AJCSE
ASIAN JOURNAL OF COMPUTER SCIENCE ENGINEERING

www.ajcse.info

Asian Journal of Computer Science Engineering 2017; 2(2):01-14

REVIEW ARTICLE

An Extensive Review of Piezoelectric Smart Structure and Controller for Active Vibration Control

***J. R. Chaudhari [1], Dr. C. R. Patil [2]**

[1] *Mechanical Engineering Department, SSGB COE&T, Bhusawal, India - 425 201*
[2] *Mechanical Engineering Department, PRMIT&R, Badnera, India - 444 701*

Received on: 15/01/2017, Revised on: 30/02/2017, Accepted on: 10/03/2017

ABSTRACT

Nowadays, vibration is one of the major issues in the environment, which may cause some serious injuries to the human health. Vibration may occur due to mechanical oscillation from industrial machines, railway track nearby human reside, and many more reasons. It needs to be eradicated with proper controlling techniques. Active vibration control is a technique in which the vibration of a structure is controlled by applying counter force to the structure that is appropriately out of phase but equal in amplitude to the original force. As a result two opposite forces cancel each other and structure stops vibrating. Piezoelectric and Piezoelectric Ceramic materials have ability to transform mechanical energy to electrical energy and vice-versa can be used as sensors and actuators. The piezoelectric sensor senses the external disturbances and generates voltage due to direct piezoelectric effect while piezoelectric actuator produces force due to converse piezoelectric effect which can be used as controlling to force. After a brief overview of history of smart structures, piezoelectric transducers and control system, this section applies the brief review of design, modelling, 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.

Key words: PZT, FEA, Controllers, AVC

A Brief Review on Modeling and Analysis By Analytical And Experimental Method

Andrew J. Fleming and S. O. Reza Moheimani [1] have introduced a frequency domain system identification technique aimed at obtaining spatially continuous models for a class of distributed parameter systems. The technique is demonstrated by indentifying a simply supported beam and trapezoidal cantilever plate, both with bonded piezoelectric transducer. The work involves the development of an efficient optimization algorithm to minimize the error due to under sampling.

Dongchang Sun et. al. [2] has 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. An analytical model is presented for closed loop vibration control of a smart beam with partially debonded piezoelectric sensor/actuator patches based on the classical beam theory.

Amit Singh and Darryll J. Pines [3] 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. Dr M. Collet and Dr M. Ouisse [4] has 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. A periodic distribution of shunted piezo transducers integrated into a passive supporting structure is presented in this work. An optimization process is implemented for the design of the electronic shunt circuits so as to achieve a desired dynamical impedance of the passive/active composite beam or plate structures for wave absorption or reflection. The results obtained to indicate great potential for such a technique by increased robustness and efficiency of the

***Corresponding Author:** J. R. Chaudhari**, Email:** jitendra_rc@rediffmail.com

strategy. The proposed methodology and prototypes demonstrate potentiality and efficiency of such new smart integrated meta-composite material for controlling vibroacoustic flow.

A.K. Singh and Deepak Apte [5] have discussed a mathematical model for hysteresis in piezoelectric actuators based on domain wall bending and translation. The validity of the model has been illustrated with comparison of the experimental observations of piezoelectric stack actuator developed using PZT5H material.

Dongchang Sun and Liyong Tong [6] 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. The effect of the actuator debonding on the modal shapes is investigated through an example, and the additional modal shapes induced by the debonding are also examined. The effect of the edge debonding of an actuator patch on the modal shapes of the composite beam is studied and a scheme to best restore the closed loop control, which has been worsened by the actuator debonding, is theoretically and experimentally demonstrated.

Alberto Donoso and Jose Carlos Bellido, [7] 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. They proposed the numerical procedure which allows finding polarization profiles which take on two values i.e. either positive or negative polarization, that isolate particular vibration modes in the frequency domain.

K.B. Waghulde, Dr. Bimleshkumar et al [8] has constructed smart beam using a Lucite beam, PZT actuator and PVDF sensor to control vibration response to broadband disturbance. A dSPACE controller was installed and integrated with related electronics to create an active control set up.

Hui Zhang et. al. [9] has investigated, a theoretical model of radially polarized piezoelectric ceramic tubes based on Timoshenko beam model. Based on the model, the particular attentions is devoted to effects of the boundary conditions at two ends of flexural resonance frequencies of the piezoelectric ceramic tubes.

Dr. Chandrashekhar Bendigeri and Ritu Tomar [10] have presented the formulation of the finite element for static analysis based on isoparametric formulation. The finite element code for analysis of smart structure is developed using MATLAB programming language. The finite element code developed for smart structure analysis and electromechanical analysis of the smart composite structure is found to have good agreement with the experimental results.

F.Ebrahimi, A.Rastgo [11] has presented Analytical investigation into the free vibration behavior of circular functionally graded (FG) plates integrated with two uniformly distributed actuator layers made of piezoelectric (PZT4) material on the top and bottom surfaces of the circular FG plate based on the classical plate theory (CPT). The detailed mathematical derivations are presented 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.

Jin-Chein Lin and M.H. Nien [12] 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. A compensator is used in the first three modes to perform the shape control of the smart beam, which can attenuate the spillover of vibration so that the stability of the numerical simulation has been compared to those obtained with the experimental tests and a good correspondence has been obtained in all the case.

M Sunar and B. O. Al-Bedoor [13] has 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. The piezoelectric equations obtained using the Hamilton's principle together with the finite element approximation are utilized to extract the voltage outputs of the PZT sensor. Theoretical, numerical and experimental results showed excellent performance of the sensor in reading vibration signals of the beam.

Fayaz R. Rofooei and Ali Nikkhoo [14] 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. The method of Eigen function expansion is used to transform the equation of motion into a number of coupled ordinary differential equations. A classical closed-loop optimal control algorithm is employed to suppress the dynamic response to the system, determining the required voltage of each piezoactuator at any time interval. The efficiency of the control algorithm was investigated using a number of square piezo patches that were uniformly distributed over the lower surface of the plate the response to the system, especially those near the resonant states, was reduced to the desired target displacement with fairly low levels of applied voltages. Finally, increasing the area of the employed piezo patches would reduce the maximum required voltage for controlling the response to the system.

