CHAPTER - 2
LITERATURE SURVEY

2.1 A Brief Technical Review of Piezoelectric Smart Structures and Controllers

After a brief overview of history of smart structures, piezoelectric transducers and control system, this section applies the brief review of design, modeling, experimentation, Finite Element Method, design and implementation of controllers and some optimal methods to a few applications. It is based on the overall review of all the references. These early experiments/applications have more than just an historical value. More applications have been considered in future.

2.1.1 A Brief Review on Modeling and Analysis by Analytical and Experimental Method

A.K. Singh and Deepak Apte [002] have discussed a mathematical model for hysteresis in piezoelectric actuators based on domain wall bending and translation.

Ahmad Gharib et. al. [004] have developed an analytical solution for analysis of functionally graded material (FGM) beams containing two layers of piezoelectric material, used as sensor and actuator.

Alberto Donoso and Jose Carlos Bellido [005] have dealt with finding the shape of distributed piezoelectric modal sensors for circular plates with polar symmetric boundary conditions. The problem is treated by an optimization approach, where a binary function is used to model the design variable: the polarization profile of the piezoelectric layer.

Amit Singh and Darryll J. Pines [007] have developed an integrated model of periodic 1-D structures with piezoelectric actuators for complete active/passive
control. An analytical model is also developed to predict the performance of the periodic rods and beams with piezoelectric actuators acting as controllers.

Andrew J. Fleming and S. O. Reza Moheimani [010] have introduced a frequency domain system identification technique aimed at obtaining spatially continuous models for a class of distributed parameter systems.

Dongchang Sun and Liyong Tong [021] have presented an equivalent model for smart beams with partially debonded piezoelectric actuator/sensor patches to analyze the effect of the actuator debonding on both open loop and closed loop behaviors.

Dongchang Sun et. al. [022] have investigated the effect of debonding on vibration control of beams with piezoelectric actuators and sensors. Both collocated and non-collocated control schemes are used to study the effects of sensor or actuator debonding on active vibration control of smart beams.

Dr M. Collet and Dr M. Ouisse [023] have proposed a synthesis of new methodologies for developing a distributed, integrated shunted piezo composite for beams and plates applications able to modify the structural vibro-acoustical impedance of the passive supporting structure so as to absorb or reflect incidental power flow.

Dr. Chandrashekhar Bendigeri and Ritu Tomar [024] have presented the formulation of the finite element for static analysis based on isoparametric formulation.

F. Ebrahimi, A. Rastgo [028] have presented the detailed mathematical derivations and numerical investigations performed for FG plates with two surface-bonded piezoelectric layers. The results are verified by those obtained from three-dimensional finite element analyses.

Fayaz R. Rofooei and Ali Nikkhoo [029] have derived the governing differential equation of motion for an un-damped thin rectangular plate with a
number of bonded piezoelectric patches on its surface and arbitrary boundary conditions, by using Hamilton’s principle.

Gyuhae Park et. al. [034] have presented experimental investigations of vibration testing of an inflated, thin-film torus using smart materials.

Hui Zhang et. al. [038] have investigated, a theoretical model of radially polarized piezoelectric ceramic tubes based on Timoshenko beam model. Based on the model, the particular attentions are devoted to effects of the boundary conditions at two ends on flexural resonance frequencies of the piezoelectric ceramic tubes.

J. Tang and K. W. Wang [043] have proposed to develop an active-passive hybrid vibration confinement system by using piezoelectric network actuators. A new simultaneous optimization / optimal eigenvector assignment approach is developed.

Jin-Chein Lin and M.H. Nien [047] have investigated modeling and vibration control of a smart beam using piezoelectric damping-modal actuators/sensors. Theoretical formulations based on damping-modal actuator/sensors and numerical solutions are presented for the analysis of laminated composite beam with integrated sensors and actuators.

K. Jayakumar et. al. [051] have studied nonlinear free vibrations of simply supported piezo-laminated rectangular plates with immovable edges. Frequency ratios of various vibrating modes are computed. Nonlinear frequencies of fundamental vibration of piezo-laminated plates of six lamination schemes (viz., asymmetric, symmetric, balanced, cross-ply, angle-ply and symmetric cross-ply) are also computed.

