Chapter 1

Introduction and Literature Review

This chapter deals with a brief introduction and review of literature pertaining to the magneto-electro-elastic composite, smart structure, nonlinear analysis of smart structures, active constrained layered damping (***ACLD***) *treatment, and the piezoelectric composites* (***PZCs***)*. Based on the comprehensive review of literature, the scope of the research work for this dissertation has been identified and the objectives of the thesis have been presented. In the end, organization of the thesis chapters has been delineated.*

1.1 Magneto-Electro-Elastic composites

Enhanced demand for high performance control design in combination with recent advances in material science and emerging technologies in the production of advanced composites has resulted in the development of a class of systems termed as smart, intelligent or adaptive structures. A new class of adaptive structures or smart composites composed of piezoelectric (ferroelectric) and magnetostrictive (ferromagnetic) materials has been emerged. Such structures or composites are generally being referred as magneto-electro-elastic (**MEE**) structures or multiferroic composites. These composites have attracted significant attention of the researchers over the past several years on account of their encouraging properties for applications in actuators, sensors, sonar applications, space structures, spintronics, transducers, ultrasonic imaging devices etc. The unique property of the **MEE** composites is that they have the ability to covert energy from one form into the other among the magnetic, the electric and the mechanical energies (Harshe *et al*., 1993; Schmid, 1994; Pan, 2001; Pan and Heyliger, 2002; Bichurin, *et al*., 2007; Nan *et al*, 2008; Zhai *et al*., 2008). The schematic representation of these energy interactions in the **MEE** solids is presented in Fig. 1.1.

The effects of **MEE** coupling have been observed in both single-phase materials as well as in composites made of piezoelectric and magnetostrictive phases. However, composites made of piezoelectric and magnetostrictive phases in particular, **$BaTiO_3$**

(barium titanate) and **$CoFe_2O_4$** (cobalt ferrite) can exhibit significantly high electromagnetic coupling effect in comparison to individual constituent phases (Grossingera *et al*., 2008). Further, the properties of **MEE** composites can be greatly improved by using layered/laminated double, triple or multilayer piezoelectric-piezomagnetic composites than the bulk/fiber form due to the absence of leakage current and the ease of poling to align the electric dipoles (Bichurin *et al*., 2003). On account of these interesting multi behavior properties, the **MEE** composites gained significant importance and needs an extra conscientious and concern in the design and analyses of smart composite structures.

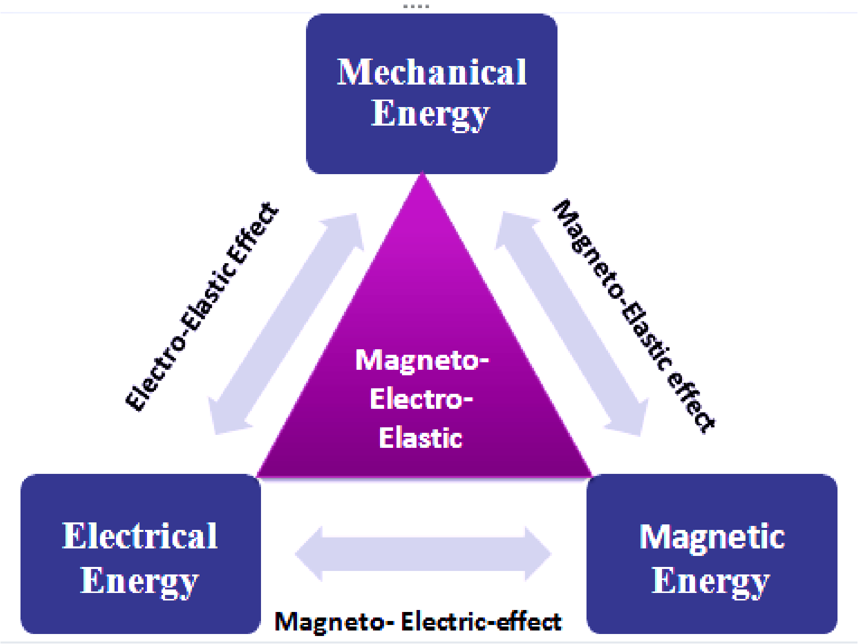


Fig. 1.1 Schematic representation of energy interaction in Magneto-electro-elastic solids

