discovered in1880 by Jacques Curie and Pierre Curie, however, the term piezoelectricity was coined by W.G. Henkel in 1881.G.Lippman discovered the reverse process that is to say on an application of electric field mechanical stresses could be developed in 1880. Which was experimentally proven by Curie brothers in 1881.

Piezoelectric materials can be natural or synthetic. Natural occurring crystals include quartz, topaz, silk, wood etc. While as synthetic are quartz like ceramic polymers and composites. Out of 32 piezoelectric crystal structures, these are further grouped into seven sub-classes as cubic, orthorhombic, hexagonal, trigonal, monoclinic, tetragonal, and triclinic. All of these are elastic in nature, triclinic is anisotropic, orthorhombic is orthotropic material and cubic is anisotropic material. And out of 32, only 20 piezoelectric crystal structures show piezoelectric properties and out of those 20, a mere of 10 such sub-classes are polar that is to say show natural unschooled polarization in the absence of mechanical stress due to existing electric dipole moment amalgamated in their unit cells. The other ten crystal structures are non-polar that is to say polarization transpire only after application of mechanical load.

There are various types of ceramics manufactured by humans with perovskite crystal structure, one of the fundamental crystal lattice structure e.g. Barium titanate BaTiO3, Lead titanate PbTiO3, and Lead Zirconium Titanate Pb[ZrxTi1-x)O3] has perovskite structure. The chemical structure is ABO3 type.Wherin A is typically Pb(Ba), the large size metal ion and B ordinarily Ti(Zr), denotes small size metal ion an illustrated in figure 1.2 Formation of piezoelectric ceramics require mixing of suitable powders of constituent metal oxides in apt ratio, the mixture is heated to around 800-1000 degree Celsius to obtain consistency. Which is then mixed with an organic binder and shaped into structural elements with requisite forms (rods, discs, plates etc.).These elements are discharged as per particular time and temperature program in the course of which powder particles coalesce into solid mass by means of heating and achieves a dense crystalline structure. The elements upon cooling are sculptured or cropped to desired requirements and electrodes are put across appropriate surfaces. Above Curie temperature which is 150-350 degree Celsius for most of the piezo-ceramics, each ceramic element reveal a cubic symmetry with zero dipole moment, in the phase known as paraelectric phase. At temperatures below Curie temperature, it manifests into a rhombohedral or tetragonal symmetry with a dipole moment, this is the ferroelectric phase. At about 106V/m applied electric field to a ferroelectric polycrystalline it passes via Curie temperature, thus spontaneous polarization starts to exist, aligning polarization vectors in more or less uniform direction. This phenomenon is known as polling. After polling a net polarization is established in the ceramic element. At this very point, on application of mechanical stress, the extent of polarization will decrease or increase and will exhibit distinctive piezoelectric behaviour. Piezocomposite materials are an updated version of present piezoceramic. These are classified into two piezopolymers wherein material is dipped in the electrically passive matrix (like PZT immersed in epoxy matrix) and piezocomposites which are in turn made of two piezoceramic materials (like BaTiO3) fibers fortifying a PZT matrix. There exist many crystals having piezoelectric properties, piezoelectric properties get revealed in them as a result of the influence of electromagnetic fields on matter. Piezoelectric materials can be divided into two classes: polar and non-polar piezoelectrics. For example, Pb5Ge3O3, PZT, BaTiO3, are polar piezoelectrics, and Bi12GeO20, KH2PO4, TeO2, Bi12SiO20, are non-polar piezoelectrics. The non-zero dipole moment per unit volume of polar piezoelectric materials (ferroelectrics) in contrast to non-polar piezoelectrics is the only difference between the two and hence polar piezoelectrics possess spontaneous and abrupt polarization. The piezoelectric modules of polar materials are substantial according to the classical theory of piezoelectricity than those of non-polar materials and in fact, the difference that exists between polar and non-polar piezoelectrics.

RELATION: PIEZOELECTRIC, PYROELECTRIC AND FERROELECTRIC MATERIALS

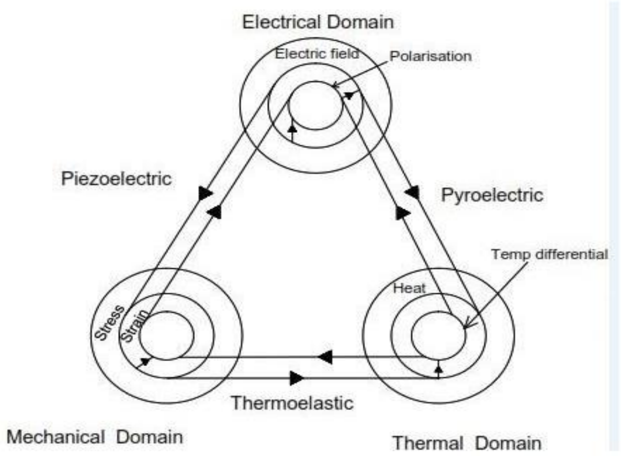
All pyroelectric materials are piezoelectric in nature but not all piezoelectric materials are pyroelectric. However ferroelectric forms a subset of the set of pyroelectricity, as they are polar materials in which the direction of the polar axis can be changed on employment of an electric field and as a result they are both pyroelectric and piezoelectric. As many of the largest pyroelectric and piezoelectric effects occur in ferroelectric materials, they have become very important technologically.

Lead Zirconium Titanate (PZT) a piezoceramic with a chemical composition [Pb(Zr1-x Tix)O3)], is a solid solution of lead zirconate and lead titanate, generally doped with other materials to generate definite properties and is obtained by heating a mixture of oxide powders of lead, zirconium and titanium to about 800 to 10000 C first to get a perovskite PZT powder, which is then mixed with binder and sintered into the desired shape. The resultant unit cell is elongated in one of the directions and exhibit a permanent dipole moment along this axis. Domain is defined as a miniscule region within the ceramic which have same direction of polarization, Since the ceramic, however consist of many randomly oriented domains, it has no net polarization, Polarization is created by process of polling where in a material when subjected to high potential difference at very high temperature above its Curie temperature in a particular direction followed by abrupt cooling in order to retain the deformation caused in the crystal. This effect is utilized when a PZT is bonded to a structure inducing positive or negative bending moment. One key factor in polling is the temperature at which polling is performed. As domain wall motion is thermally activated, the polling process is often performed at an elevated temperature to propel a higher degree of domain reorientation, leading to larger polarization and higher piezoelectric coefficient.