Ken Susanto [053] presents an analytical model of PLSCB, which includes the computation of natural frequencies, mode shapes and transfer function formulation using the Distributed Transfer Function Method (DTFM).
Kunal V. Joshi and P. M. Mujumdar [054] address the development of an efficient methodology to simultaneously determine, the optimal size and location of a given number of piezoelectric patch actuators, as well as controller gains, in order to satisfactorily and effectively control a designated number of structural vibration modes, with minimum spillover into residual modes, subject to actuation limit, total actuator area and closed loop damping ratio constraints.

L. Azrar et. al [056] have developed modal analysis for linear and nonlinear vibrations of deformed sandwich piezoelectric beams with initial imperfections. The mathematical formulation is developed for the multimodal analysis.

L. Q. Yao et. al. [059] have studied the dynamic characteristics of piezoelectric bending actuators under low and high electric fields by using the asymptotic theory of non-stationary vibrations.

Limei Xu et. al. [062] determines the optimal dimension of a piezoelectric actuator attached to a multilayered elastic plate clamped at both ends by a theoretical analysis. The first-order theory for laminated piezoelectric plates is used.

M Sunar and B. O. Al-Bedoor [067] have carried out numerical and experimental studies to investigate the usability of a piezoceramic (PZT) sensor placed in the root of a stationary cantilever beam for measuring structural vibrations. The ability of the sensor for picking up the vibration signals during both the transient and steady-state phases is investigated.

Marcus Neubauer and Jorg Wallaschek [070] describe the damping performance of shunted piezo-ceramics for passive LR-networks, negative capacitance shunts (LRC) and the SSDI-switching technique.
Nadav Peleg et. al. [078] have applied the structural topological design methodologies to the positioning of patches of piezoelectric (PZT) actuators on vibrating plane structures in order to reduce the total radiated sound.

P. Pertsch et. al. [082] explains DC and AC degradation mechanisms as well as the unique design of the PICMA co-fired actuators which is properly adapted to both load cases. Besides some characteristics of the actuators results of DC- and AC-reliability investigations are presented.

Ronny Calixto Carbonari and Emílio Carlos Nelli Silva [090] presented examples herein are limited to two-dimensional models once in most part of applications of these actuators they are planar devices to illustrate the method.

Tamara Nestorovic et. al. [103] have presented the control system design based on a non-linear model reference adaptive control law (MRAC) used for the vibration suppression of a smart piezoelectric mechanical structure.

Ugur Aridogan et. al. [106] have presented an active vibration suppression of a smart beam using self-sensing piezoelectric actuator.

Victor Giurgiutiu and Andrei N. Zagrai [108] have developed and used an analytical model based on structural vibration theory and theory of piezoelectricity to predict the electro-mechanical (E/M) impedance response, as it would be measured at the piezoelectric active sensor’s terminals.

Yaowen Yang and Aiwei Miao [116] have developed an electromechanical impedance EMI model for beam structures, which takes into account the effect of beam vibration caused by the external excitations. An experimental study is carried out to verify the theoretical model.

Yong Xie et. al. [117] have studied the internal balance method theoretically as well as experimentally, In this method the study was done on working on a DSP TMS320F2812-based experiment system with a flexible plate and bringing forward an approximating approach to accessing the internal balance modal coordinates.
2.1.2 A Brief Review on Finite Element Modeling and Analysis

A. Benjeddou [001] has discussed the advances and trends in the formulations and applications of the finite element modeling of adaptive smart structural elements.

Antonio Zallo and Paolo Gaudenzi [011] have extended the adaptive shell finite element from 4-node to 9-node and 16-node elements. An active layer made by a piezoelectric material or a similar active medium is assumed to be included in a stacking sequence of a laminated shell.

C.H. Nguyen and S.J. Pietrzko [015] have presented the simulation of adaptive structures with shunt circuits via the finite element method (FEM).

Henrique Santos et. al. [036] have addressed the bending and free vibrations of multilayered cylindrical shells with piezoelectric properties using a semi-analytical axisymmetric shell finite element model with piezoelectric layers using the 3D linear elasticity theory.