Research concerned with the coupled magneto-electric effect in elastic media has received growing attention of the researchers. Boomgaard *et al*., (1976) developed the material consisting of piezoelectric and piezomagnetic phases and studied the effect of magneto-elastic coupling. Bracke and Van (1981) developed the composite material which has both magnetostrictive and piezoelectric properties for a broad band magnetoelectric transducers. Harshe *et al*., (1993) investigated theoretically and experimentally the magnetoelectric composites of **PZT-$CoFe_2O_4$** and **$BaTiO_3$-$CoFe_2O_4$** with various connectivity. Avellaneda and Harshe (1994) demonstrated the magnetoelectric effect in piezoelectric/magnetostrictive multilayer (2-2) composites. Nan (1994) estimated the multiphase magneto-electro-elastic material constants in terms of volume fraction of the constituent materials. Benveniste (1995) derived certain exact relationships for the effective magneto-electro-elastic modulli. Pan (2001) demonstrated the exact solutions of simply supported multilayered magneto-electro-elastic plates under surface and internal loads by using modified Stroh formalism and propagator matrix method. The same approach was extended for exact solutions of functionally graded magneto-electro-elastic (**FGMEE)** plates by Pan and Han (2005) and free vibration analysis by Pan and Heyliger (2002). They pointed out that some of the lower order natural frequencies are similar to the corresponding frequencies of the pure elastic plate. Lage *et al*., (2004) presented the layerwise partial finite element model for static analysis of **MEE** plates. Buchanan (2004) computed the natural frequencies of vibrations for **MEE** layered infinite plate. Several methods have been implemented to investigate the free vibration analysis of **FGMEE** plates, namely, independent state equations by Chen *et al*., (2005), finite element method by Bhangale and Ganesan (2006) and discrete layer method by Ramirez *et al*., (2006). Haitao *et al*., (2008) studied the static/dynamic analysis of functionally graded (**FG**) and layered **MEE** plate. The finite element model based on a higher order shear deformation theory for static and free vibration analysis of **MEE** plates has been developed by Moita *et al*., (2009). Liu and Chang (2010) derived the closed form expressions for the transverse vibrations of the **MEE** thin plates. Phoenix and his co-workers (2009) presented the static and dynamic analyses of coupled **MEE** problems. Most recently, Li and Zhang (2014) investigated the free vibration of **MEE** plates resting on a Pasternak foundation based on the Mindlin theory and the buckling analysis of **MEE** plates resting on Pasternak foundation has been studied by Li (2014). Further, significant research has been reported on the analysis of the **FGMEE** plates (Jiangyi *et al*., 2006; Rajesh *et al*., 2006a; Li *et al*., 2008; Wu and Lu, 2009; Ootao *et al*., 2011; Bishay, *et al*., 2012, Lang *et al*., 2013) and the **MEE** beams (Anandkumar *et al*., 2007; Kumaravel *et al*., 2007; Daga *et al*., 2009; Huang *et al*., 2010; Milazzo and Orlando, 2012).

In addition, considerable research is devoted to the study of the **MEE** shell structures. For instance, Hou and Leung (2004) studied the transient response of the **MEE** hollow cylinders subjected to dynamic loads. Annigeri *et al*., (2006) carried out the free vibration analysis of clamped-clamped **MEE** cylindrical shells. Wang and Ding (2007) investigated the radial vibrations of piezoelectric/magnetostrictive composite hollow sphere. Daga *et al*., (2008) studied the transient response of **MEE** cylinder by semi-analytical finite element method. Bhangale and Ganesan (2005) carried out the free vibration analysis of **FGMEE** cylindrical shells by the finite element method. Tsai *et al*., (2008) presented the static analysis of the three-dimensional doubly curved **FGMEE** shells by an asymptotic approach. Pradhan (2009) presented the analytical solutions for functionally graded (**FG)** shells with embedded magnetostrictive layers. Qin (2010) investigated a circular cylindrical shell made of transversely isotropic, non-ferromagnetic, perfectly electro-conductive material immersed in an axially aligned magnetic fields and a thermal field. Wu and Tsai (2010) investigated the dynamic responses of **FGMEE** shells using the method of multiple scales. Lang and Xuewu (2012) carried out the buckling and vibration analysis of **FG** magneto-electro-thermo-elastic circular cylindrical shell by considering the mechanical, electric, magnetic and thermal coupling effects. Rajesh *et al*., (2006b) studied the free vibration of **FG** non-homogeneous **MEE** cylindrical shells. Badri and Al-Kayiem (2012) developed the model for dynamic analysis of piezolaminated shell structure with embedded smart material lamina and influenced by magneto-thermo-electro-elastic load. Abbas and Zenkour (2013) studied the **FGMEE** hollow cylinder considering thermal effects. Further, extensive research is devoted to the prediction of the effective properties of **MEE** composites (Aboudi, 2000, 2001; Kalamkarov and Georgiades, 2002; Chen *et al*., 2002; Lee *et al*., 2005; Wang *et al*., 2009; Jin-Yeon, 2011; Naresh and Arockiarajan, 2012, 2014) and fiber reinforced **MEE** composites (Kuo, 2011; Badri *et al*., 2011; Espinosa *et al*., 2011; Tan and Tong, 2002).

Recently, extensive research is also devoted to the fracture and crack related problems in structures made of the **MEE** composites (Zhong, 2009; Rojas-Díaz *et al*., 2010; Wang *et al*., 2010; Zhou, *et al*., 2011; Rangelov *et al*., 2011; Liu *et al*., 2013). Although, **MEE** structures have gained remarkable attention of the researchers in recent years, very few research on the large deflection analysis of the **MEE** plates have been reported in the literature. Xue *et al*., (2011) proposed the analytical solutions for the large-deflections of rectangular **MEE** thin plate under the action of a transverse static mechanical load. They observed that the coupling effect on the deflection is negligible for the **MEE** plate made of different volume fractions of piezoelectric and piezomagnetic phases. Sladek *et al*., (2012) presented the meshless local Petrov-Galerkin method to analyze the effects of boundary conditions and layer thickness on functionally graded multiferroic composites for enhancement of magnetoelectric coefficients. The same method is extended to the large deformation of the **MEE** thick plates (Sladek *et al*., 2013) under the static and time-harmonic mechanical load and stationary electromagnetic load. Milazzo (2013) analyzed the large deflection of **MEE** laminated plates using first order shear deformation theory. Alaimo *et al*., (2013) proposed an equivalent single-layer model for the large deflection analysis of multilayered **MEE** laminates by the finite element method. Chen and Yu (2014) developed the geometrically nonlinear multiphysics plate model and analyzed the **MEE** laminated composites by applying the variational asymptotic method. Zheng *et al*., (2008) investigated the active control of the shape and vibration of piezoelectric, **MEE** and **FGM** structures and presented the dynamic responses of the cylindrical shell.