A higher coefficient of piezoelectricity, high coupling factor and lofty Curie temperature Tc makes material desirable for broader band of piezoelectric applications. In some of the applications piezoelectric materials are required to operate at extremely higher temperatures. A lot needs to be done in order to make suitable piezoelectric materials with higher Curie temperatures (Tc). Since available piezoelectric materials are expected to undergo thermal degradation and faster aging when subjected to soaring temperatures. Degradation of piezo electrical properties due to loss of polarization is called thermally activated aging.

Minimization of ageing effect restricts application of materials till half of their curie temperatures.

PZT is a very handy and versatile material. It is chemically dormant and exhibits very high sensitivity. The sensing capability of a PZT patch is utilized in sensing conductance to monitor health of a structure. Key features include low cost, small size, dynamic performance, and fast response, almost unending stability, long range of linearity and high energy conversion efficiency. PZT patches of any shape, size or thickness can be manufactured at a relatively low cost and can be utilized over a broad range of pressures without serious non-linearity. Since it is characterized by a high value of modulus of elasticity. If heated above Curie temperature which varies from 150-350 degree Celsius ferroelectric effect vanishes in the crystals. It can also lose piezoelectricity when subjected to high electric fields above 12 kV/cm reverse to polling direction (depolling) and can lead to permanent change in the dimension of sample. PZT patches are great actuators owing to their high stiffness. Their use vary from single to multi-layered PZT systems e.g. deformable mirrors, mechanical micro positioners, biomorphic actuators. Their brittle character makes them prone to poor conformability to curved surfaces and bending and fluctuation of electrical properties with temperature is another limitation.



Basically three kinds of physical behaviour prevail in a Ferroelectric crystal. They are piezoelectricity, pyroelectricity and thermo-elasticity related as shown in above figure.

The three domains driving each other basically depict the basic effect. However, in every instance there is the minimum of one other way over which the process can occur, of course the coupling coefficients are assumed to be non-zero for that specific process for the crystal or material to be considered. The roundabout effects are called secondary effects.

Piezo layers are either sandwiched between metallic layers or bonded on top and bottom of metallic layer. These act as both mechanical strain sensors and electrically activated actuators as well. These laminated structures have been analyzed for sensing, actuation and shape control. The research articles include characterization, formulation, structural analysis, vibration and noise control application and debonding analysis that occur during application.

CHARACTERISATION OF PIEZOELECTRIC MATERIALS

Devonshire, A.F., [1, 2] did substantial studies of piezoelectric material (BaTiO3) Barium Titanate. He articulated free energy expression as a function of polarization and strain, he gauged crystal transition during thermal changes. Dielectric constants, Strain, internal energy and self-polarization as a function of temperature have been tabulated. Using these relation, estimates of material coefficients have been acquired and are related with experimental observation.

Bechman, R., [3] used resonant method to determine the elastic and piezoelectric constants of Barium Titanate ceramics, bars, plates and disks. He acquired analytically electro mechanical coupling factor of this material by use of measured material constants.

Kahn et al. [4] obtained a characteristic relation to elaborate the changes of magnitudes of polarization vectors with respect to direction of an externally applied uniaxial stress in Lead Zirconate Titanate. The process of material samples for the experimental determination of material characteristics d33 and d31 has been determined, Outcome of his experiments displayed a coherence with the theoretically drawn response. For instance value of piezoelectric shear coefficient was obtained. The calculated d15 when compared with measured values have shown a very good correlation.

Takahashi,T., [5] documented the complications included in polling of Lead Titanate ceramics wherein he detailed the sintering process, the polling characteristics and piezoelectric properties of the material.

Yarlagadda et al.,[6] gave an experimental overview of heat capacity, heat generation and thermal conductivity. It has been seen in the temperature range as low as 22K the heat capacity of PZT-5H is half the heat capacity of PZT-4S whereas PZT-4S has double the heat capacity of PZT-5H at 155K.Also the thermal conductivity of PZT-5H is half thermal conductivity of PZT-4S in the temperature range of 15-300K.Additionally it was also found under similar operating conditions there is approximately two third loss in the dielectric properties of PZT-4S which is a hard piezoceramic than in PZT-5H which is a soft piezoceramic.

Dutta et al. [7] made several samples of Lead Zirconate Titanate with varying ratios of Zr/Ti and analysed the effects of including Lanthanum and Bismuth in the PZT piezoceramis.He measured dielectric constants and loss factor. He also showed how far material properties are effected with change in temperature.

A comparative studies of assessing the material properties by the formulation given in IEEE standards [8] and a three dimension finite element analysis of material sample has been demonstrated.

Rogers and Giurgiutiu [9] have chalked out exhaustive study of power and energy characteristic of PZT, electrostrictive (PMN) and magnetostrictive (TERFENOL) solid state actuators. PZT and Terfenol actuators have been found to have ample amount of hysteresis losses while electrostrictive actuators have zero loss. In this paper, the primary equations of piezoelectricity and piezomagntism have been applied for the study of these actuators. This study gives important performance data of these actuators and their electro-mechanical conversion efficiency.

Chopra and Sirohi [10] have produced the application of piezoceramic actuators for developing the rotor systems which is smart enough. For AC as well as DC excitations free strain reaction of piezoceramic actuators have been investigated experimentally. Nonlinear hysteretic consequences and phase lag of strain reaction viz a viz applied loading have been obtained. These guys also addressed issue of accidental depolling and repolling (the appropriate method of repolling).

Agrawal [11] analysis the disintegrating characteristic features of relaxor ferroelectric materials. These materials vary from regular ferroelectric materials since they have very high dielectric constants and the electrostriction effects. Additionally these display a peak in dielectric constant upon varying temperature and operational frequency.

Using Laser ablation deposition method, Lanthanum modified Lead Titanate with 20% Lanthanum content (PLT20) have been prepared. Thermal annealing process was used to achieve crystallization. Using the thin films the effect of Lanthanum the pyroelectric and dielectric properties have been investigated in [12] the pyroelectric materials have been seen to have low dielectric constants and high detectivity figures of merit. Thus making them unbeatable formed pyroelectric sensors in high performance infrared detectors. Takayama et al. [13] have demonstrated the fabrication and basic properties of one and two dimensional pyroelectric infrared sensors which can be used for thermal imaging and identification of objects. The fabricated array sensors have been exposed to infrared radiation and their performance characteristic have been gauged. Thus after obtaining a relation between the temperature of infrared radiating object and output voltage of sensor, the two are correlated.

Seo and Kim [14] studied the link between applied potential and activation method of EAPap actuators. It has been noticed that paper with soft wood have favourable properties for EAPap as compared to other paper. A tip deflection of 3 mm has been achieved in a 30 mm long paper beam with 2 X 106 V/mm actuation voltage. Supple speakers, materials with active good absorbing qualities and device with smart control shape have been prepared by EAPaps.