Jens Becker et. al. [046] have studied the impact of parameters of the passive electrical network on modal damping ratios as well as the variation of the patch thickness by ANSYS models.

Jose M. Simoes Moita et. al. [049] have presented a finite element formulation for active vibration control of thin plate laminated structures with integrated piezoelectric layers, acting as sensors and actuators.

K. Ramkumar et. al. [052] have presented work deals with the active vibration control of isotropic and laminated composite box type structure under thermal environment using finite element method.

M.A.R. Loja et. al. [063] deals with the development of a family of higher order B-spline finite strip models applied to static and free vibration analysis of laminated plates, with arbitrary shapes and lay-ups, loading and boundary conditions.
M.C. Ray and H.M. Sachade [064] deals with the derivation of a finite element model for the static analysis of functionally graded (FG) plates integrated with a layer of piezoelectric fiber reinforced composite (PFRC) material.

M. Rahmoune and D. Osmont [065] have proposed a finite element model to solve both actuator and sensor problems without using the electrical DOFs.

Marcelo A. Trindade and Ayech Benjeddou [069] have extended refined sandwich beam finite element (FE) model to vibration analysis, including dynamic piezoelectric actuation and sensing.

Mercedes C. Reaves and Lucas G. Horta [073] have presented the development, modeling, and testing of two structures: an aluminum plate with surface mounted patch actuators and a composite box beam with surface mounted actuators.

Olli Kursu et. al. [080] have presented an analytical model, a finite element analysis and measured results for a planar, parallel and symmetrical piezoelectric bimorph structure.

Premjyoti G. Patil and Y.S. Kumara Swamy [084] have proposed a mathematical model for the deformation of cantilever beam using Finite Element Method that makes the approach so efficient.

Q. Chen and C. Levy [085] have discussed the temperature effects on frequency, loss factor and control of a flexible beam with a constrained visco-elastic layer and shape memory alloy layer (SMA).

S. Valliappan and K. Qi [097] have proposed a smart mild steel damper to provide active damping for seismic control of structures. Smart finite element formulation is outlined for the numerical analysis of the proposed control device.

S.Y. Wang [098] has proposed a finite element model for the static and dynamic analysis of a piezoelectric bimorph.
S.X. Xu and T.S. Koko [099] have presented a general purpose design scheme of actively controlled smart structures with piezoelectric sensors and actuators. The proposed scheme can make use of any finite element code with piezoelectric elements, and control design is carried out in state space form established on finite element modal analysis.

Wanlin Zhou and Jianpeng Chen[110] have combined the finite element inverse analytic method with the BP nerve network and proposes a way to identify the localization of the impact force acting on composite plates.

Y.D. Kuang et. al. [114] have developed an analytical modeling of a circular curved beam with asymmetric surface-bonded piezoelectric actuators. In numerical examples, both the FEM results and the straight unimorph chosen as a special case are used to validate the present model.

Yu-Hsi Huang, Chien-Ching Ma [118] have used the cantilever and completely free quartz plates and the experimental results are verified by the finite element (FEM) analysis.

Z.K. Kusculuoglu et. al. [119] have presented a finite element model of a beam with a piezo-patch actuator. Both the beam and the patch actuator are modelled using Timoshenko beam theory.

2.1.3 A Brief Review on Control Techniques and Their Applications

A. Mukherjee and A. Saha Chaudhuri [003] have presented the geometric nonlinear dynamic analysis and control of piezo-laminated beams. In case of constant gain feedback control the effect of stiffening of the structure due to actuation increases rapidly with the increase in the in-plane compressive force.

B J G Vautier and S O R Moheimani [013] have used in a control feedback scheme to reject disturbance vibrations acting on a cantilevered beam.

B. Yan et. al. [014] have described a self-contained four-channel programmable controller designed to provide flexible sensing and control
functions for situations requiring heavy computational load, real-time control, high-speed data acquisition, and fast signal processing.

Chen Long-Xiang et. al. [017] have presented an experimental study of delayed feedback control using a flexible plate as research object. A treating method for multiple time delays is proposed.

D. C. Sun and L. Tong [018] have investigated the vibration control of the composite beam integrated with curved piezoelectric fibers.