Jayakumar et. al. [15] has 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.

Tang and K. W. Wang [16] has proposed to develop an active-passive hybrid vibration confinement system by using piezoelectric network actuators. A new simultaneous optimization / optimal eigenvector assignment approached is developed. The passive and active elements of the control system will be synthesized in a concurrent manner to complement each other, which enables us to have better vibration suppression performance over a larger portion of the structure with less control power input.

Tamara Nestorovic et. al. [17] has 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. Direct MRAC was suggested as a control technique for the dynamic vibration control of piezoelectric structures. The basic MRAC algorithm is modified by augmenting the integral term of the control law in order to provide the robustness of the control system with respect to the stability. This approach provides preserving the boundness of the system states and adaptive gains, with small tracking error over large ranges of non-ideal conditions and uncertainties. The results illustrate excellent performance of the controller and convergence of the adaptive gains. Due to fast calculations which are required for the real time implementation of the control law and the objective technical limitations of the computer system, the effect of the control was tested and shown through the simulation results using the FEM model of a funnel shaped piezoelectric structure.

Kunal V. Joshi and P. M. Mujumdar [18] 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 [19] has 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.

Yaowen Yang and Aiwei Miao [20] have developed an electromechanical impedance EMI model for beam structures, which takes into account the effect of beam vibration caused by the external excitations. The fundamental formulation of EMI model is first derived from a simply supported beam with external excitations. In the experiments, an aluminum beam specimen bonded with a PZT sensor is tested. The effect of external excitation (vibration) on PZT admittance signature could not be neglected if the external excitation frequency and PZT's actuation frequency are comparable.

Limei Xu et. al. [21] determines the optimal dimension of a piezoelectric actuator attached to a multilayered elastic plate clamped to both ends by a theoretical analysis. The first-order theory of laminated piezoelectric plates is used. The numerical result shows that when the actuator length takes a particular value, the center flexural displacement of the elastic plate reaches a maximum.

Yong Xie et. al. [22] has 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. The results show that internal balance model reduction is effective in reducing the order formthe flexible plate. The proceeding method of extracting internal balance modals coordinates is feasible and effective.

Marcus Neubauer and Jorg Wallaschek [23] describe the damping performance of shunted piezo-ceramics for passive LR-networks, negative capacitance shunts (LRC) and the SSD1-switching technique. An optimization of linear LR- and LRC-shunts with negative capacitances is presented, which are based on a complex eigen value analysis and the frequency response. A negative capacitance increases the damping capability, and an optimal capacitance value and the stability boundary are determined.

Ronny Calixto Carbonari and Emilio Carlos Nelli Silva [24], the TOPOPT based on the density method (SIMP) was implemented to design flex tensional piezoelectric actuators. To illustrate the method, 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.

Ugur Aridogan et. al. [25] has presented the use of self-sensing piezoelectric actuator for an active vibration suppression of the smart beam with robust controller which is designed for the stable and the effective suppression of free and the first resonance forced vibration. Active vibration control of a smart beam is achieved with employment of piezoelectric patches as self-sensing actuators via designed robust controller. The experimental work performed on the suppression of free and forced vibrations shows the effectiveness of these self sensing actuators with the robust controller.

P. Pertsch et. al. [26] 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 result from DC and AC reliability investigations are presented. This is ensured by three patented unique design features: 1.ceramic insulation layer protection, 2. Slot segmentation and 3. Slot by passing contact strip layout.

A Brief Review on Finite Element Modeling and Analysis

M.A.R. Loja et. al. [27] deals with the development of a family of higher order B-spline finite strips model applied to static and free vibration analysis of laminated plates, with arbitrary shapes and lay-ups, loading and boundary conditions. The performance of the present model is analyzed by comparing them with some exact and numerical alternative solutions. From the studies carried out, one can conclude from its less computationally expensive characteristics, when compared to standard displacement finite element models based on the same higher theory

C.H. Nguyen and S.J. Pietrzko [28] have presented the simulation of adaptive structures of shunting circuits of the finite element method (FEM). Extensive numerical results are obtained in using the FEM code ANSYS Multiphysics, which has piezoelectric coupling capabilities as well as electric finite elements to be used in the R–L circuit simulation. Extensive numerical results were obtained for three flexural eigen frequencies of the adaptive beam, with successfully calculated high values up to 35% in reduction of the harmonic maximum beam vibration amplitude.

M.C. Ray and H.M. Sachade [29] 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. The finite element solutions revealed that the activated PFRC layer is more effective in controlling the deformations of the FG plates when the layer is attached to the surface of the FG plate with minimum stiffness than when it is attached to the surface of the same with maximum stiffness. The responses from the FG plates under the combined actions of uniformly distributed mechanical load and the uniformly distributed voltage applied to the PFRC layer has also been provided. The investigation into the effect of variation on the piezoelectric fiber orientation on the performance of the activated PFRC layers revealed that in general the performance of the PFRC layers to become maximum if it is integrated with the softest surface of the FG plate.

K. Ramkumar et. al. [30] has presented work deals with the active vibration control of isotropic and laminated composite box type structure under thermal environment using finite element method. The procedure adopted to simulate the dynamic behaviour of the system and to design the active control showed a satisfactory agreement with finite element solution of references. On the basis of the developed procedure by FE it was observed that the parameter such as active damping, stacking sequences and fibre angle has significant influence on the frequency response of the composite box structure and compare to 3D beam element, plate finite element can be used for predicting both local and global active damping behavior of box structure.

Antonio Zallo and Paolo Gaudenzi [31] 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. Piezoelectric and thermoelastic induced strain field are modelled in the finite element formulation. The numerical performance of 4-node, 9node and 16-node has been compared and the convergence to analytical or numerical results available on the open literature is evaluated. The study shows the predicting capabilities of the elements and their numerical effectiveness.