ELECTROTHERMOELASTIC FORMULATION

The foundation of thermodynamic theory of simple material was laid by Coleman [15].A material which is considered simple is characterised as a continuous sequence wherein the stress at a specified interval of time is governed by previous strain applied. In order to fabricate the thermo-elastic problem theory, he utilized the basic principles of physics viz conservation of energy, conservation of mass, conservation of linear and angular momentum etc.

The governing equation of thermo-elasticity are derived from the conjecture of dwindling memory (deformation and temperature consummated in the remote past has minimal effect on current values of stress, entropy, heat flux and energy than deformation and temperature which happened in the latest past).

Boundary conditions were deduced by Eringen and Suhubi [16], constitutive equations and basic field equations for a simple micro-elastic solid, taking into considerations rotations and 'micro' deformations. The duo have also taken care of inertial spin, surface tension higher order effects and stress moments in their formulation. Eringen [17] has deducted constitutive equations, boundary conditions and equation of motion for a micro-polar fluid. These fluids are effected by micro rotational motions and spin inertia. Hence these type of fluids can support couple stresses and distributed body couples. Fluid equations have been acquired for density, velocity and micro-rotation vector. Mindlin [18] has derived equations with two dimensions for vibrations of piezoelectric crystal at higher frequency taking into consideration, electric potential, mechanical displacement and temperature change. Field variable have been extended to thickness in terms of power series. These field variable have been incorporated in a integral equation instead of putting them in variational form of virtual work.

An energy dissipation function has also been inserted in the integral equation. Unique theory has been employed to find the unique solution of a single layer piezo plate for unknown field variable.

A microscopic theory for the dynamic response of polycrystalline ferroelectric materials have been exhibited by Chen and Peerey [19].Their formulation comprises of the effect of the change in magnitude of electric dipoles and orientation of domains leading to energy loss. The constitutive relation contain the history of the evolution of the temperature, strain and the electric field.

Generalised thermo-elasticity theory applicable for piezoelectric materials have been revealed by Chandrasekharaiah [20].The main thrust was on articulation for the generation of finite speed thermal signals. After Lagrangian formulation of continuum mechanics, Pak and Hermann [21] has derived governing equations, constitutive relations and the boundary conditions for an elastic dielectric material. The interaction between electric field and polarisation in represented as a stress tensor denoted as Maxwell stress tensor. This phenomenon brings forth an equilibrium equation of a nonlinear body force term.

Tierstern [22] applied preliminary conservation laws of continuum physics to a macroscopic model in order to deduct the non-linear governing equations of electro-thermo elasticity. His presumption comprised of a simple material with overlapping inertia upon each other. He also deducted equilibrium equations via balancing forces, separating electronic continuum from material continuum under effect of external electric field. Applying the laws of thermodynamics to a continuum model, he derived the constitutive equations. He obtained exact boundary conditions using variational formulation, He highlighted that the objectives of interaction between electric field and material polarization is to render the stress tensor non symmetric and initiate in the equilibrium equation a non-linear body force term.

Kalpakidis and Massalas [23] have elaborated the electro-thermo elastic formulation of Tiersten [22] by introducing quarter pole electric moments and the dependence of rate of change of absolute temperature with respect to time in the constitutive relations. They made their formulation on the basis of inequality in entropy production and invariable of the first law of thermodynamics. Under rigid body rotation and translation. Taking the approach of Tiersten [22],Venkatesan and Upadhyay [24] have displayed the analysis of the smart structure using electro thermoelastic formulation. The effects of interaction between and polarisation and electric field have been reflected.

Chen and Montgomery [25] presented a microscopic theory based on domain switching under the influence of an external electric field to model the butterfly loop and the hysteresis loop observed in ferroelectric materials. The butterfly loop is observed in the variation of strain with respect to electric field and the hysteresis loop is observed when polarization is varied with respect to electric field. A non-linear rate law relating the alignment of dipoles with the direction of electric field has been formulated. Using the constitutive relations of the stress and electric displacement along with rate law, the authors have constituted hysteresis loop have been correlated with experimental results.

Bassiouny et al [26] exhibited a thermodynamical formulation capable of predicting electro-mechanical hysteresis effects in ferroelectric ceramics. This theory applies thermodynamic interval variables able to model both electric and plastic hysteresis effects. This is brought about by formulating evolution equation for residual electric polarisation, plastic strain and both electrical and mechanical hardening. Some of the samples have been investigated to evaluate the piezoelectric and electrostrictive couplings.

Formulation for polarisation reversal in piezoelectric materials have been presented by Zhang and Rogers [27].A ferroelectric material comprises of millions of domains, each of domain have thousands of unidirectional dipoles which are randomly oriented with regard to each other. On the application of strong DC electric field, polarisation vectors in domains get reoriented along the external field known as domain switching. This domain switching dynamics applies to model the hysteresis effects. Combination of phenomenological part and the microscopic properties have revealed to be good way to elaborate the non-linear induced strain field behaviour and electromechanical hysteresis.

Jha et al., [28] have devised a mathematical paradigm for hysteresis behaviour of piezoelectric materials. The very paradigm considers the effects of temperature, pressure and amplitude of the electric field on the shape of hysteresis curve.

Using Helmholtz free energy second and first law of thermodynamics an expression of entropy production rate for ferroelectric hysteresis process has been derived by Crawley, E.F.,[29].A distribution process has been assumed for domain orientation and respective distribution parameter are selected as the internal state variables. Using this formulation they have sculptured the hysteresis effects in ferroelectric materials.

Last two decades the demand of designing and development of smart structure has been alarmingly increased, a holistic research activity have been observed in the open literature on the analysis of smart structure. Broadly classified into three basic classes-studies dealing with beams, plates and shells. A detailed summary on smart technology is briefed in Chopra, I., [30].and described implementation of smart technology to rotor system of helicopter in detail.

An overview of recent development in smart structures aimed at alleviating aero elastic response in helicopters has been elaborated by Friedmann, P.P., [31].In addition he exhibited the scaling laws associated with small scale model to full scale configuration.

STRUCTURAL ANALYSIS OF BEAMS

Experimental progress of a Cantilever beam containing piezoelectric actuators as an element and its analysis was established by Crawley and Louis[32].They have entailed the manufacture of smart beams minutely.

Various dynamic and static experimentation has been carried out utilizing distinct test specimen and their analysis was compared theoretically. Hence it was thereby drawn that embedded or surface mounted piezo patch segments were preferable because these curb the propagation of damage more than continuous piezo patches reason being it is possible to control separately effect of individual piezo patch on structural response.