1.2 Smart Structures

The design of efficient, high performance lightweight flexible structures is becoming challenging task not only in aerospace industries but also in automotive, civil, marine, medical and high precision applications. These structures are susceptible to large vibrations with long decay time because of their flexibility and low internal damping. This often leads to the structural fatigue and instability which may lead to serious deterioration of the structural performance. Such possibilities of failure can be mitigated by integration of an active control system onto the host structure and the performance of the overall structure under operation can be enhanced. These structures are commonly defined as systems whose dynamics can be monitored or modified by distributed sensors and/or actuators, in accordance with an integrated control law, to accommodate time-varying extrinsic inputs or changing environmental conditions (Smith, 2005). A flexible structure coupled with distributed actuators and sensors made of piezoelectric materials as shown in Fig.1.2 is able to achieve self-controlling and self-sensing capabilities and is customarily known as "Smart Structure" (Crawley *et al.*, 1988).

The main components of the smart structures are passive material part, active material parts and the control architecture. The passive material part of a smart structure is the load bearing host structure generally called as substrate which can be any structure like beams, plates, shells etc., composed of the conventional materials. The active material parts of the smart structure are the layers/patches of smart materials such as, piezoelectric materials which perform the operations of sensing and actuation. Piezoelectric materials can easily be integrated with the load bearing structures by surface bonding or embedding into it. The control system controls the output in accordance with the externally applied reference signals.

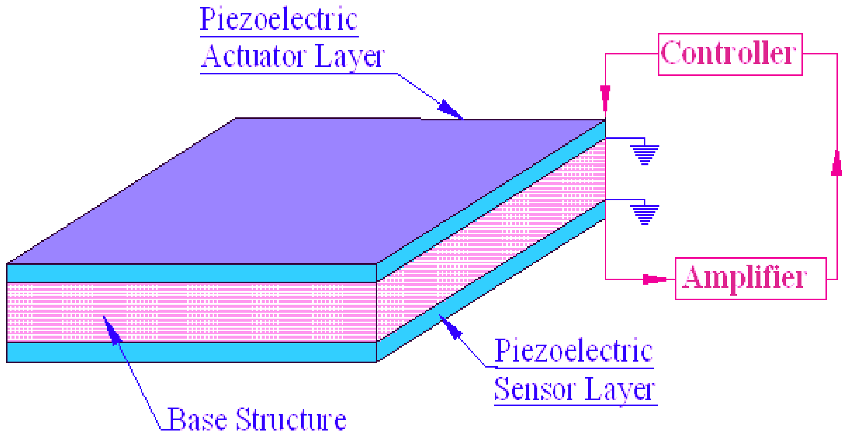


Fig. 1.2 Schematic representation of a typical smart structure

In an expedition of developing high performance smart structures, Forward (1981) first established the feasibility of the effectiveness of the piezoelectric actuators to damp out two closely placed orthogonal bending modes of a cylindrical fiberglass mast employing a simple rate damping control law. Another pioneering work showing the effectiveness of the use of distributed piezoelectric actuator in controlling the deformable mirror surface is due to Chiarappa and Claysmith (1981). Subsequently, Bailey and Hubbard (1985) demonstrated the use of piezoelectric materials as distributed sensors for the active control of cantilever beam. The design and analysis of an active distributed damper for the control of a thin cantilever beam was also presented by Bruke and Hubbard (1987), Crawley and de Luis (1987) and Im and Atluri (1989). Miller and Hubbard (1987) first demonstrated the use of piezoelectric materials as distributed sensors for Euler-Bernoulli Beam. Next, Tzou and Panditha (1987) used these materials for tactile sensors of robot manipulators and Crawley *et al.*, (1988) demonstrated the use of piezoelectric technology for control of intelligent structures. A great deal of research on smart structures has been reported on exact solutions (Ray *et al.*, 1992, 1993, 1998; Heyliger and Saravanos, 1995; Batra *et al.*, 1996; Vel and Batra, 2001; Luo and Tong, 2003, Ray and Sachade, 2005), analytical solutions (Tzou and Gadre, 1989; Crawley and Lazarus, 1991; Dimitriads *et al.*, 1991; Clark *et al.*, 1993), finite element analysis (Baz and Poh, 1988, 1990, 1996; Robbins and Reddy, 1991, Ha *et al.*, 1992; Reddy, 2004; Mannini and Gaudenzi, 2004; Hamed and Negm, 2004; Cotoni *et al.*, 2006) and on the active control analysis (Lee and Moon, 1990; Tzou and Gadre, 1990; Hanagud *et al.*, 1992; Birman, 1993; Gu *et al.*, 1994; Varadan *et al.*, 1997; Ray, 2003; Agarwal and Treanor, 1999; Song, *et al.*, 2000; Balamurugan and Narayanan, 2001; Sun *et al.*, 2002; Kusculuoglu and Royston, 2005; Narayanan and Balamurugan, 2003; Nguyen and Tong, 2004, 2007; Song, *et al.*, 2006; Balamurugan *et al.*, 2007; Gupta *et al.*, 2007).

1.3 Active Constrained Layer Damping Treatment

Monolithic piezoelectric materials used in distributed actuators and sensors have low electro-mechanical coupling coefficients. Hence, high control voltage is required for satisfactory control of vibrations of host structures. Further research on the masterly use of these low-control-authority monolithic piezoelectric materials led to the development of active constrained layer damping (**ACLD)** treatment (Baz and Ro, 1995; Azvine *et al.*, 1995). In a typical **ACLD** treatment, the performance of the passive constrained layer damping (**PCLD**) treatment has been significantly enhanced by replacing the constraining layer by an active constraining layer made of smart materials such as piezoelectric materials/1-3 piezoelectric composites (**PZC**). The constrained layer made of viscoelastic material is sandwiched between the host structure and the active piezoelectric constraining layer. The low-stiff constrained viscoelastic layer in the **ACLD** treatment undergoes large transverse shear deformations causing more energy dissipation.