Premjyoti G.Patil and Y.S.Kumara Swamy [32] have proposed a mathematical model for the deformation of cantilever beams using Finite Element Method that makes the approach so efficient. The mathematical model formulated will lay a strong foundation to wipe out the menacing effects of such beam deformation due to the vibrations without any computational as well as implementation complexities.

M. Rahmoune and D. Osmont [33] have proposed a finite element model to solve both actuator and sensor problems without using the electrical DOFs. A finite element model was proposed to solve both actuator and sensor problems without using the electrical DOFs. They have proved that the results of the standard finite elements are of the same order as the experimental and analytical ones. They have shown that the model without the modified elasticity matrix is valid when the piezoelectric films are very thin (1% of thickness of the steel layer). This is due to the fact of neglecting the bending of piezoelectric films. Also, we have shown that if the thickness film is 1% higher than the thickness of non piezoelectric layer, the numerical results of the model with modified elasticity matrix, are of the same order as the experimental and analytical ones.

Henrique Santos et. al. [34] has 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. A numerical procedure based on the Fourier series expansion of the circumferential direction and finite element method in the (z r) plane is used. Numerical results obtained with the present model are found to be in good agreement with other finite element solutions.

Jose M. Simoes Moita et. al. [35] has presented a finite element formulation of active vibration control of thin plate laminated structures with integrated piezoelectric layers, acting as sensors and actuators. The active control capability of composite structures covered with piezoelectric layers is investigated, using the finite element method. A finite element model for active control of thin laminated structures ofpiezoelectric sensor and actuator layers, based on the Kirchhoff classical theory, has been developed. To achieve a mechanism of active control of the structure dynamic response, a feedback control algorithm is used; coupling the sensor and active piezoelectric layers, and the Newmark method is considered to calculate the dynamic response to the laminated structures. The results obtained, shows that the negative velocity feedback control algorithm used in this model is effective for an active damping control of vibration response.

Z.K. Kusculuoglu et. al. [36] has presented a finite element model of a beam with a piezo-patch actuator. Both the beam and the patch actuator is modeled using Timoshenko beam theory. This model is used to generate an expression of factored form of stiffness and mass matrices. Two experimental studies have validated the theoretical developments. It is also observed that the use of the introduced model becomes more important when the piezoceramic and base layers thickness is large and shear and related rotational inertia become more important. The system is actively driven by the PZT wafer and a passive control application is studied for the first mode of the system; it is shown that the model is capable of simulating both active and passive control.

Q. Chen and C. Levy [37] have discussed the temperature effects on frequency, loss factor and control of a flexible beam with a constrained viscoelastic layer and shape memory alloy layer (SMA). The effects of damping layer shear modulus and damping layer height as affected by the temperature are also discussed.

S.Y. Wang [38] has proposed a finite element model for the static and dynamic analysis of a piezoelectric bimorph. A PVDF bimorph beam and a PZT bimorph plate are used to verify the present model. Numerical examples show that the present model can well predict both the global and local responses such as mechanical displacements, modal frequencies as well as the through the-thickness electric potentials, all in good agreement with those from full 3D finite element model or 3D elasticity theory solution. The performance of 2D plane models has been evaluated as less accurate in predicting the static and dynamic responses if transversally isotropic piezoelectric materials are involved.

Mercedes C. Reaves and Lucas G. Horta [39] have presented the development, modeling, and testing for two structures: an aluminum plate with surface mounted patch actuators and a composite box beam with surface mounted actuators. Three approaches to modeling structures containing piezoelectric actuator using the commercially available packages: MSC/NASTRAN and ANSYS are presented. It is shown that global versus local behavior of the analytical model and test article must be considered when comparing different approaches. Also, improper bonding with actuators greatly reduces the electrical to mechanical effectiveness of the actuators producing anti-resonance errors

S.X. Xu and T.S. Koko [40] have presented a general purpose design scheme for actively controlled smart structures of piezoelectric sensors and actuators. The proposed scheme can make use of any finite element code with piezoelectric elements, and control to design is carried out in state space form established on finite element modal analysis. The present scheme can be adapted to the design of actively controlled smart structures of non-piezoelectric sensors or actuators. Numerical results indicate that the locations of piezoelectric sensors and actuators may have significant influence on the integrated system and control performance. Proper placement of sensors and actuators should be sought in practical design practice through parameter studies to identify optimal control design for maximum control effect.

Y.D. Kuang et. al. [41] has developed an analytical modeling on 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. The deformation characteristics of the actuator-driven beam are investigated by examining the effect of the different geometric setups of the beam systems on the deflection. The effect of the thickness, location and length of the actuator on the deformation of a cantilever beam is also investigated.

S. Valhappan et. al [42] has 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. The numerical simulation results show that the smart damper can effectively increase the damping effect of the system, and the prediction algorithm is slightly more efficient than the optimal control algorithm for the problems analyzed in this paper because the prediction control algorithm can alleviate the effect of time delay of the control systems.

A Brief Review On Control Techniques And Their Applications

Ismail Kucuk et. al. [43] has considered active control of a vibrating beam using piezoelectric patch actuators. The explicit solution to the problem is developed by using eigen-function expansions of the state and adjoint variables. Optimal control theory is formulated with the objective function specified as a weighted quadratic functional of the dynamic responses to the beam which is to be minimized at a specified terminal time. Numerical results are presented to assess the effectiveness of the proposed control mechanism and to compare the behaviors of the uncontrolled and controlled beams. The problem formulation is applicable to isotropic beams and piezoelectric materials which can be generalized to anisotropic materials using the applicable constitutive relations.

B. Yan et. al. [44] has described a self-contained four-channel programmable controller designed to provide flexible sensing and control functions of situations requiring heavy computational load, real-time control, high-speed data acquisition, and fast signal processing. The system is self-contained and can be programmed using a wide range of software languages and hardware interfaces. Its features make it suitable for research and development projects in universities and for industrial control.