Mujundar et al. [33] have brought forth the summary of investigations done on bimorph actuators and smart beams. For different actuation voltages the static response of deformation has been taken. The experimental results were counter checked with analytic results and the results were very well correlated.

Zhang and Sun [34] have submitted theoretical formulation of an adaptive beam actuation issue in both shear mode (aluminium beams sandwiched with piezopatchs) and extensive mode (piezo patch on bottom and top of aluminium core). Using variational laws, the principle electro elastic equations have been deducted. Axial stress in piezoelectric material in shear mode actuation present is minuscule small reason being the piezoelectric material located at the neutral axis of the beam. On the contrary in extension mode actuation, axial stress is very large again for the very reason of piezopatch being farther away from the neutral axis Shear mode actuation is preferred because the piezoelectric material cannot start greater axial stresses attributing to its brittle nature. Aldraihem and Ahmad [35] have evolved analytical models and achieved absolute solutions for smart beams with piezoelectric actuators for the cases of shear and extension mode actuation. Jordan canonical form using state space approach, the problem of beam bending stands solved. Minor difference are noticed in the extension-mode actuation case whereas Major difference has been noticed between deflections for the first order beam theory for the shear mode actuation of a smart beam.

Shen [36] has made a finite element model beam with multiple piezo patches for actuation and sensing of a smart beam which is inspired by Timoshenko beam theory including shear deformation effects. Using variations laws, governing equation and boundary conditions are formed. Cantilever piezoelectric bi-morph beam has been analysed. Under static and dynamic conditions. The problem of sensing in smart Cantilever beam with multiple patches has also been sorted.

Robbins and Reddy [37] have put to use of layer wise displacement theory to examine piezoelectricity actuated beams. The outcomes from this survey were correlated with the conventional shear deformation theory with higher order and the requirement of multi-layer modelling for cross sections with non-homogenous nature is carried out.

Bengeddou, A., [38] have displayed a formulation for finite element in order to analyze adaptive sandwich beam for shear/extension actuation mechanism. Timenshenko's beam bending theory has been utilized for the thick host Euler-Bernoulli's beam theory for outer materials to explain the transverse shear of the core. A beam element with four mechanical degrees of freedom per mode has been used. The degrees of freedom have been taken as the transverse displacement and its derivative along span, relative and mean axial displacements. The deformation of the cantilever beam under extension actuation (surface bonded piezo patches on the cantilever beam) and shear mode actuation (piezo core sandwiched between metallic strips) has been measured. It is the shear mode actuation which happens to be less vulnerable to debonding problems. Hence for firm beams extension mode actuation is least preferred than that of shear actuation mechanism. Upon computing bending natural frequencies, these have been found to be higher for extension mode actuation mechanism. A beam finite element has been made for laminated beams with piezo layers in [39].It is five nodded beam element with electric potential and mechanical displacement rotations as nodal degrees of freedom. The displacement and stress variations along the length of the beam have been obtained for both mechanical and electrical loading of the beam. Natural frequencies of the beam have been obtained for two cases.

(i) Including the electrical DOF and (ii) without electrical DOF.

Incorporation of electrical degrees of freedom lowers the natural frequencies of the beam.

An overall three dimensional large deformation piezoelectric thermo-viscoelastic formulation was designed by Hilton et al [40].The very design takes into consideration anisotropy of materials thermo viscoelasticity and piezoelectricity. Thermal expansion, curving and aging effects have been included in the anisotropic nonlinear viscoelastic constitutive relations. The induced potential in the piezopatch of a smart cantilever has been evaluated under both static and dynamic loading at the tip of the beam.

Tzou and Ye [41] have displayed a 3-D piezo thermoelastic thin hexahedron finite element with three integral DOF using variational formulation. For a single piezo patch steel cantilever beam, Electro-thermoelastic analysis has been carried out. Thermal influences on the sensing and control of PZT steel laminated cantilever beam have been studied. Numerical analysis reveal temperature fluctuations remarkably effect the electrical potential distribution on sensor and actuator piezoelectric layers are significant.

Copper and Pilkey [42] have developed a systematic solution technique for the thermoelastic problem of a beam with temperature distribution of arbitrary quasi-static which creates a wholesome shear and transverse normal stresses. Using temperature distribution and stress resultants, the stress distribution on a cross section are calculated. The results of the technique are correlated with three dimensional thermo elastic solution to reflect the efficiency of the proposed solution method.

A description of the mesh free point interpolation technique has been submitted by Liu et al.[43]. Static deflection of bi-morphed beams under an external actuation voltage has been acquired. These results when examined with the traditional finite element method using Abacus and results have developed a good comparison. These editors have also surveyed the dynamics of composite plate with piezo actuators.

Ryu and Wang [44] have measured the actuation effectiveness of the surface bonded piezo patches in curved beams under static conditions. The influence of interfacial peeling stresses have been incorporated in the formulation. Parametric investigations has been done to evaluate the effects of radius of the curved beam. Young's modulus of the bonding layer and thickness of bonding layers,piezo actuators and base structure. Piezoelectric patch is assumed to be a point moment actuator and thereby the actuation authority has been drawn. Analytical results have been correlated with experimental data. The results depicts interfacial peeling stress has a key role for this base structures.

Thakkar and Ganguli [45] have put to use Hamilton's principle to draw the torsion of isotropic rotor blades with surface bonded piezoceramic actuators and non-linear equations of motion for elastic bending. The effect of torsional way of rotating beams and piezoceramic actuation in bending have been examined. It is revealed that effectiveness of the piezoactuation in bending and twisting of the beam is reduced by the centrifugal stiffening effect during rotation of beam.

Cesnik,et al..[46]-[47], have elaborated the modelling and analysis of an active twist helicopter rotor blade with embedded piezo-composite materials.

STRUCTURAL ANALYSIS PLATES

Yu, Y. Y., [48] introduced methodical summary of non-linear and linear model of piezoelectric and elastic plates. The author has framed an extensive dialogue on the variational formulation of the equation of motion in 3-D piezoelectricity and elasticity.Applications of non-linear and linear dynamical modelling of piezoelectric layers and elastic laminates have been explained.

Ha, S. K., et al. [49] has submitted formulation of a finite element for the dynamic and static response analysis of laminated composite beams and plates having distributed piezoelectric ceramic patches.The response analysis was performed on both mechanical and electrical loadings.

The theoretical formulation was based on based on variational principle.An eight node 32-degrees of freedom brick element have been made. They have differentiated the theoretical results with the experimental data for bending and twisting of a composite cantilever plate.The results have exhibited a favourable accord.