The control effort required for causing high transverse shear deformations is conformable with the low-control authority of the existing monolithic piezoelectric materials. Thus, to accomplish the task of active damping of vibrations of smart structures, better performance of the piezoelectric materials of low control authority is achieved when they are employed as the constraining layer of the **ACLD** treatment rather than when they are directly attached to the host structures. Also, if the constraining layer of the **ACLD** treatment is not activated with applied voltages, the **ACLD** treatment becomes the **PCLD** treatment. Thus, the **ACLD** treatment provides both passive and active damping simultaneously when under operation (Baz and Ro, 1996; Baz, 1998). Therefore, in the same damping treatment, a broader band control is achieved benefiting from the advantages of simplicity, stability, fail-safe, low-cost (passive) and adaptability (Preumount, 2002; Shen, 1994; Yellin and Shen, 1996; Varadan *et al.*, 1997; Park and Baz, 1999a,b; Ro and Baz, 2002, Vasques, *et al.*, 2006). The schematic diagram representing the passive and active **ACLD** treatment is shown in Fig. 1.3 (Baz, 1995).

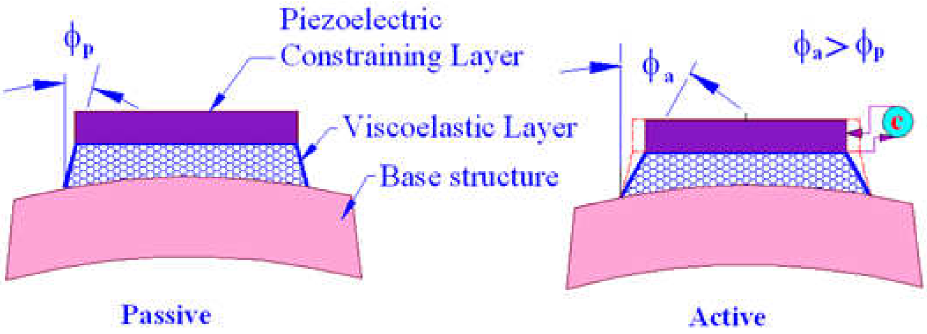


Fig. 1.3 Schematic diagram of passive and active **ACLD** treatment.

Although, research on active multilayered treatment was initiated by Baz and Poh (1988), Baz and Ro (1994) had introduced the effectiveness and relative simplicity of **ACLD** treatment to the broader research community. However, the successful experimental work on the **ACLD** treatment (Baz, 1996) has motivated the researchers to carry out further investigations on the use of the **ACLD** treatment for active damping of composite structures. Optimization of energy dissipation characteristics of beams and plates integrated with the **ACLD** treatment has been studied by Baz (1997a), and Ray and Baz (1997). Baz (1997b) developed a globally stable boundary control strategy to damp out the vibrations of beams fully treated with the **ACLD** treatment and also studied (Baz, 1998) robust control of beam using **ACLD** treatment Ray (1998) studied the optimal control of laminated plates with piezoelectric sensor and actuator layers. Crassidis *et al.* (2000) carried out the analysis for control of a beam integrated with **ACLD** treatment. Baz (2000) also carried out the spectral finite element **(FE)** analysis for controlling longitudinal wave propagation in rods treated with **ACLD** treatment. Lam *et al.* (2000) showed that the control effort needed to damp out the vibrations of structures using **ACLD** treatment can be significantly lower than that in case of purely active control. They modeled the constrained viscoelastic layer using Golla-Hughes-McTavish (**GHM**) method. Park and Baz (2001) investigated the comparison between the **FE** analysis of **ACLD** using classical and layer-wise laminated theories. Ray *et al.* (2001) demonstrated the use of **ACLD** treatment for significant control of linear vibrations of thin cylindrical shells by both experimental and theoretical investigations. Jeung and Shen (2001) developed a generalized **FE** model of plates and shells integrated with the **ACLD** treatment.

Chantalakhana and Stanway (2001) investigated the performance of the **ACLD** treatment for clamped-clamped plate. Lim *et al.* (2002) implemented the closed loop finite element modeling of the **ACLD** in time domain analysis. Illaire and Kropp (2005) studied the quantification of damping mechanisms of active constrained layer treatments. Chattopadhyay *et al.* (2001) studied the influence of number of segments of the **ACLD** treatments along with their placements on the vibration control of composite plates. Liu and Wang (2002) demonstrated the enhanced **ACLD** for broadband vibration suppression. Batra and Geng (2002) studied the comparison of damping augmentation mechanism for **ACLD** treatment.