Chen Long-Xiang et. al. [45] has presented an experimental study of delayed feedback control using a flexible plate as research object. A treating method of multiple time delays is proposed. Piezoelectric (PZT) patches are used as actuators and foil gauges as sensors. The optimal positions of PZT actuators on the plate are determined using the particle swarm optimizer (PSO). Numerical and experimental results show that time delay in control systems may cause the degradation of control efficiency if it is not treated as control design. Delayed feedback control is a feasible strategy that may be used for structural control.

K. B. Waghulde, Dr. Bimleshkumar [46] has presented comprehensive study on 2-D simply supported beam with PZT actuator and sensor for the effect of the piezoelectric actuator placement on controlling the structural vibrations. To optimize results, controllers were designed using LQR control theory. Additionally, optimal control theory is being used to directly optimize low-order controllers.

A. Mukherjee and A. Saha Chaudhuri [47] has 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 to the increase in the in-plane compressive force.

D. C. Sun and L. Tong [48] has investigated the vibration control of the composite beam integrated with curved piezoelectric fibers. The sensor equations and actuator equations of the curved fibers are derived employing line integrals. A new method to design modal sensors and modal actuator is given by means of shaping the curvatures of the piezoelectric fibers. With the modal sensors and modal actuators designed using the curved piezoelectric fibers, the independent modal space control can be performed and good control results have been achieved.

Dunant Halim and S. O. Reza Moheimani [49] has introduced a class of resonant controllers that can be used to minimize structural vibration using collocated piezoelectric actuator-sensor pairs. The proportional controller increases the damping of the structure so as to minimize a chosen number of resonant responses. The controller structure is chosen such that closed- loop stability is guaranteed and can be designed such that the spatial H_2 norm of the system is minimized. Experimental validation on a simply supported beam is presented showing the effectiveness of the proposed controller.

Dell'Isolaa et. al. [50] has focused on a completely passive electric circuit analog to an Euler beam aimed for distributed vibration control. The designed electric circuit is constituted only by capacitors, inductors and ideal transformers; its hardware realization exploiting truly passive electric elements has been proved.

B J G Vautier and S 0 R Moheimani [51] have used in a control feedback scheme to reject disturbance vibrations acting on a cantilevered beam. In the analysis it is shown that the dynamics for the coupled piezoelectric beam system differs depending on whether voltage or charge is used to drive the piezoelectric actuator. During the analysis we have also demonstrated that the dynamics (i.e. the poles) for the coupled piezoelectric beam system differs depending on whether electrical charge or voltage is used to drive the piezoelectric actuator. Therefore care must be taken when modeling the plant as this will affect the design of the feedback controller

I.S. Sadek et. al. [52] has evaluated an analysis of the solutions to various feedback control laws applied to vibrating simply supported plates. The feedback controls implemented include displacement, velocity, and a combination of these.

K. B. Waghulde, Dr. Bimleshkumar [53] has done study of smart materials and sensor for the effect of the piezoelectric actuator placement on controlling the structural vibrations. The analysis is carried out for 2D beam and 3D plate with PZT actuator and sensor.

Gustavo Luiz C. M. de Abreu and Jose F. Ribeiro [54] has designed and evaluated the performance of a feedback H., controller to suppress vibration of a flexible cantilever beam provided with strain actuator and sensor. It was observed that such a controller resulted in suppression of transverse vibrations of the entire structure by minimizing the spatial H_∞ norm of the closed-loop system. The controller was obtained by solving a standard H_∞ control problem of a finite-dimensional system. It is important to say that the methodology presented here can be extended to more sophisticated structures, such as thin plates.

J.M. Sloss et. al. [55] has studied the effect of axial force in the vibration control of beams by means of an integral equation formulation, which facilitates the numerical solution to the problem of finding the eigen frequencies and eigen-functions of a freely vibrating beam controlled by piezo patch sensors and actuators.

L. Gaudiller and S. Bochard [56] has 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. Karagtille [57] has 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. [58] has described the design and experimental evaluation of an optimal feedback control strategy to suppress global broadband structural vibration of a flexible plate. Luang Wang et. al. [59] has proposed a $H\infty$ method of the vibration control of an iron cantilever beam with axial velocity using then on contact force by permanent magnets.

Marek Pietrzakowski [60] 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. It is shown that electromechanical coupling due to the direct piezoelectric effect in the actuator layers increases the global plate stiffness and the plate natural frequencies. The comparison of dynamic characteristics calculated for the actively damped plate has confirmed the natural frequency increase due to the eigen electric potential induced in the piezo actuators and also proved a weak influence on the active damping effectiveness for thin laminated plates.

Mohd Fuaad Rahmat et. al. [61] has 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. [62] has 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. [63] has presented the design and implementation of a spatial H_∞ controller of the active vibration control of a smart beam. Additionally, spatial identification of the beam was performed. The system model of the smart beam was obtained analytically and then improved experimentally. The free and forced vibrations of the smart beam were suppressed successfully.

Philip Shimon et. al. [64] has investigated two control methodologies, positive velocity feedback and H. control and two types of actuators, an inertial actuator and a distributed strain actuator. Four control architectures were developed and tested to control the first mode of a 600 (15.24 cm) square aluminum plate that was acoustically excited. The algorithms used two different actuators and two different control methodologies. Accelerometer placement was tested using two of the controllers to determine how location affected performance. An additional study was undertaken to study the spill-over effects (unintentionally exciting higher modes) and effects of accelerometer placement when patch actuators were used. The results showed that spill-over did occur, yet it was small, especially with the H_∞ controller.

S. Belouettar et. al. [65] has studied nonlinear vibrations of piezoelectric/ elastic/piezoelectric sandwich beams submitted to active control. The active control of the linear and nonlinear vibrations of sandwich piezoelectric-elastic-piezoelectric beams has been investigated based on a proportional and derivative feedback potential control and on a complex nonlinear amplitude equation. 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. [66] has analyzed a rectangular aluminium plate vibrating in the air or in contact with water. A filtered-X least means square (FXLMS) adaptive feed-forward algorithm is applied to the system, realizing structural vibration control in linear field with an SISO approach to the first vibration modes of the plate.

