

Chapter 2

Review of Literature

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Review of Literature

2.1 Introduction

As discussed in the Chapter-1, a wide gamut of present day real life problems w.r.t. space domain are expected to be resolved by using the intelligent structural systems and smart materials.

2.1.1 Indian Space Research Context

With respect to the Indian space research scenario in ISRO, first the literature has been scanned for the in-house work carried out in this domain related to spacecrafts , launch vehicles and aircrafts . SMA based applications in the Solar Flaps of the INSAT-3A spacecraft are the first of its kind in ISRO as per the Fig 2.1. Flaps keep dangling in space to balance the unbalanced torque in space:

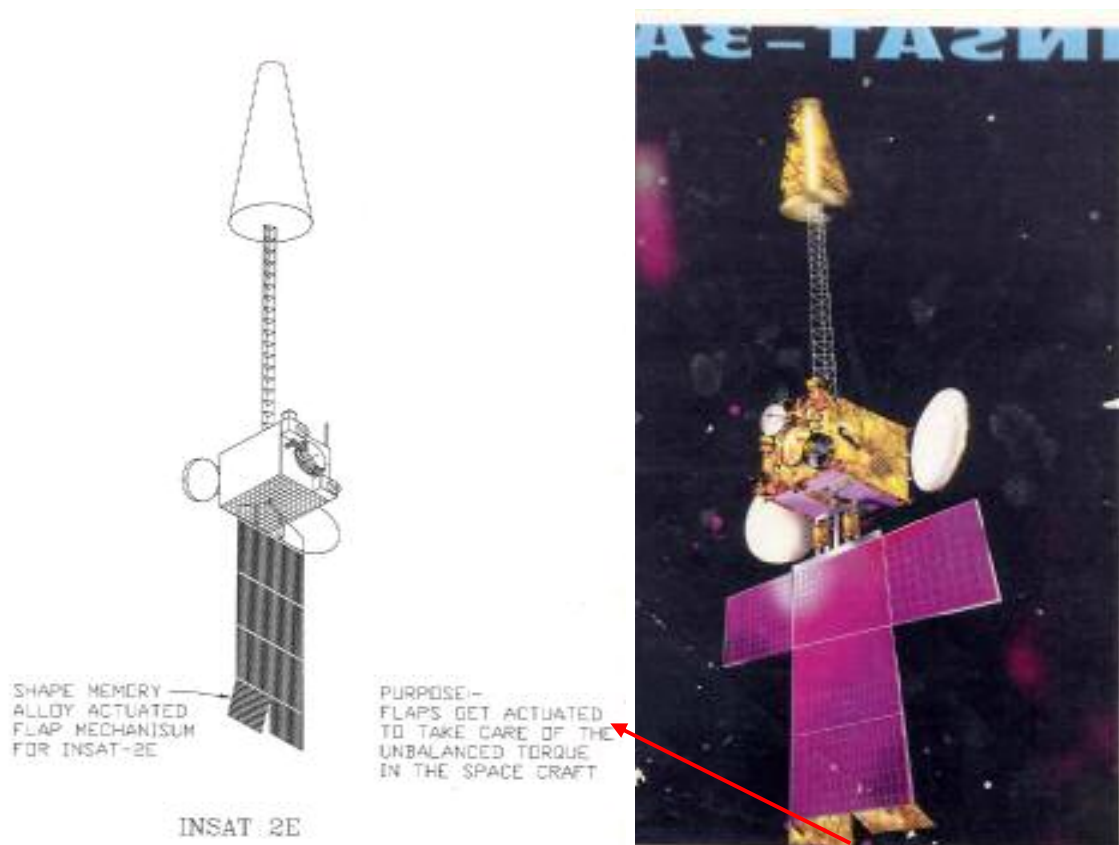


Fig 2.1 A typical INSAT spacecraft showing Solar Flaps made up SMAs

Potential applications in progress using smart materials w.r.t Indian space programme are shown in Fig 2.2. Work is going on for developing Rate Gyro Brackets (RGB) for launch vehicles to damp launch loads on main equipment bay of the rocket.