In order to form a consistent plate finite element model for coupled composite plates with induced strain actuation, Hong and Chopra [50] have used formulation based on modified thin classical laminated plate-theory. Actuators at arbitrary location have been carved as surplus plates fully integrated to the substrate laminae. Composite plates with bending twist coupling and extension twist coupling have been designed. Static tests have been performed utilizing mechanical loading and induced strain. The theoretical results are compared with measured data for twist and bending deformation.They have achieved unison results between theory and experiment for the case of twist induced due to extensional strain using piezo actuation. In the case of twist due to bending, theoretically assumed induced twist is noticed to be relatively lower than the experimental results.

Reddy et al.[51] showed static linear analysis of square and simply supported plates having piezoelectric lamiae. Coupled electro-elastic formulation has been utilized to form layer-wise finite element model for solving the actuation problem. It has been noticed that primary variables (u,υ,w,ϕ) are promptly anticipated than the secondary variables$(\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{yz}, \sigma_{xz}, \sigma_{xy}, D_x, D_y$ and $D_z)$.Cubic approximation of the fields variables along the thickness direction accurately anticipate primary as well as secondary variables.

Maiti, D. K., [52] have designed assembled with plate bending elements layered piezoelectric elements in a general purpose shareware like NASTRAN. Theoretical results exhibiting the response of the plate under electrical actuation has been shown. Location of actuator has been comparatively much prompt when placed away from the support. For cantilever plates, it is when actuator patch is kept along width is more accurate than when placed along the length.

Dube, G. P., [53] portray piezo thermo-elastic resolution is exhibited for infinitely elongated, orthotropic, simply supported, piezoelectric flat panel in cylindrical bending under thermal, mechanical and electro static loadings. Fourier series expansion for displacement, electric potential and temperature has been utilized, to fulfil boundary conditions at the longitudinal edges. The differential equations are reduced from governing equations. Outcomes are exhibited for electrostatic and thermal loadings. The peak values of the stresses and displacements can be minimised by appropriate actuation of piezo patches. Effects of thickness to width ratio of piezo panel on the transverse displacement, axial stress and axial displacement have been scrutinized.

For the analysis of smart complex plates, Chattopadhyay et al. [54] have framed coupled thermal piezoelectric mechanical theory. Governing equations are achieved using variational principle. Under thermal loading the deformation of compound plates with piezoelectric actuators has been analysed. Results point out that the stacking sequence has the impact on both temperature and displacement fields. The coupling between thermal, electrical and mechanical effects minimize the deflection of plate.

The issue of transient heat conduction in a cylindrical panel having cross-ply lamina and piezoelectric material has been addressed by Ootao and Tanigawa [55].In a cylindrical panel, the piezoelectric layer is made of cadmium selenide solid and the cross ply laminate is made up of alumina fibre reinforced aluminium composite. The mechanical displacement, electrical potential distribution, stress and temperature change in the composite panel for a non-uniform heat supply in the circumferential direction are evaluated.

For the analysis of smart composite plates having piezoelectric polymer actuators and sensors on the basis of electro hygro-thermo piezo viscoelasticity, Yi et al. [56] have made a finite element model. It has been noticed that the vibration amplification of composite beams and plates decrease due to viscoelastic damping and active control. The influence of PVDF layer on controlling the dynamic response of beams and plates have been studied.

3-D exact vibrational analysis of a transverse isotropic piezoelectric cylinder shaped panel has been revealed by Ding et al [57].Under certain boundary conditions three dimensional solutions have been acquired by variable separation method. Numerical results of non-dimensional frequencies have been seen to be higher for piezoelectric panel rather than a non-piezo panel.

Zhu et al. [58] have designed a dynamic model for the anticipation of developed torsional vibration by extension twisting coupling of piezoelectric laminates with anisotropic composite laminates. Hamilton's principle has been utilized to draw the equations of motion. For a sinusoidal applied voltage, the amplitude of twisting angle of the laminate has been evaluated for different damping factors.

Ishihara and Noda [59] analysed the dynamic behaviour of piezo thermo elastic laminate. The natural frequencies of laminate to time varying load have been elaborated. The results reveal the impact of transverse shear on the natural frequency becomes prominent with increase in the thickness to length ratio of the composite laminate. It also revealed that plate deflection due to mechanical/thermal loads can be directed by the application of external voltage across the piezo patches.

Chattopadhyay et al. [60] detailed dynamics of piezoelectric actuators with the delaminated composite plates. He developed a sophisticated higher order theory on the basis of finite element model. The theory makes a more precise illustration of stress free boundary condition and displacement field at delamination interfaces and at free surfaces. It is revealed that vivid changes in the dynamic properties of the plates are observed due to delamination. Vibration control of composite laminate, with and without delamination has been studied and the results show weakening of control authority due to presence of delamination.

Hao [61] surveyed boundary value problem of a planar piezoelectric material, the electrical induction in the medium is supposed to be minimal. Using conformal mapping method the issue is solved for stress tensor.

Shuyu [62] has investigated a piezoceramic thick disk resonator for the coupled vibration. This coupled vibration of the disk is in turn reduced to two equivalent vibrations, one representing the equivalent longitudinal vibration and the other equivalent radial vibration. It is observed that the coupled vibration is actually resonant frequencies of the disk which can be calculated analytically. Theoretical results are very much in unison with measured resonant frequencies.

STRUCTURAL ANALYSIS OF SHELL

A generic thermo piezo elastic theory for lean piezo shell was framed by Tzou and Howard [63]. The theory has been deducted with the help of Kirchhoff's-Love theory and linear piezo thermo electro elasticity. Piezo thermo elastic equations include thermal induced loads as well as conventional electrical and mechanical loads. The very use of the theory to piezo material beam, piezoelectric cylindrical shell and a piezoelectric ring has been explained. A technique is developed for the modelling of dynamic and static response of piezo-laminated shells with anisotropy consisting of discrete actuators and sensors by Pletnor and Abramovich [64]. Kirchhoff's-Love theory has been used in deduction of equations. The piezoelectric induced loading has been demonstrated by an equivalent mechanical loading. This method has been utilized to laminates with one structural lamina with piezo actuators bonded on one or both sides. The distortion of the cylindrical panel under electrical loading has been analysed critically. The impact of the stiffness contribution of the piezo-layer to the structure has been chalked out. The steady state response of a cantilever plate actuated by piezo-actuators has been availed for correlation of experimental data with analytical results to authenticate the current model.

A 3-D thin shell assemble holding coherent piezoelectric distributed sensors and actuators has been elaborated by Chen et al.[65].An eight node 40 degrees of freedom shell component has been developed for modelling a thin shell assemble. A PVDF bi-morph cantilever beam under actuation has been analysed to authenticate the current model. The first nine structural vibrational model shapes and the associated induced voltage distribution in the piezo sensors of the shell structure have been exhibited.