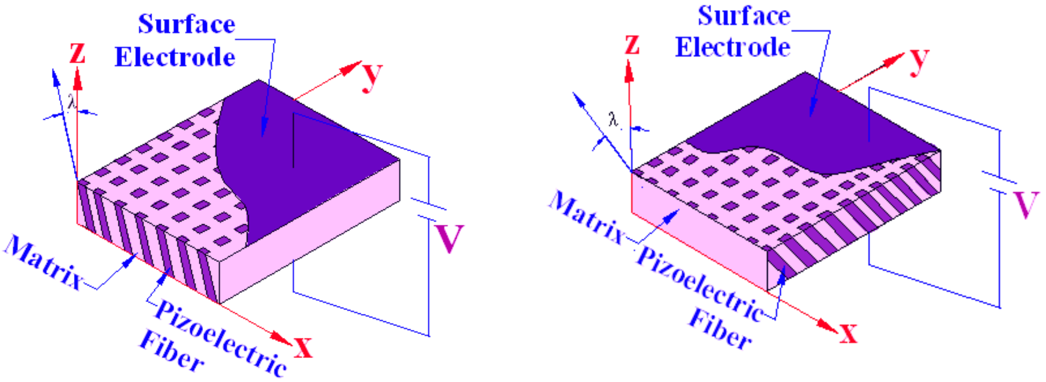
As an important application, Chattopadhyay *et al.* (2002) used **ACLD** treatment to enhance aeromechanical stability and control of smart composite rotor blades. Ro and Baz (2002a) investigated vibration control of plates using self-sensing **ACLD** networks and also determined the optimal placement of **ACLD** patches using the modal strain energy approach (Ro and Baz, 2002b). As an important study, the effect of debonding in **ACLD** patches on the control of smart beams has been investigated by Sung and Tong (2003). Ray and Reddy (2004) investigated the optimal control of thin circular cylindrical laminated composite shells using **ACLD** treatment. Badre-Alam *et al.* (2004) presented an analysis of the interlaminar stresses in **ACLD** treatments. Langote and Seshu (2005) carried out experimental investigation on active vibration control of a beam using hybrid active/passive constrained layer damping treatment. Vel and Baillegeon (2005) studied the static deformation, vibration and active damping characteristics of cylindrical composite shells with piezoelectric shear actuators. Pradeep and Ganesan (2006) studied the **ACLD** of composite beams in the presence of the thermal environment. Recently, Kumar and Singh (2009, 2010) presented experimental results for the vibration and damping characteristics of **ACLD/PCLD** treated beams. Kumar and Ray (2012a, b) carried out the frequency response control and geometrically nonlinear vibrations of smart laminated composite sandwich plates undergoing **ACLD** while Kanasogi and Ray (2013) analyzed the same for skew laminated composite plates. Kundalwal *et al.* (2013) studied the performance of the **ACLD** patches for controlling the responses of smart laminated fuzzy fiber reinforced composite shells using 1-3 piezoelectric composite material as the constraining layer. They demonstrated that the damping characteristics of these structures can be improved significantly using piezoelectric composites as the materials of the constraining layer of the **ACLD** treatment.

1.4 Piezoelectric Composites

Piezoelectric materials possess the ability to respond significantly to the stimuli of different physical natures. Consequently, piezoelectric materials can be used as distributed sensors and actuators in flexible structures with various degrees of tailoring and complexity (e.g. as fibers). It is well known that brittle fibers are efficiently exploited to form polymer matrix composites with significantly enhanced properties suitable for structural applications. Possibly, this may be the driven force to the researchers to develop the piezoelectric composites (**PZC**s) with brittle piezoceramic fibers. Consequently, if the monolithic piezoelectric materials such as **PZT**, **PZT**5**H** etc, are used in the form of a fibers to reinforce the epoxy matrix particularly in 1-3 connectivity, the resulting 1-3 piezoelectric composite (**PZC**) possess the effective material properties significantly superior to those of the monolithic piezoelectric materials and are characterized by good conformability and strength (Newnham *et al*., 1980,). In addition, PZT/polymer composite with 1-3 connectivity is characterized with low density, high electromechanical coupling factor and improved impedance matching (Newnham *et al*., 1978; Janas and Safari, 1995; Smith and Shaulov, 1998; Tressler *et al*., 1999). Being a composite material, the **PZC**s have the ability to cause orthotropic actuations also.

Various micromechanics models were proposed to predict the effective properties of these **PZC**s from the properties of their constituents. For example, Chan and Unsworth (1989) derived a simple micromechanics model for the analysis of piezoelectric ceramic/polymer 1-3 composites. Smith and Auld (1991) predicted the effective properties of vertically reinforced 1-3 **PZC** materials using the strength of material approach of micromechanics. Dunn and Taya (1993) used the Mori-Tanaka and differential micromechanics theories and considered the coupled electroelastic behavior for predicting the effective electroelastic modulli of piezoelectric composites. These composites offer many unique and attractive features like improved mechanical performance and electro-mechanical coupling, and are useful for studying the thickness mode oscillations of structures. The constructional feature of a lamina made of the vertically/obliquely reinforced 1–3 **PZC** (Smith and Auld, 1991; Ray et al., 2009) is schematically illustrated in Fig 1.4. A layer of the obliquely reinforced 1-3 **PZC** material in which the piezoelectric fibers are coplanar with the ***xz***-plane with their orientation angle being **λ** with the **z**-axis is illustrated in Fig. 1.4(a). The piezoelectric fibers can also be coplanar with the **yz**-plane while the orientation angle with the **z**-axis is **λ** as shown in Fig. 1.4 (b). In case of the obliquely reinforced 1–3 **PZC**, the orientation angle (**λ)** is nonzero while it is zero for the vertically reinforced 1–3 **PZC**. The piezoelectric fibers of the 1-3 **PZC** are poled along their length while the top and the bottom surfaces of the lamina are electroded.

Widespread research has been carried out to analyze the performance characteristics of these **PZC** materials as the materials of the distributed actuators or constraining layer of the **ACLD** treatment for active control of linear deformations and vibrations of laminated structures (Ray and Reddy, 2005; Ray, 2006; Ray and Mallik, 2005; Ray and Pradhan, 2006, 2007, 2008; Ray and Balaji, 2007; Ray and Pradhan, 2010).



(a) (b)

Fig. 1.4 Schematic representation of the **ACLD** patches with vertically/obliquely reinforced 1-3 **PZC**s in which (a) piezoelectric fibers are coplanar with the vertical ***xz***-plane (b) piezoelectric fibers are coplanar with the vertical **yz**-plane.