Dunant Halim and S. O. Reza Moheimani [025] have introduced a class of resonant controllers that can be used to minimize structural vibration using collocated piezoelectric actuator-sensor pairs.

F. Dell’Isolaa et. al. [027] have focused on a completely passive electric circuit analog to an Euler beam aimed for distributed vibration control.

G. Song et. al. [030] have presented a review for vibration suppression of civil structures. Special emphasis is laid upon smart structures with piezoelectric control actuation.

G.W. Butler [031] focuses on the development of a numerical performance model to better understand the coupling between the actuators and the turbulent flow field.

Gustavo Luiz C. M. de Abreu and Jose F. Ribeiro [033] have designed and evaluated the performance of a feedback $H_{\infty}$ controller to suppress vibration of a flexible cantilever beam provided with strain actuator and sensor.

Hiraku Sakamoto and K. C. Park [037] have derived optimal feedback laws for two kinds of active controllers using partitioned structural modeling.

I.S. Sadek et. al. [039] have evaluated an analysis of the solutions for various feedback control laws applied to vibrating simply supported plates. The feedback controls implemented include displacement, velocity, and a combination of these.
Ismail Kucuk et. al. [040] have considered active control of a vibrating beam using piezoelectric patch actuators. The explicit solution of the problem is developed by using eigen-function expansions of the state and adjoint variables.

J.M. Sloss et. al. [042] have studied the effect of axial force in the vibration control of beams by means of an integral equation formulation, which facilitates the numerical solution of the problem of finding the eigen-frequencies and eigen-functions of a freely vibrating beam controlled by piezo patch sensors and actuators.

Kougen Ma [055] have investigated the dynamic behavior and control of a clamped rectangular plate with bonded piezoelectric ceramic patches by experimentally.

L. Gaudiller and S. Bochard [057] have presented the principle of a new adaptive controller MIMO, making it possible to render nearly constant the dynamic behavior of multi-articulated flexible structures in spite of changes in the geometry of their masses.

L. Malgaca and H. Karagülle [058] have analyzed an active control of a smart beam under forced vibration. Control actions, the finite element (FE) modeling and analyses are directly carried out by using ANSYS parametric design language (APDL).

Lee, Y.K et. al. [060] have described the design and experimental evaluation of an optimal feedback control strategy to suppress global broadband structural vibration of a flexible plate.

Liang Wang et. al. [061] has proposed an $H_\infty$ method for the vibration control of an iron cantilever beam with axial velocity using then on contact force by permanent magnets.

M. Sridevi and P. Madhavasarma [066] have designed a controller that minimizes the structural vibration using $H_\infty$ controller.
Marek Pietrzakowski [071] has formulated models of piezoelectric coupled laminated plates based on Kirchhoff’s and Mindlin’s kinematic assumptions involving the electric potential distribution, which satisfies the Maxwell electrostatics equation.

Mohd Fuaad Rahmat et. al. [075] have investigated the performance of few different control approaches that consist of conventional controller, modern controller and intelligent controller for a ball and beam system.

Moon K. Kwak et. al. [076] have concerned with the dynamic modeling, active vibration controller design and experiments for a cylindrical shell equipped with piezoelectric sensors and actuators. The dynamic model was derived by using Rayleigh–Ritz method.

Omer Faruk Kircali et. al. [081] have presented the design and implementation of a spatial $H_{\infty}$ controller for the active vibration control of a smart beam. Additionally, spatial identification of the beam was performed.

Philip Shimon et. al. [083] have investigated two control methodologies, positive velocity feedback and $H_{\infty}$ control and two types of actuators, an inertial actuator and a distributed strain actuator.

Rajiv Kumar [088] has investigated adaptive controllers based on minimum variance, pole placement and linear quadratic techniques.

Robert A. Canfield et. al. [089] have investigated numerically the effectiveness of piezoelectric actuators in reducing vibratory response due to buffet loads on the F-16 ventral fin.