A mixed laminate theory for piezoelectric shells has been designed in curvilinear coordinates by Saravanos [66], assuming layer wise theory for the electric potential and single layer theory for the displacements. The coupled governing equations for piezoelectric laminates have been deduced using eight node finite element model, the static and dynamic characteristics have been analysed. The results of static deformation analysis of a shell structure under external mechanical loading exhibited that uncoupled model over predicts deflection and the sensed voltages in the piezo patches. The influence of curvature of the shell structure on the piezo electric sensors placed on the outer and inner surface has been elaborated.

Hill and Farris [67] have applied for boundary element to the issues related to 3-D linear piezoelectricity. The solution of the problem provides electric potentials, elastic displacement, normal flux densities and tractions. The formulation has been worked on a problem of a unit cube of piezoelectric material subjected to uniform displacement and a spherical void in an infinite solid subjugated to a constant internal tension. The model appeared to be operative in capturing the localized fields as a result of notches and holes in smart structures. The research can be extended survey of cracks in piezoelectric materials.

A cross ply laminated cylindrical shell with piezoelectric actuators subjected to combined thermal, mechanical and electrical loadings was examined via Post buckling analysis as displayed by Shen and Li [68] classical theory with Von-Karman-Donnell type of kinematic non-linearity form the basis of governing equations. Hybrid laminated cylindrical shells are extended version of the boundary layer theory of shell buckling. The impact of applied voltage, temperature, stacking sequence and shell geometric parameters in composite laminates on the buckling load are analysed.

A layer-wise theory has been framed by Carrera in [69] for the analysis of multi layered double curved shells made of orthotropic laminae. The theory has been applied to certain issues concerning orthotropic cross ply laminated cylindrical, spherical and circular shells subjugated to loadings which is static. Based on the results it is revealed that multilayer theory leads to better solution than a equivalent single layer theory. It is thus drawn that an optimum analysis of transverse stress requires multi-layer analysis [70]

VIBRATION AND NOISE CONTROL

Sunar and Rao [71] have submitted an intensive review of technological developments in the field of control and sensing of supple structures with embedded piezoelectric materials. They have established core area which are sure to entice future research .Like the establishment of sensor/actuator robust control methodologies, productive power generation and signal conditioning units and environmental effects on smart structures.

Librescu et al.[72] has exhibited a dual method engrossing the consolidation of (i) Composite tailoring and (ii) adaptive matter technology to check the dynamic response of a thin-walled closed cell wing assemble subjugated to outer voltages.

Popular effects such as transverse shear, warping restraint and anisotropy have as well been investigated and their impression on the cantilever structure's dynamic response has been measured.

Raja et al. [73] has designed a model of composite sandwich beams with piezoelectric actuators for the vibration control. Using LQR quadratic regulators independent model, Space control. The authors approximated the active stiffness and damping introduced due to the piezo actuators. They have shown that for identical control effect, shear mode actuation is productive in curbing the vibration rather than the extension bending actuation.

Sun and Huang [74] have given a critical solution of compound beams with piezoelectric sheathe. Vibration control of the beam using velocity feedback has been acquired. The numerical results imply that displacement decay increased with the increase in feedback control gain. Shih [75] surveyed the control of piezoelectric laminated curved beam and distributed vibration sensing. The model includes the mass and stiffness characteristics of the sensor and actuator.The sensitivity of sensors with regard to thickness has been analysed. Increase in thickness will in turn increase sensitivity. Parametric studies reveal that piezoelectric polymer layers with the distributed surface bond efficiently curb the oscillation and improvise the system damping.

Park and Choi [76] have surveyed the vibration control of a cantilever beam using piezoelectric films and electro-rheological fluids. Vibration control performance has been assessed by suppressing the tip deflection of the cantilever beam under forced vibration.The authors have conveyed the use of these two types’ actuators is superior in tailoring response characteristics of the smart structure instead of a single type of actuation scheme.

Pereira et al [77] have designed an experimental model of a cantilever beam using PVDF actuator for controlling the vibration. The sensor used was an accelerometer placed at the free end of a cantilever beam.These control schemes, namely constant amplitude negative velocity feedback, Lyapunov control and constant gain negative velocity feedback have been utilized for the vibration control of the cantilever beam. The theoretically anticipated results are correlated with data obtained experimentally.It is noticed that Lyapunov control has the excellent performance in comparison to the other two control schemes. Theoretical and experimental probes were done by Park and Baz [78], to study active vibration control of plates utilizing vital restrained layer damping.

In order to explain the dynamics of the plate finite element models have evolved.The vibration of the plate has been actively controlled making use of derivative and proportional control laws,.The vibration attenuation chara cteristics of the plate are witnessed to enhance remarkably with the increase in the control gain.

A comparison of the results with experiment suggests the vital restrained layer damping method to be very fruitful in controlling structural vibrations.

To model the dynamic and static response of laminated composites plates embedded with piezoelectric actuators and sensors, Liu et al [79] have displayed a finite element formulation.The converse and direct piezoelectric effects are promptly used to control the dynamic response of the composite plate via a closed loop control, employing an algorithm of velocity feedback control,.The shape control of a flat plate under a uniformly distributed mechanical load has been analysed. The impact of the position of actuators and sensors on shape and vibration control of the composite plate and the stacking sequence has been studied.

Using linear quadratic regulator Ang et al. [80] have surveyed the piezoelectric composite plates for vibration control. By establishing an ideal performance function as a comparable estimate of the overall input energy, kinetic energy and strain energy of the system,the problem was reduced to three design variables.The maximum input voltage and the active damping ratio are expressed in terms to three design variables.Numerical results were generated to demonstrate the result of three design variables on the amplitude and the active damping ratio.Computational cost gets immense drop down as the control problem was reduced to three design variables.

Tsai and Wang [81] have studied effectiveness of active-passive piezo-electric hybrid networks on vibration control of structure.The passive- active configuration consists of piezoelectric patch with a passive resistance-inductance shunt circuit and an active voltage source.In this technique the structural energy can be dissipated and transferred by the tuned resistance-inductance circuit in a passive manner,while the piezo actuator actively clamp down the vibration of base structure driven by the control voltage.It is shown that this active-passive hybrid control can endure a large extent of uncertainty in the system than a system which is purely active.In yet another survey,Morgan and Wang [82] have used passive-active piezoelectric absorber for controlling the vibration of a structure which is subjected to a harmonic excitation whose frequency varies with time.An approximate tuning law and the conditions for the closed loop system stability have been deducted.