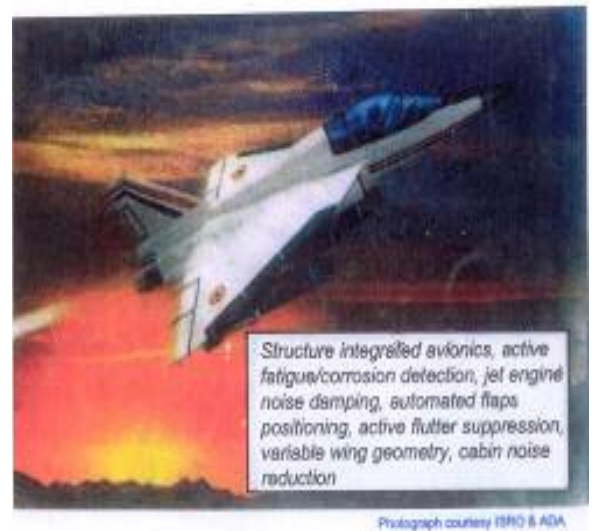


Fig.2.2 Rate Gyro Brackets (RGB) for launch

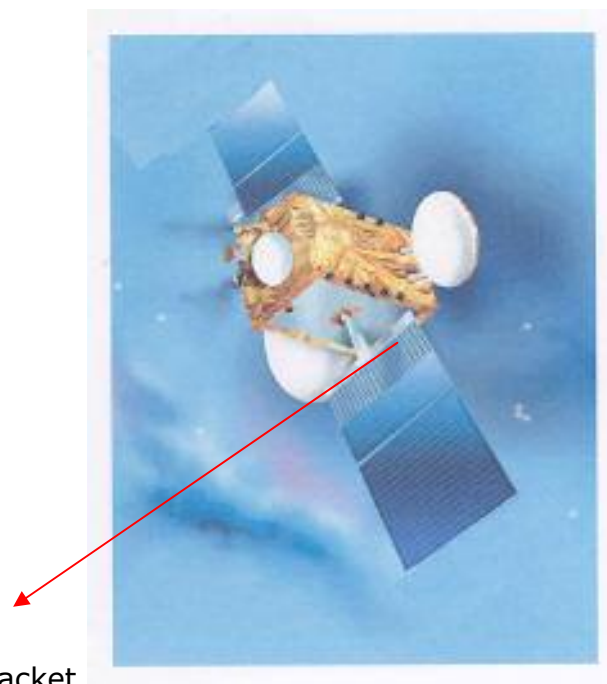


Fig.2.3 Passive vibration damping concept for the Solar panels brackets

One of the attempts to develop smart aircraft antenna at Centre for Air borne Systems (CABS) B'lore[11] is illustrated in Fig 2.4 :

STUDY OF CABS
SMART
ANTENNA MODEL

- 1) TISC/CABS JOINT VENTURE
- 2) 4-SLACS SPENT
- 3) 2 LACS ON CONSULTANCY
- 4) CMTI BANG. FOR HIGH PRECISION ENG.WORK
- 5) EFFORTS ON TO MAKE THE MODEL OPERATIONAL

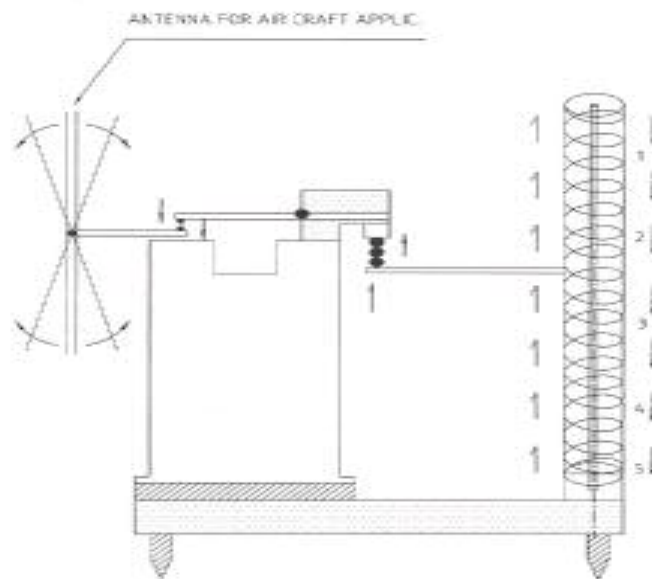


Fig 2.4: Smart aircraft antenna at CABS using Terfinol-D rods

As it is hitherto fore not fully explored domain, many more possible applications may see the light of the day. Smart materials such as PZT's, PVDF Films and shape memory alloys have attracted many researchers around the world in vibration control, shape control, thermal control in aerospace structures. Recent studies on smart structures have found potential applications in spacecraft antennas.