1.5 Nonlinear Analysis of Smart Structures

In the preceding sections, a brief review of literature on the magneto-electro-elastic structures, active constrained layer damping, piezoelectric composites and linear analysis of smart structures has been presented. Considerable interest has also been placed on the geometrically nonlinear analysis of smart structures. Owing to the flexibility of composite structures and small material damping, vibrations induced in the structure may lead to large amplitudes. Thus, the effect of geometrically nonlinear deformations becomes prominent in the behavior of composite structures (Reddy and Chao, 1981; Reddy, 1983).

Many researchers performed the active control of geometrically nonlinear analysis of composite structures using piezoelectric sensors and actuators for attenuating the undesired vibrations. For example, Birman (1992) proposed a theory of geometrically nonlinear composite plates with piezoelectric stiffeners. Pai *et al.* (1993) studied the refined nonlinear model of piezoelectric plate laminates. Tzou and Zhou (1995) investigated the dynamic control of nonlinear circular plates/shells composed of two surface piezoelectric layers and one isotropic elastic layer. Icardi and Sciuva (1996) analyzed large deformations of multilayered plates with induced strain actuators. Reddy (1999) analyzed large deformations of laminated composite plates integrated with piezoelectric sensors and actuators. Yi *et al.* (2000) presented a nonlinear dynamic analysis of structures integrated with piezoelectric sensors/actuators. Moita *et al*. (2002) investigated the geometrically nonlinear analysis of composite structures with integrated piezoelectric sensors and actuators. Mukherjee and Choudhuri (2002) analyzed the large deformations of piezoelectric structures. Gao and Shen (2003) developed the **FE** model for the geometrically nonlinear analysis of piezolaminated plates and shells. Lentzen and Schmidt (2004) presented a nonlinear bending analysis for simply-supported shear deformable un-symmetric cross-ply laminated plates integrated with piezoelectric actuators and subjected to combined action of mechanical, electrical and thermal loads. Lentzen and Schmidt (2005) developed a **FE** model for geometrically nonlinear static and dynamic analyses of smart composite structures. Huang *et al*. (2005) analyzed nonlinear dynamic responses of simply-supported shear deformable cross-ply laminated plates integrated with piezoelectric actuators. Fernandesn and Pouget (2006) studied the static and dynamic electromechanical responses of the structure equipped with piezoelectric actuators. Kulkarni and Bajoria (2006) derived a finite element model based on the higher order shear deformation theory for the geometrically nonlinear analysis of smart thin and sandwich plates.

Furthermore, Ray and Shivakumar (2009) analyzed the active constrained layer damping of geometrically nonlinear vibrations of laminated composite plates using horizontally reinforced piezoelectric fiber reinforced composite (**PFRC**). Xian and Shen (2009) dealt with the nonlinear vibrations and dynamic responses of shear deformable **FG** plates embedded with **PFRC** actuators. Tanveer and Singh (2010) studied the nonlinear forced vibrations of laminated piezoelectric plates. Sarangi and Ray (2011b) investigated the performance of the **ACLD** treatment in which the constraining layer is made of the vertically reinforced 1-3 **PZC** for active damping of nonlinear transient vibrations of laminated composite plates. Fakhari and Ohadi (2011) investigated the large amplitude vibration control of smart laminated composite plate and the functionally graded material plates under thermal gradient and transverse mechanical loads using integrated piezoelectric sensor/ actuator layers. Behjat and Khoshravan (2012) proposed the geometrically nonlinear static and free vibration analysis of piezoelectric plates. Recently, Kiani *et al*., (2013) developed an analytical procedure for the dynamic analysis of active control of doubly curved **FGM** panels in both time and space domain. Control of geometrically nonlinear vibrations of smart laminated sandwich plate (Kumar and Ray, 2013) using active constrained layer damping treatment has also been analyzed.

1.6 Analysis structures under magnetic fields

During the last few decades, investigation on the influence of applied magnetic field on the behavior of the flexible structures has been increased significantly. Moon and Pao (1969) studied ferromagnetic beam-plate vibrating in a transverse magnetic field and observed that the natural frequency of the plate decreases with increasing magnetic field intensity. Kabashima *et al*. (1990) studied the mechanical behavior of a thin metal plate in time varying magnetic field. Takagi *et al*. (1992) conducted an experiment of thin plate deflection in magnetic field and presented some computational analyses by using the T-method. Qin *et al*. (2003) investigated the implication of magnetoelastic loads on the free vibration behavior and stability of circular cylindrical shells and the finite dimensional effects is addressed systematically. Effect of an applied transverse impulsive magnetic field on the vibration and bending of cantilever conductive thin plate has been studied by Zheng *et al*. (2005). Korobkov *et al*. (2007) studied the influence of the transverse and the longitudinal magnetic fields on the eigen frequencies of the rectangular plate and observed that the transverse magnetic fields reduce the eigen frequencies of the plate's vibration. Wei *et al*. (2007) carried out the theoretical and experimental analysis of ferromagnetic plate subjected to an inclined magnetic field and soft ferromagnetic beam subjected to steady uniform magnetic field. Their results reveals that the frequency of the plate increases with increasing applied magnetic field. Zhupanska and Sierakowski, (2007) studied the effects of an electromagnetic field on the mechanical response of composites. Niu *et al*., (2008a) studied the active vibration control of beam through electro-magnetic constrained layer damping and extended the same work for hybrid vibration control of cylindrical shell by Niu *et al*., (2008b). Gao *et al*., (2010) presented the analysis of electro-magneto-thermo-mechanical behaviors of conductive circular plates under a time-dependent magnetic field. Barakati and Zhupanska (2012) analyzed the effect of a pulsed electromagnetic field on the dynamic response of electrically conductive composites. They also observed that the increase in the magnetic induction tends to reduce the amplitude of vibrations of the plate and noticed more rapid decay at the higher induction magnitude. Tripathi and Gangadharan (2012) employed the semi-active coil based electromagnetic vibration suppression of a cantilever beam integrated with a copper coil and permanent magnet and validated the model experimentally using semi-active damping concept. Wang (2013) developed the magnetoelastic model for soft ferromagnetic plates with nonlinear magnetization in an applied magnetic field based on generalized magnetoelastic variational principle and Hamilton's principle. Golubeva *et al.* (2013) presented the vibration analysis of ferromagnetic dielectric plates in longitudinal magnetic fields.