Davis and Lesieutre [83] have framed a solid-state tunable vibration absorber.

In this gadget the piezoelectric elements are used as device stiffness and their net stiffness are adjusted electrically using a capacitive shunt circuit. Experimental results show an average enhancement of about 10 db in vibration reduction across the tuning frequency range as compared to pure passive absorber tuned to a specific frequency. This gadget has ample advantages viz simplicity in the design and low power consumption.

Cross and Fleeter [84] have experimentally probed an airfoil in a stator row for the suppression of vibration. Wakes generated by an upstream rotor has been directed to excite the airfoil in the chord -wise bending mode. Piezoelectric patches have been bonded on the surface of the foil.

It has been also noted that the strain induced in the piezoelectric patches due to airfoil vibration introduce voltage across the patches because of shunting the dissipation of electrical energy occurs, thereby reduces the mechanical energy linked with the airfoil vibrations.

Marouze and Cheng [85] have submitted the use of a newly developed a THUNDER which is a unimorph thin layer composite piezoelectric sensor and driver for isolation of vibration. It is fabricated in order to get considerable displacements than conventional piezoelectric actuators and to deform out of plane under applied voltage. The study shows that the THUNDER actuators have the prospects for use in active vibrations control appliances.

Vibration suppression of laminated composite beams have been analysed by Subramanium [86] using magnetostrictive (Terfenol-D) layers.Velocity feedback control law has been availed to control the vibration. In an exhaustive parametric study effects of lamination schemes, location of magnetostrictive layers on vibration of beam and its material properties have been analysed. Gupta and Bhattacharya [87] have studied the effect of magnatostrictive layers on a flexible beam.

Khan et al. [88] has used piezoelectric elements for vital sound control across a fluid loaded plate. Transfer function matrices relating the main acoustic origin and the secondary (piezoelectric actuators) source on the acoustic pressure in the fluid domain have been made using the finite element code, ANSYS. To optimise the locations of earnestly selected set of piezoelectric elements Tabu search method has been availed, in order to acquire a drop down in sound pressure level.

Lee et al [89] have experimentally verified the transmitted noise reduction of passive and active hybrid panels. The hybrid active panels are made of two aluminium plates with air gap in between. In one of the plates piezoelectric sensors and actuators are embedded. Sound absorbing stuff is bonded on the aluminium plate structure in order to achieve considerable reduction of transmitted noise in the mid frequencies only. The air gap causes reduction in high frequency noise and piezo-actuators are used to cancel the noise at low frequency. It is revealed that these hybrid panels have the capacity to reduce noise over the broad frequencies range.

Low frequency volume velocity vibration control using a small panel with piezoelectric (PVDF) actuators and sensors have been exhibited by Lee et al.[90].An array of quadratically shaped PVDF actuators has been placed on the panel and a uniform force is reported to have appeared. Yet another array of 4x4 accelerometers has been used as volume velocity sensors.Frequency response of the plant at low frequencies have been noted to show a remarkable decrease in the magnitude with increase of frequency.

Using simple direct velocity feedback control attenuation of about 8db in acoustic levels of power has been acquired.

Esmailzadeh et al. [91] conducted noise control studies on a duct using hybrid noise control.Dynamics of a loudspeaker ad a microphone which in cooperate electromechanical and mechanico acoustical couplings have been embraced in the mathematical model. It has been observed that the performance of the forward and hybrid active noise control systems depend on the dynamic behaviour of the acoustic duct which in turn depends on the boundary conditions. Additionally it has been noticed that the performance of the active noise control system and sound pressure in the duct are determined by the placement of the primary and secondary source.

Application of smart materials

Chopra [30] has exhibited a marvellous review on the application of smart structures to helicopter rotor blades. Various concepts using smart structural application have been detected. Focus of applications of smart materials to helicopters lies along two very discrete directions. Which are a) establishment of embedded smart structures to control and actuate the distortion of the blades or panel members in the fuselage and b) establishment of smart actuator on a sub system which can be blended to the helicopter blades to generate control forces for vibration reduction in fuselage or to actuate a trailing edge flap.

Bernhard and Chopra [92] have hover tested a vital rotor blade tracking edge flap that was being steered by piezo induced bending torsion compound beam. Bending response has been minimised and the twisting response enhanced by special lay-up sequence of a composite beam fused with piezo-ceramic element phasing. Fabrication of two model rotor blades has been done with each having a blade radius centred of 90%, a flap of 3% span and 20%chord,.A deflection amplitude of 1.5 to 2 degrees has been reported at a rotor speed at 900rpm.

Centolanza et al. [93] developed a shear induced piezoelectric tube in concurrence with lever-cusp hinge amplification device for generating hinge moments and trailing edge flap deflections. Prototype of actuator flap system was guided by a finite element model of the actuator tube and trailing edge flap (including inertial loading and aerodynamic). Induced shear tube actuator has been found as a favourable control device.When compared to a conventional rotor blade trailing edge moment controlling devices. Strub [94] presents a description on the full scale development of a rotor flap control with piezoelectric X-frame actuators.

Boller [95] has taken the design aspects, issues related to damage, damage prevention and damage management for aircraft structures on the basis of state of the art inspection and monitoring procedures. On destructive testing method has been considered for health monitoring of aircraft structures on the basis of state of art inspection and monitoring procedures. For health monitoring of aircraft structures. NDT method has been proposed and use of fibre optic or piezoelectric sensors with highly developed signal processing for this very purpose has been recommended. Soh et al. [96] have taken health monitoring aspects of RCC bridge. Piezoceramic patch sensors are utilised to monitor the damage occurrence and its propagation due to travelling load excitation. Using RMS of the deviations n patch signatures the damage extent has been gauged in non-parametric forms. Damage progression has been shown in unison with non-parametric index.

Review of the smart material actuator characterisation has been carried out by Pomirleanu and Giurgiutiu [97]. A large force (large stroke) piezoelectric actuator has been sculptured and characterised. Established on mechanical and electrical envelops, design tools have been suggested. Piezoelectric actuators have been included in the very design guidelines.

DEBONDING OF PIEZOELECTRIC ACTUATORS AND SENSORS

Jin, c., et al [98] carried out theoretical study of piezoelectric actuators for their coupled electromechanical performance that arose due to partial debonding of adhesive layer between piezo patch and host structure, when treated with electric loads preferably not of low frequency range. A model of an actuator with layer of adhesive bonding that is not perfect experiences shear deformation was assumed to simulate the 2-D electro-mechanical performance of the integrated system. An analytical solution furnished, and numerical simulation was conducted for special cases.The solution of the resultant integral equations furnished as functions of the interfacial stress is methodical solution of the problem. The effect of debonding layer upon the actuation process was studied by conducting a numerical simulation.