S.O. Reza Moheirnam and Dunant Halim [67] 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.

Xing-Jian Dong et. al. [68] has employed the linear quadratic Gaussian (LQG) algorithm for controller designed. The control law is then incorporated into the ANSYS finite element model to perform closed loop simulations. Numerical results are presented to demonstrate the efficiency of the proposed scheme for simulating an actively controlled piezoelectric structure. A complete active vibration control system comprising the cantilever plate, the piezoelectric actuators, the accelerometers and the digital signal processor (DSP) board is set up to conduct the experimental investigation. From the experimental results, it is observed that satisfactory performance of vibration attenuation can be achieved.

Shengquan Li et. al. [69] has presented a novel composite controller based on disturbance observers (DOB) for the all-clamped panel by considering the spillover and harmonic effect of real active vibration control by an optimal linear quadratic regulator (LQR) strategy. In order to solve the difficulty of determining the weight matrices of LQR, a chaos optimization method based on logistic map is proposed so that the weight matrices can be tuned automatically.

Tamara Nestorovic [70] has presented active control of smart structures of a focused frame of piezoelectric applications for active vibration and noise attenuation with potentials for the use in mechanical and civil engineering.

V. Sethi and G. Song [71] has 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. The system identification coupled with the observer designs and LQR control represents the completeness of the control system design. The model obtained using system identification with a 90% fit accurately represents the dynamics of the system as verified experimentally.

Senthil S. Vel and Brian P. Baillargeon [72] deals with the experimental and numerical assessment of the vibration suppression of smart structures using positive position feedback controllers.

J. R. Chaudhari and C. R. Patil [73] has considered fixed free rectangular cantilever beam for active vibration control and analyzed using ANSYS. Uncrack and crack beam with same cross section used for analysis and natural frequency and amplitudes of free vibration determine both from ANSYS 14.5 and experimental setup. Both the experimental and ANSYS results indicate that piezoelectric patch as an actuator is an effective method for the vibration suppression.

4. A BRIEF REVIEW ON OPTIMAL PLACEMENT OF PZT PATCHES

Dunant Halim and S.O. Reza Moheimani [74] has suggested a criterion for the optimal placement of collocated piezoelectric actuator sensor pairs on a thin flexible plate using modal controllability measures. An additional spatial controllability constraint is added in the optimization procedure for the reduction of control spillover effect. From the experiments, our optimization methodology resulted in the placement of a collocated piezoelectric actuator–sensor pair that gave sufficient observability/controllability of selected modes.

J. Ducarne et. al. [75] has proposed the optimization based on maximizing the modal electro-mechanical coupling factor (MEMCF), which is assumed to be the main free parameter that governs the shunt optimization and performances. A simple system geometries and configurations have been investigated in the present study and the optimization strategy can be applied to more complex geometries for which no closed-form expressions of the MEMCF are available, by using a finite-element model to compute it for a given position and geometry of the piezoelectric patches

Dongchang Sun and Liyong Tong [76] 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.

K.D. Dhuri and P. Seshu [77] has 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. Finite element approaches has been used for the evaluation of the objective functions (controllability and natural frequency change). The Pareto optimal solutions to three cases, viz. maximum controllability, minimal change in natural frequencies and good trade-off of former two are discussed.

Xiaojian Liu and David William Begg [78] 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. [79] has developed an optimal placement method of the locations of piezoelectric actuators and sensors based on the degree of observability and controllability indices for cantilever plate. The modal frequencies and damping ratios of the plate setup are obtained by identification method. The analytical and experimental results demonstrate that the presented control method is feasible, and the optimal placement method is effective. Simulations and experimental results on the actual process have shown that the proposed control method by combining PPF and PD can suppress the vibration effectively, especially for vibration decay process and the smaller amplitude vibration.

Ali Reza Mehrabian and Aghil Yousefi-Koma [80] have used the optimization methodology for the placement of piezoelectric actuator pairs for effective vibration reduction over the entire structure. A novel actuator optimal positioning algorithm is developed based on neural networks of a smart fin as a scaled model of F/A-18 vertical tail. The proposed algorithm is able to solve any actuator/sensor optimal positioning problem of different flexible smart structures.

Isabelle Bruant Laurent Proslier [81] deals with the optimization of piezoelectric actuators locations on axially functionally graded beams for active vibration control. The eigen problem is solved using Fredholm integral equations. The optimal locations of actuators are determined using an optimization criterion, ensuring good controllability of each eigen mode of the structure.

The linear quadratic regulator, including a state observer, is used for active control simulations.

CONCLUSION:

In this review paper, an extensive technique work based on PZT structure and control techniques are reviewed thoroughly. The ultimate aim of the proposed review is to present the use of PZT as smart structure and various control techniques for vibration control. This paves the path for the classifications which categorize the use of PZT in the effective manner. Thus, this review paves the path for the budding researchers to be acquainted with various techniques existing in this field.