1.7 Scope and Objective of the Dissertation

The comprehensive literature review presented in the previous section reveals the growing interest in the research on structural analysis of magneto-electro-elastic (**MEE**) structures. However, the literature concerning large deformations of the **MEE** composite structures is meager although the **MEE** structures are being thin and flexible in most of the applications. Due to the flexibility of structures and small material damping, vibrations induced in the structures may lead to large amplitude vibrations with longer decay time resulting in the failure of the structure caused either by structural fatigue or instability. Consequently, it is imperative to conquer the issues concerned with the deterioration of structures due to large amplitude vibrations using active control strategy. The implementation of the **ACLD** treatment over the last two decades has been recognized as an exceptionally efficient means for achieving the active vibration control of flexible structures. In the **ACLD** treatment, the smartness of piezoelectric materials i.e., the converse effect possessed by piezoelectric materials is exploited for the control of vibrations of the structures. Hence, the concept of the **ACLD** treatment may be utilized to produce the efficient smart structures such that the catastrophic consequence of large amplitude vibrations may be alleviated.

It is evident from the literature review on the piezoelectric materials that the 1-3 **PZC** materials provide a wide range of material properties and are superior to that of the monolithic piezoelectric materials. The 1-3 **PZC** materials like vertically/obliquely reinforced 1-3 **PZC**s are commercially available and most suitable for constraining layer of the **ACLD** treatment to obtain the efficient damping characteristics of the host structures. Comprehensive analysis of the **ACLD** of geometrically nonlinear vibrations of conventional laminated composite structures (Gao and Shen, 2003; Sarangi and Ray, 2010, 2011a, 2011b), **FG** structures (Panda and Ray, 2008a, b, c, 2009) and sandwich structures (Kumar and Ray, 2013) has been reported in the literature. However, the research on the **ACLD** of geometrically nonlinear vibrations of magneto-electro-elastic (**MEE**) or multiferroic composite structures like plates, shells and functionally graded **MEE** (**FGMEE**) plates and shells using the vertically/obliquely reinforced 1-3 **PZC** has not yet been reported in the open literature. The dynamic characteristics of the **MEE** plates and shells undergoing **ACLD** may not be similar to that of the conventional thin composite plates and shells because of the complication involved due to electroelastic and magnetoelastic coupled fields. This lacking of knowledge provides an ample scope for further research.

Laminated/layered composite structures can be tailored to design advanced structures while the discontinuity or mismatch in the properties of each layer at the interface between the two adjacent layers may cause interlaminar shear stresses that may lead to the initiation of imperfection like delamination, crack etc. The mismatch of properties in the top and the bottom layers can be alleviated by replacing the top and bottom layers of the **MEE** structure with functionally graded materials (**FGM**s) of piezoelectric and magnetostrictive constituents where the properties of the top and bottom layers vary across the thickness according to a standard power-law (Bhangale and Ganesan, 2005; Zenkour, 2005a, 2005b) while maintaining continuity of properties at the interfaces. The resulting structure where the top and bottom layers are replaced by such **FGM**s becomes a **FGMEE** structure. The static/dynamic analysis, exact solutions and free vibrations of **FGMEE** plates/shells have been studied in detail by Pan and Han, 2005; Bhangale and Ganesan, 2005; Ramirez *et al*., 2006; Haitao *et al*., 2008 ;Tsai *et al*., 2008. But the **ACLD** of geometrically nonlinear vibrations of **FGMEE** plates and doubly curved **FGMEE** shells has not yet been reported and this provides further scopes to fill the gap in the literature.

The influence of magnetic fields on the dynamics of ferromagnetic plates has been reported in the literature (Zheng *et al*. 2005; Wang, *et al*. 2005; Korobkov *et al*. 2007;Tanaka *et al*., 2009; Gao *et al*., 2010; Barakati and Zhupanska, 2012; Golubeva *et* *al*. 2013; Wang, 2013). However, this study has not been extended to the **MEE** structures. Further, the **MEE** substrate itself consists of smart materials such as piezoelectric/magnetostrictive materials. Hence, it is imperative to investigate if the electric and the magnetic fields in which the **MEE** structures are under operation can be exploited for attenuating the geometrically nonlinear vibrations of the **MEE** structures. This provides the motivation to accomplish the task on the active control of the **MEE** structures.

The main goal of this dissertation is to investigate the performance of the vertically/obliquely reinforced 1-3 **PZC**s as the materials of the constraining layer of the **ACLD** treatment for controlling the geometrically nonlinear vibrations of smart magneto-electro-elastic plates and shells by taking into consideration of the above mentioned aspects. In order to accomplish the goal, the following theoretical analyses have been carried out:

1. Smart damping of geometrically nonlinear vibrations of magneto-electro-elastic plates using vertically/obliquely reinforced 1-3 **PZC** materials (Kattimani and Ray, 2014b).
2. Active control of large amplitude vibrations of smart magneto-electro-elastic doubly curved shells using vertically/obliquely reinforced 1-3 **PZC** materials (Kattimani and Ray, 2014a).
3. Smart damping of geometrically nonlinear vibrations of functionally graded magneto-electro-elastic plates using vertically/obliquely reinforced 1-3 **PZC** materials.
4. Smart damping of large amplitude vibrations of functionally graded smart magneto-electro-elastic doubly curved shells using vertically/obliquely reinforced 1-3 **PZC** materials
5. Smart damping of geometrically nonlinear vibrations of fiber reinforced magneto-electro-elastic plates and shells using vertically/obliquely reinforced 1-3 **PZC** materials.
6. Active damping of geometrically nonlinear vibrations of magneto-electro-elastic plates and shells without using **ACLD** treatment.