The study suggest that for cases of comparatively low frequency, the rise in thickness of bonding layer will yield surging level of shear stress for the inside surfaces of the actuator and reduce stress concentration at the debonded edges. For cases of somewhat high-frequency the rise of the bonded layer thickness ensure a remarkable change in the distribution of shear stress. When bonding layer thickness is taken into account the geometry of the actuator and the material combinations show noteworthy dominance on the distribution of shear stress distribution.

Mathematical models were developed by Ikeda, T., et al. [99] linear as well as non-linear on the foundation of Timoshenko beam theory for analysing deformational behaviour of beam with a brace of partly debonded piezo actuators under buckling load. For axial force in debonded belt greater than the Euler buckling load the piezo actuator in that terrain, was presumed to induce only Euler buckling load. The results shows, when actuators are debonded from the edge the performance is same as that of beam with actuators abridged in length by the debonded portion. However with both ends still bonded and debonding in the middle no degradation occurs before debonding region buckles, after buckling deterioration of performance does occur.

Seeley and Chattopadhyay [100]-[101] carried out experimental studies of beams with partially debonded piezo actuators from its edges and comparison of results with numerical ones based on higher order beam theory, with increase in debonding length the frequency of vibration, in general was found to decrease and non-intuitive trend was found for frequency with debonding length both for experimental & simulation studies due to new localized mode established owing to the flapping movement of the debonded piezo actuator.

Tong, et al [102] offered analytical beam model for debonded piezo actuators and sensors and alter in dynamic potential was examined numerically, the debonding effects on sensing (by impetuous shear force at the free end) and actuating (by impetuous voltage on piezo actuator layer) behaviour were studied, edge debonding was found to underachieve appreciably in tip deflection and sensor yield than debonding in the middle portion.

Wang and Meguid [103] carried mathematical studies on piezoceramic actuator bonded to an elastic agency pre-empting plane strain conditions to exist for the static electromechanical behaviour. The influence on shear stress of debonding at the interface was carried out on the footing of set of singular integral equations in terms of interfacial shear stress by trimming of the debonded portion of actuator and employing an equivalent stress on the bonded portion of an Actuator.

The impact of debonding of piezo patches in smart beams have been shown by Sun and Tong [104] the authors have elaborated a partially debonded piezoelectric sensor and actuator patches containing in thin walled curved beam mathematical model. Imposing conditions of both force and displacement continuity at an interface separating bonded and debonded belts as basis for modelling the debonded regions. Governing equations have been drawn for both debonded and bonded parts. In debonding region both peel and shear stresses are supposed to be zero where as in the bonding region both of these stresses have been included. Based on this model a closed loop control model has been examined. Influence of debonding of sensor and actuator patches on closed and open loop control have been studied. They have drawn that edge debonding has a remarkable effect on close loop control. Further they noticed debonding on edges of their piezo patches is more pronounced in shallow curved beam. The analysis carried convey that debonding degrades the sensing and actuating abilities of the beam and edge debondings of piezo sensor and piezo actuator appreciably alter distributions of internal force in the beam core

Zheng and Shi [105] evolved a solid FEM model for the vibration analysis of smart curved beam and reported the effect of debondings on frequencies.

Congrui and Xiadong [106] have deliberated upon load transmitted to the host material by piezo actuators as a function of geometrical and material properties of the piezo actuator. The numerical analysis of the affect of the geometrical and the material discrepancy of the adhesive layer upon feedback of the coupled structure is put forth. Both debondings at the edge and at the middle of composite structure are discussed and their outcome on stress distribution is elaborated. The simulation indicate with rise in the bonding thickness will amplify the shear stress distribution in the interior of the actuator, and fall of the strain concentration at the tips of the actuator. Also, for enhancing performance of the actuators care need to be exercised for choosing material blends of the actuator and core structure.

Xiaoxia et al. [107] have established a 2-D de-lamination model to probe the consequences of the implementation of the vector field on energy release rate of the delaminated piezoelastic laminates. Simulation studies for fracture modes I and II of the PZT/elastic laminates unveil that outcome of vector fields (both positive and negative electricfields) on the energy release rate of a smart structure is governed by the material properties of the smart and elastic layer's and thickness ratio. Therefore picking the proper material properties of each lamina will upgrade the fracture strength of smart structures.

Wang et al. [108] applied exponential cohesive zone model to debondings of adhesive surface in finite element analysis and presented equations for fracture modes I and II ERR at the site of crack interface for a straight crack and its stress in PZT composite beams. These have been indicated in terms of common material and geometry properties, random choice of longitudinal loads, bending moments and horizontal shear forces at the location of the interface crack tip.

Luo and Tong [109] carried out finite element analysis on a smart plate and presented the precise numerical results based on continual adhesive layer sandwiching the PZT and the core plate. The analysis for adhesive stress distribution of PZT smart plates and counterpart forces in the core plate generated by ferroelectric actuator specify the constraints of equivalent forces and the presence of the twisting moment and in plane shear forces near the PZT edges. The analysis does incorporate the shear and peel stiffness of the adhesive and thus present cognizance into the interactive behaviors of the PZT smart plates, also display that for flexible smart plate and PZT debonding studies the significance of peel stresses. The presented analysis is proposed to be manoeuvred by assigning a zero value to adhesive's stiffness to probe PZT debonding's.

Dongchang, S. and Liyong, T. [110] have presented a model with shallow curved beam under consideration, assuming the piezoactuators and piezosensors to be partially debonded. The equations for bonded and debonded regions are based on transfer of peel and shear stress in bonded belt while in debonded belt no such process occur Imposing the force and displacement continuity at the interface dividing bonded and debonded belts, a closed loop vibration control is achieved. Investigation of the effects of the debonded piezo-electric layer on the control stability of smart structures has been investigated. The presence of edge debonding is shown to degrade the activating and sensing capabilities.

CONCLUDING REMARKS

A numerical technique like finite elements is suitable for analysis of smart structures that needs modelling based on electro thermal elastic formulation .In addition to above research's the other techniques include delamination and debonding. This sort of research will be study of partial or full debonding of a piezo-layer from the metallic host material of the smart cantilever beam. During operation a smart structure may undergo debonding at interfaces between piezo layer and metallic host. This technique effects the promptness of structure. In order to introspect this, a provision needs to be kept in the stiffness matrix for extra degrees of freedom for debonded region. The generation of additional nodes due to debonding for a specific portion of length and their solution for displacement, strain and stress will give an idea of debonding in that portion.

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