REFERENCES

1. Andrew J. Fleming and S. O. Reza Moheimani, (2003), "Spatial System Identification of a Simply Supported Beam and a Trapezoidal Cantilever Plate", IEEE Transactions on Control Systems Technology, Vol. 11, NO. 5, pp. 726-736.
2. Dongchang Sun, Liyong Tong, Satya N. Atluri, (2001), "Effect of Piezoelectric Sensor/ Actuator Debonding on Vibration Control of Smart Beam", International Journal of Solids and Structures 38, pp. 9033-9051.
3. Amit Singh, Darryll J. Pines, (2002), "Active/Passive Vibration Reduction of Periodic 1-D Structures Using Piezoelectric Actuators", 43`d AIAA/ASME /ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Denver, Colorado, pp. 1-13.
4. Dr. M. Collet, Dr. M. Ouisse, (2011), "New Methodology for Vibroacoustic Energy Diffusion Optimization by Mean of Distributed Electromechanical Devices", CSMA, Colloque National EN Calcum DES Structures, pp. 1-8.
5. A.K. Singh and Deepak Apte, (2006), "Modeling and Analysis of Hysteresis in Piezoelectric Actuator", Defence Science Journal, Vol. 56, No. 5, pp. 825-833.
6. Dongchang Sun, Liyong Tong, (2004), "An Equivalent Model for Smart Beams with Debonded Piezoelectric Patches", Journal of Sound and Vibration 276, pp. 933-956.
7. Alberto Donoso, Jose Carlos Bellido, (2009), "Distributed Piezoelectric Modal Sensors for Circular Plates", Journal of Sound and Vibration 319, pp. 50-57.
8. K. B. Waghulde, Dr. Bimleshkumar et. al, "Vibration Control of Cantilever Smart Beam by using Piezoelectric Actuator and Sensor" International Journal of Engineering and Technology, Vol. 2(4) 2010, 259-262
9. Hui Zhang, Shu-yi Zhang, Tian-hua Wang, (2007), "Flexural Vibration Analyses of Piezoelectric Ceramic Tubes with Mass Loads in Ultrasonic Actuators", Journal of Ultrasonics 47, pp. 82-89.
10. Dr. Chandrashekhar Bendigeri, (2011), "Studies on Electromechanical Behavior of Smart Structures by Experiment and FEM", International Journal of Engineering Science and Technology, pp. 2134-2142.
11. F. Ebrahimi, A.Rastgo, (2008), "Free Vibration Analysis of Smart FGM Plates", International Journal of Mechanical, Industrial and Aerospace Engineering, pp. 94-99.
12. Jin-Chein Lin, M.H. Men, (2005), "Adaptive Control of a Composite Cantilever Beam with Piezoelectric Damping-Modal Actuators/Sensors", Journal of Composite Structures 70, pp. 170-176.
13. M. Sunar and B 0 Al-Bedoor, (2008), "Vibration Measurement of a Cantilever Beam using Root Embedded Piezoceramic Sensor", Journal of Mechanical Engineering Science, Vol: 222 Part-C, pp. 147-161.
14. Fayaz R. Rofooci, Ali Nikkhoo, (2009), "Application of Active Piezoelectric Patches in Controlling the Dynamic Response of a Thin Rectangular Plate under a Moving Mass", International Journal of Solids and Structures 46, pp. 2429-2443.
15. K. Jayakumar, D. Yadav, B. Nageswara Rao, (2009), "Nonlinear Free Vibration Analysis of Simply Supported Piezo-Laminated Plates with Random Actuation Electric Potential Difference and Material Properties", Journal of Communications in Nonlinear Science and Numerical Simulation 14, pp. 1646-1663.
16. J. Tang, K. W. Wang, (2003), "A Simultaneous Active-Passive Approach for Structural Vibration Confinement using Piezoelectric Actuators", 44`h AIAA/ASME/ASCE/AHS Structures,

Structural Dynamics, and Materials Conference, Norfolk, Virginia, pp. 1-11.

17. "Tamara Nestorovic Trajkov, Heinz Koppe, Ulrich Gabbert, (2008), "Direct Model Reference Adaptive Control Design and Simulation for the Vibration Suppression of Piezoelectric Smart Structures", Journal of Communications in Nonlinear Science and Numerical Simulation 13, pp. 1896-1909.
18. Kunal Joshi and P. M. Mujumdar, oncurrent Optimum Design of Piezoelectric Actuator and Controller for Smart Vibration Control, 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Newport, Rhode Island, pp 1-20
19. L. AZrar, S. Belouettar, J. Wauer, (2008), "Nonlinear Vibration Analysis of Activity Loaded Sandwich Piezoelectric Beam with Geometric Imperfections", Journal of Computers and Structures 86, pp 2182-2191
20. Yaowen Yang and Aiwei Miao, (2008), "Effect of External Vibration on PZT Impedance Signature", Open Access Journal of Sensors, pp. 68466859.
21. Limei Xu, Hualong Du, Yuaontai Hu, Hui Fan, and Jiashi Yang, (2009), "Size Optimization of a Piezoelectric Actuator on a Clamped Elastic Plate", IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, pp. 2015-2022.
22. Yong Xie, Tong Zhao, Guoping Cal, (2011), "Model Reduction and Active Control for a Flexible Plate" Acta Mechanics Solids Sinica, Vol. 24, No. 5, Published by AMSS Press, Wuhan, China, pp. 467-476.
23. Marcus Neubauer, Jorg Wallaschek, (2011), "Vibration Damping with Shunted Piezoceramics: Fundamentals and Technical Applications", Mechanical Systems and Signal Processing, pp. 1-17.
24. Ronny Calixto, Emilio Carlos, (2004), "Design of Piezoelectric Actuators using the Topology Optimization Based on Density Method", ABCM Symposium Series in Mechatronics, pp. 672-681
25. Ugur Aridogan, et al., (2009), "Active Vibration Suppression of a Smart Beam Via Self-Sensing Piezoelectric Actuator", Ankara International Aerospace Conference, METU, Ankara TURKEY, pp. 1-8.
26. P. Pertsch, S. Richter, D. Kopsch, N. Kramer, J. Pogodzik, E. Hennig, (2006), "Reliability of Piezoelectric Multilayer Actuators", Contribution to the ACTUATOR 2006 conference, Bremen, Germany, pp. 1-3.
27. M. A. R. Loja, et al., (2001), "Analysis of Piezolaminated Plates by the Spline Finite Strip Method", Journal of Computers and Structures 79, pp. 2321-2333.
28. C.H. Nguyen, S.J. Pietrzko, (2006), "FE Analysis of a PZT-Actuated Adaptive Beam with Vibration Damping using a Parallel R—L Shunt Circuit", Journal of Finite Elements in Analysis and Design 42, pp. 1231-1239.
29. M. C. Ray, H.M. Sachade, (2006), "Finite Element Analysis of Smart Functionally Graded Plates", International Journal of Solids and Structures 43, pp. 5468-5484.
30. K. Ramkumar, N. Ganesan and N. Shanmugam, (2011), "Finite Element Based Active Vibration Control Studies on Laminated Composite Box Type Structures under Thermal Environment", International Journal of Applied Engineering Research, pp. 221-234
31. Antonio Zallo, Paolo Gaudenzi, (2003), "Finite Element Models for Laminated Shells with Actuation Capability", Journal of Computers and Structures 81, pp. 1059-1069.
32. Premjyoti G.Patil, Y.S.Kumara Swamy, (2009), "An Efficient Model for Vibration Control by Piezoelectric Smart Structure Using Finite Element Method", European Journal of Scientific Research, Vol.34 No.4, pp. 485494.
33. M. Rahmoune, D. Osmont, (2010), "Classic Finite Elements for Simulation of Piezoelectric Smart Structures", Mechanika. Nr.6(86), pp. 50-57.
34. Marcelo A. Trindade a, Ayech Benjeddou, (2008), "Refined Sandwich Model for the Vibration of Beams with Embedded Shear Piezoelectric Actuators and Sensors", Journal of Computers and Structures 86, pp. 859869.
35. Henrique Santos, Cristovao M. Mota Soares, Carlos A. Mota Soares, J.N. Reddy, (2008)" A Finite Element Model for the Analysis of 3-D Axisymmetric Laminated Shells with Piezoelectric