1.8 Contributions from the dissertation

The following contributions in the field of **MEE** smart composite structures have been made towards the preparation of the dissertation:

1. Three dimensional nonlinear **FE** models are developed to study the **ACLD** of geometrically nonlinear vibrations of the homogeneous, functionally graded and fiber reinforced smart **MEE** plates and shells. The vertically/obliquely reinforced 1–3 **PZC** materials are considered as the candidate material for the constraining layer of the **ACLD** treatment
2. The constrained viscoelastic layer is modeled by implementing the **GHM** approach in time domain for the **ACLD** of geometrically nonlinear vibrations of the smart **MEE** plates and doubly curved shells.
3. Layer-wise transverse deformations of the overall **MEE** structures are considered to utilize the vertical actuation by the vertically/obliquely reinforced active constraining 1-3 **PZC** layer of the **ACLD** treatment.
4. Emphasis has been placed on investigating the influence of variation of the piezoelectric fiber orientation angle on the control authority of the **ACLD** treatment.
5. Backbone curves of the **MEE** structures are derived to determine the applied step load which cause substantial nonlinearity in the uncontrolled responses.
6. The necessity of the **ACLD** treatment on the control of geometrically nonlinear vibrations of the **MEE** plates and shells has been investigated by applying the control voltage and the magnetic fields directly to the layers of the **MEE** substrate.

1.9 Overview of the Thesis

This thesis contains eight chapters. In the first chapter, a brief introduction and review of literature on the **MEE** structures, the **PZC** composites, the **ACLD** treatment and linear and nonlinear analyses of smart structures have been presented. Subsequently, the scope of the present research is identified and the objectives of the present research are defined. Next, the contributions from the present research are highlighted.

The present study is devoted to investigate on the control of geometrically nonlinear vibrations of the smart magneto-electro-elastic plates and shells by using 1-3 **PZC** composite. For such investigation, the kinematics of deformations of **MEE** plates and shells is described by a layerwise high order shear deformation theory. For incorporating geometric nonlinearity the von Kármán type strain-displacement relations are considered. The **GHM** approach is implemented for modeling the viscoelastic layer in time domain and a simple velocity feedback control law is employed to incorporate the active damping.

Chapter 2 deals with the detailed formulation and finite element (**FE**) modeling for the **ACLD** of geometrically nonlinear vibrations of the **MEE** plates. The constraining layer of the **ACLD** treatment is made of the vertically/obliquely reinforced 1-3 **PZC** material. Influence of material stacking sequence, the **ACLD** patch location on the top surface of the plate, effect of coupled fields and boundary conditions on the **MEE** substrate plate is considered for presenting the numerical results.

In chapter 3, the **FE** analysis studied in chapter 2 has been extended to demonstrate the performance of the vertically/ obliquely reinforced 1-3 **PZC** material as the material of the constraining layer of the **ACLD** treatment for controlling the geometrically nonlinear vibrations of the functionally graded magneto-electro-elastic (**FGMEE**) plates. The **FGMEE** substrate plate with different configurations, power law index, boundary conditions and the effect of electroelastic and magnetoelastic coupled fields are considered for investigating the performance of the **ACLD** treatment.

Chapter 4 is concerned with the performance of the **ACLD** patches for controlling the geometrically nonlinear vibrations of the **MEE** doubly curved shells with 1-3 **PZC** material as the material of the constraining layer of the **ACLD** treatment. Substrate **MEE** shells with the paraboloid and the hyperboloid configurations are considered for this study. Influence of the curvature ratio, the curvature aspect ratio, the thickness aspect ratio on the nonlinear frequency ratios of the **MEE** doubly curved shells has also been investigated.

The three dimensional **FE** model for the control of geometrically nonlinear vibrations of the **FGMEE** paraboloid and hyperboloid shells using the vertically/obliquely reinforced 1-3 **PZC** material has been addressed in Chapter 5. The effect of power law index, curvature ratio, the curvature aspect ratio, the thickness aspect ratio and the effect of piezoelectric fiber orientation angle in the 1-3 **PZC** constraining layer on the performance of the **ACLD** treatment for controlling the geometrically nonlinear vibrations of the **FGMEE** shells have been investigated.

Chapter 6 deals with the control of geometrically nonlinear vibrations of fiber reinforced magneto-electro-elastic (**FRMEE**) plates and **FRMEE** doubly curved shells. Effect of boundary conditions, electro-elastic and magneto-elastic coupled fields, piezoelectric (**$BaTiO_3$**) fiber volume-fraction in the substrate and piezoelectric fiber orientation angle in the 1-3 **PZC** constraining layer on the control of geometrically nonlinear transient vibrations has been studied.

Smart control of geometrically nonlinear vibrations of magneto-electro-elastic (**MEE**) plates and doubly curved shells without using the **ACLD** treatment has been investigated in chapters 7. The importance of the **ACLD** treatment for optimum control of geometrically nonlinear vibrations of the **MEE** plates and shells has been investigated by activating the piezoelectric and the magnetostrictive layers of the **MEE** substrates in presence of the electric and the magnetic fields.

Finally, in chapter 8, the important conclusions from the dissertation and the future scope of work in line with this research are delineated. The list of references and the appendices are provided at the end of the dissertation.