S. Belouettar et. al. [091] have studied nonlinear vibrations of piezoelectric/elastic/piezoelectric sandwich beams submitted to active control. The proportional and derivative potential feedback controls via sensor and actuator layers are used and adopted the Harmonic balance method and the Galerkin procedure.
S. Carra et al. [092] have analyzed a rectangular aluminium plate vibrating in air or in contact with water. A filtered-X least mean square (FXLMS) adaptive feed-forward algorithm is applied to the system, realizing structural vibration control in linear field with a SISO approach on the first vibration modes of the plate.

S.O. Reza Moheimani and Dunant Halim [096] have introduced an alternative procedure to the mode acceleration method when the underlying structure model includes damping and show that the problem can be cast as a convex optimization problem that can be solved via linear matrix inequalities.

Senthil S. Vel and Brian P. Baillargeon [100] deals with the experimental and numerical assessment of the vibration suppression of smart structures using positive position feedback controllers.

Seung-Bok Choi [101] has studied a robust control for the structure-borne noise of a smart plate by adopting the piezoelectric actuators and has been designed the frequency domain robust $H_\infty$ controller.

Shengquan Li et al. [102] have presented a novel composite controller based on disturbance observer (DOB) for the all-clamped panel by considering the spillover and harmonic effect in real active vibration control by an optimal linear quadratic regulator (LQR) strategy.

Tamara Nestorovic [104] has presented active control of smart structures within a focused frame of piezoelectric applications in active vibration and noise attenuation with potentials for the use in mechanical and civil engineering.

V. Sethi and G. Song [107] have designed a full-state linear quadratic regulator (LQR) controller by using the identified model. To achieve the full state feedback, an observer is designed based on the identified model.
Xing-Jian Dong et. al. [113] have employed the linear quadratic Gaussian (LQG) algorithm for controller design. The control law is then incorporated into the ANSYS finite element model to perform closed loop simulations.

Yan-Ru Hu and Alfred Ng [115] have developed an approach for active vibration control of flexible structures with integrated piezoelectric actuators using control theory.

### 2.1.4 A Brief Review on Optimal Placement of PZT Patches

Ali Reza Mehrabian and Aghil Yousefi-Koma [006] have used the optimization methodology for the placement of piezoelectric actuator pairs for effective vibration reduction over the entire structure.

Dongchang Sun and Liyong Tong [020] have designed and developed a Quasi-model actuator to actuate the designated modes by means of modulating the voltage distribution of PZT patches and a criterion for optimal placement of patches is presented based on the minimizing the observation spillover.

Dunant Halim and S.O. Reza Moheimani [026] have suggested a criterion for the optimal placement of collocated piezoelectric actuator–sensor pairs on a thin flexible plate using modal controllability measures.

J. Ducarne et. al. [041] have proposed the optimization based on maximizing the modal electro-mechanical coupling factor (MEMCF), which is assumed to be the main free parameter.

K.D. Dhuri and P. Seshu [050] have used maximum controllability and minimal change in natural frequencies for the multi-objective genetic algorithm (MOGA) to identify the optimal locations and sizing of piezoelectric sensors/actuators.
U. Ramos and R. Leal [105] have maximized the transversal displacement produced by 8 pairs of piezoelectric actuators optimizing their location in a space of 56 possible locations.

Xiaojian Liu and David William Begg [112] have considered quadratic performance index and model controllability for the development of the smart system to make the multidisciplinary system work efficiently and optimally.

Zhi-cheng Qiu et. al. [120] have developed an optimal placement method for the locations of piezoelectric actuators and sensors based on the degree of observability and controllability indices for cantilever plate.

According to the brief review of the work, many researchers have worked on the control area by using piezoelectric material as element of smart structure. It has been believed that these early experiments/applications have more than just an historical value and also they have used the point-wise method to control the amplitude of vibration of the beam and plates. The effect of this piezoelectric material on the structure and the controller have not been discussed in details.

Hence it was felt to author that still the more research required to find out the settling time using four controllers (LQR, LQG, spatial $H_2$ and $H_\infty$) at different positions by using Piezoelectric materials. To validate the same, experimental as well as Finite Element Methods have been used. Also, All the control techniques have been implemented for location of piezoelectric actuators and sensors for smart structures (Beam and Plate) under cantilever and simply supported conditions.