Sensors and Actuators: Bending and Free Vibrations", Journal of Computers and Structures, pp.940-947.

36. Jose M. Simoes Moita , Isidoro F.P. Correia, et al., (2004), "Active Control of Adaptive Laminated Structures with Bonded Piezoelectric Sensors and Actuators", Journal of Computers and Structures 82, pp. 1349 1358.
37. Z. K. Kusculuoglu, B.Fallahi, T.J. Royston, (2004), "Finite Element Model of a Beam with a Piezoceramic Patch Actuator", Journal of Sound and Vibration 276, pp. 27-44.
38. Q. Chen, C. Levy, (1999), "Vibration Analysis and Control of Flexible Beam by using Smart Damping Structures", Elsevier, Composites: Part B 30, pp. 395-406.
39. S.Y. Wang, (2004), "A Finite Element Model for the Static and Dynamic Analysis of a Piezoelectric Bimorph", International Journal of Solids and Structures 41. pp. 4075-4096.
40. Mercedes C. Reaves and Lucas G. Horta, (2001), "Test Cases for Modeling and Validation of Structures with Piezoelectric Actuators", American Institute of Aeronautics and Astronautics, AIAA, pp. 1-11.
41. S.X. Xu, T.S. Koko, (2004), "Finite Element Analysis and Design of Actively Controlled Piezoelectric Smart Structures". Journal of Finite Elements in Analysis and Design 40, pp. 241-262.
42. Y.D. Kuang, X.Q. He, C.Y. Chen, G.Q. Li, (2009), "Modeling and Deformation Characteristics of a Circular Beam with Asymmetric Piezoelectric Actuators", Journal of Composite Structures 90, pp. 263-269.
43. S. Valliappan. K. Q1, (2003), "Finite Element Analysis of a 'Smart' Damper for Seismic Structural Control", Journal of Computers and Structures 81, pp. 1009-1017.
44. Ismail Kucuk, et al., (2011), "Optimal Vibration Control of Piezolaminated Smart Beams by the Maximum Principle", Journal of Computers and Structures 89, pp. 744-749.
45. B. Yan, et al., (2002), "A Configurable Control System for Smart Structure Research", 2nd Canada-US CanSmart Workshop, on Smart Materials and Structures, Montreal, Quebec, Canada, pp. 285-291.
46. Chen Long-Xiang, Cai Guo-Ping , PanJi, (2009), "Experimental Study of Delayed Feedback Control for a Flexible Plate", Journal of Sound and Vibration 322, pp. 629-651.
47. K. B. Waghulde, Dr. Bimleshkumar, “Finite Element and Experimental Investigation and Control of Vibration of Piezoelectric Smart Beam”, International Journal of Innovative Research in Science, Engineering and Technology, Vol. 3, Issue 12, December 2014.
48.] A. Mukherjee, A. Saha Chaudhuri, (2005), "Nonlinear Dynamic Response of Piezolaminated Smart Beams" Journal of Computers and Structures 83, pp. 1298-1304.
49. D. C. Sun, L. Tong, (2001), "Sensor/Actuator Equations for Curved Piezoelectric Fibers and Vibration Control of Composite Beams using Fiber Modal Actuators/Sensors", Journal of Sound and vibration 241(2), pp. 297-314.
50. Dunant 11alim and S. O. Reza Moheimani, (2001), "Spatial Resonant Control of Flexible Structures—Application to a Piezoelectric Laminate Beam", IEEE Transactions on Control Systems Technology, VOL. 9, NO. 1, pp. 37-53.
51. F. Dell'Isola, E.G. Henneke, M. Porfiri, (2003), "Piezo-electro-mechanical Structures: New Trends Towards the Multimodal Passive Vibration Control", Smart Structures and Materials, Proceedings of SPIE Vol. 5052, pp. 392-402.
52. B.J.G. Vautier and S 0 R Moheimani, (2005), "Charge Driven Piezoelectric Actuators for Structural Vibration Control: Issues and Implementation", Institute of Physics Publishing Smart Materials and Structures 14, pp. 575-586.
53. I.S. Sadek, J.C. Bruck Jr., J.M. Sloss, S. Adali, (2003), "Feedback Control of Vibrating Plates using Piezoelectric Patch Sensors and Actuators", Journal of Composite Structures 62, pp. 397-402.
54. K. B. Waghulde, Dr. Bimleshkumar, “Vibration Analysis of Cantilever Smart Structure by using Piezoelectric Smart Material”, International Journal on Smart sensing and Intelligent Systems, Vol. 4 No. 3 Sept 2011 pp353-375.

55. Gustavo Luiz C. M. de Abreu, Jose F. Ribeiro, (2004), "Spatial H., Control of a Flexible Beam Containing Piezoelectric Sensors and Actuators", ABCM Symposium Series in Mechatronics, Vol: I, pp. 243-253.
56. J. M. Sloss, et al., (2003), "Piezo Patch Sensor/Actuator Control of The Vibrations of a Cantilever under Axial Load", Journal of Composite Structures 62, pp. 423-428.
57. l. Gaudiller, S. Bochard, (2005), "Adaptive Active Control of Flexible Structure Subjected to Rigid Body Displacements", Journal of Sound and Vibrations 283, pp 311-339
58. L. Malgata and H. Karagulle, (2009), "Simulation and Experimental Analysis of Active Vibration Control of Smart Beams under Harmonic Excitation", Journal of Smart Structure and Systems, Vol. 5, No.1, 55-68
59. Lee, Y. K. et. al., (2004), "design and Implementation of Spatial Feedback Control on a Flexible Plate", Proceedings of Acoustics, Gold Coast, Australia, pp. 375-380
60. Liang Wang, Huai-hai Chen, Xu-dong HE, (2011), " Active H_∞ Control of the Vibration of an Axially Moving cantilever Beam by Magnetic Force", Journal of Mechanical Systems and Signal Processing25, pp. 2863-2878.
61. Marek Pietrzakowski, (2008), "Piezoelectric Control of Composite Plate Vibration: Effect of Electric Potential Distribution", Journal of Computers and Structures 86, pp. 948-954.
62. Mohd Fuaad Rahmat, Herman Wahid and Norhaliza Abdul Wahab, (2010),"Application of Intelligent Controller in a Ball and Beam Control System",International Journal on Smart Sensing and Intelligent Systems Vol. 3, No.1, pp. 45-60.
63. Moon K.Kwak, SeokHeo, MoonsanJeong, (2008), "Dynamic Modeling and Active Vibration Controller Design for a Cylindrical Shell Equipped with Piezoelectric Sensors and Actuators", Journal of Sound and Vibration, pp. 1-15.
64. Omer Faruk Kircali, et al., (2008), "Spatial control of a smart beam", Journal of Electroceram 20, pp. 175-185.
65. Philip Shimon, Edmond Richer, Yildirim Hurmuzlu, (2005), "Theoretical and Experimental Study of Efficient Control of Vibrations in a Clamped Square Plate", Journal of Sound and Vibration 282, pp. 453-473.
66. S. Belouettar , L. Azrar, et al., (2008), "Active Control of Nonlinear Vibration of Sandwich Piezoelectric Beams: A Simplified Approach", Journal of Computers and Structures 86, pp. 386-397.
67. S. Carta, M. Amabili, R. Ohayon, P.M. Hutin, (2008), "Active Vibration Control of a Thin Rectangular Plate in Air or In Contact With Water in Presence of Tonal Primary Disturbance", Journal of Aerospace Science and Technology, pp. 54-61.
68. S. O. Reza Moheimani and Dunant Halim, (2004), A Convex Optimization Approach to the Mode Acceleration Problem", Journal ot'Automatics 40, pp. 889-893.
69. Xing-Jian Dong, et al., (2006), "Vibration Control of Piezoelectric Smart Structures Based on System Identification Technique: Numerical Simulation and Experimental Study", Journal of Sound and Vibration 297, pp. 680-693.
70. Shengquan Li, (2011), "Piezoelectric Vibration Control for All-Clamped Panel using DOB-Based Optimal Control", Journal of Mechatronics 21, pp. 1213-1221.
71. Tamara Nestorovic, Miroslav Trajkov, (2010), "Active Control of Smart Structures– An Overall Approach", FACIA Universitatis, Series: Architecture and Civil Engineering Vol. 8, pp. 35-44.
72. V. Sethi and G. Song, (2005), "Optimal Vibration Control of a Model Frame Structure Using Piezoceramic Sensors and Actuators", Journal of Vibration and Control, 11: pp.671-684.
73. Senthil S. Vel, Brian P. Baillargeon, (2004), "Active Vibration Suppression of Sandwich Beams using Piezoelectric Shear Actuators", Proceedings of the 2004 International Conference on Computational & Experimental Engineering & Science, Madeira, Portugal, pp. 2093-2098.
74. JR Chaudhari and CR Patil, "Active Vibration Control of Uncrack and Crack Cantilever Beam using Piezoelectric Actuator", European Journal of Advances in Engineering and Technology, 2016, 3(6): 20-25

75. Dunant lialim and S. O. Reza Moheimani, (2003), "An Optimization Approach to Optimal Placement of Collocated Piezoelectric Actuators and Sensors on a Thin Plate", Journal of Mechatronics 13, pp. 27-47.
76. J. Ducarne, O.Thomas, J.F. Deu, (2012), "Placement and Dimension Optimization of Shunted Piezoelectric Patches for Vibration Reduction", Journal of Sound and Vibration 331, pp. 3286-3303.
77. Dongchang Sun, Liyong Tong, (2001), "Model Control of Smart Shell by Optimized Discretely Distributed Piezoelectric Transducers", International Journal of Solids and Structures 38, pp. 3281-3299.
78. K. D. Dhuri, P. Seshu, (2009), "Multi-Objective Optimization of Piezo Actuator Placement and Sizing using Genetic Algorithm", Journal of Sound and Vibration 323, pp. 495-514.
79. Xiaojian Liu, David William Begg, (2000), "On Simultaneous Optimization of Smart Structures Part-1: Theory", Computer. Methods in Applied Mechanics and Engineering 184, pp. 15-24.
80. Zhi-cheng Qiu, et al., (2007), "Optimal Placement and Active Vibration Control for Piezoelectric Smart Flexible Cantilever Plate", Journal of Sound and Vibration 301, pp. 521-543.
81. Ali Reza Mehrabian, Aghil Yousefi-Koma, (2007), "Optimal Positioning of Piezoelectric Actuators on a Smart Fin using Bio-Inspired Algorithms", Journal of Aerospace Science and Technology 11, pp. 174-182.
82. Isabelle Bruant Laurent Proslier, "Optimal location of piezoelectric actuators for active vibration control of thin axially functionally graded beams", Int. J Mech Mater Des (2016)12:173-192