2.2 Literature Review in the domain of vibration damping

In this chapter , review of literature is carried out under different sections as follows :

2.2.1 Passive vibration damping

An experimental evaluation of the benefits of smart damping materials in reducing structural noise and vibration has been presented by Mehdi Ahmadian, Kristina M. Jeric, Daniel J. Inman [169]. The construction of a special test rig for measuring both vibrations and structure-borne noise has been discussed. Next, the application of smart damping materials, specifically piezoceramics with electrical shunts, in reducing the vibration of a test plate has also been discussed. It is shown by authors that the smart damping materials are able to effectively reduce the vibration peaks at multiple frequencies, with minimal amount of added weight to

the structure, as compared to passive viscoelastic damping materials. Further, according to them, the test results show that the structure-borne noise at the vibration peaks is substantially reduced with the smart damping materials. The results indicate the viability of smart materials for many industrial applications where reducing noise and vibrations is desired with minimal amounts of added weight.

B Bhattacharya, B R Vidyashankar, S Patsas and G. R. Tomlinson [158] have proposed a combined passive and active damping strategy to control vibration in structures using a Combination of layers of ferro-magnetic (passive) damping and smart (active) magnetostrictive material (Terfenol-D). Two types of combined damping systems are considered by authors i.e. a non interactive system and an interactive or hybrid system. Numerical investigations on a cantilever beam model are carried out by authors to investigate various aspects in combined damping scenario. Using variational principle, a beam Finite Element is developed by authors to study the dynamic characteristics of a beam containing both the passive and active damping layers. It is shown that the combined system could be used effectively to dampen the structural vibration over a wide frequency range. Comparisons with only passive and only active damping schemes are also made. The influence and the mode dependence of control gain in a hybrid system are clearly brought out by authors .

2.2.2 Active constrained layer damping

S. Narayanan, [162] has dwelled in the domain of damping of structures w.r.t. to vibration and noise control. Keeping in view the two categories of damping i.e. passive damping and active damping, the author has created a new subset of damping by combining passive and active damping; thereby producing a hybrid damping treatment. This paper is a review of these damping treatments including the recent advances in the hybrid damping using Active Constrained Layer Damping (ACLD) treatment.

The active / passive hybrid vibration control performance due to Enhanced smart Constrained Layer Damping (ESCLD) treatment as proposed by Liao and Wang on plate like structures has been conceived by V. Balamurugan, S. Narayanan [156]. This treatment consists of a viscoelastic Layer Constrained between a smart piezoelectric layer and the base structure being controlled. Also, the smart constraining layer is clamped to the base structure. This type of damping treatment has got both active and passive component of damping. The passive damping is through cyclic shearing of viscoelastic constrained layer which is further to the

transfer of control moments from the piezoelectric layer to the base structure through the viscoelastic layer and also by passed through the clamps a plate finite element has been formulated using first order shear deformation theory including the effect of transfers shear and rotary inertia. The effect of the viscoelastic shear layer and piezoelectric constraining layer on the mass and stiffness has been included in the model by the authors. The viscoelastic shear layer is modeled using Golla- Hughes-Me Tavish (GHM) method by authors , which is a time domain approach. The clamps (edge elements) are modeled by authors as equivalent springs connecting the smart piezoelectric constraining layer with the structure to be controlled. LQR optimal control strategy is used by authors to obtain optimal control giants. The effect of the viscoelastic material properties (shear modulus and loss factory) on the hybrid vibration control performance is studied for both SCLD (without edge elements) and ESCLD systems.

2.2.3 Active vibration control

Yan-Ru Hu, Alfred Ng [151] Flexible structures are extensively used in many space applications, for example, space-based radar antennae, space robotic systems, and space station, etc. The flexibility of these space structures results in problems of structural vibration and shape deformation, etc. In recent years, active control methods have been developed to suppress structural vibration and improve the performance of these flexible structures with integrated piezoelectric actuators using control theory. First, dynamic models for a flexible circular plate with integrated piezoelectric actuators and sensors are derived using the Rayleigh-Ritz method. An active robust controller is designed to suppress vibration of the circular plate. Robustness of the control system of the circular plate is discussed for the model parameter uncertainty. This active robust vibration control method is tested via experimental implementation. The experimental results show that the proposed robust active control method is efficient for active vibration suppression.

V. Balamurugan, S Narayanan [156] have presented the mechanics for the coupled analysis of piezolaminated plate and piezolaminated curvilinear shell structures and their vibration control performance. A plate/shell structure with thin PZT piezoceramic layers embedded on top and bottom surfaces to act as distributed sensor and actuator is considered. A C^0 continuous, shear flexible, nine-noded quadrilateral shell element is derived by authors based on field consistency principle. In the case of elements formulated based on field consistency principle, all the energy terms are numerically evaluated using a full integration scheme, irrespective of the thickness parameter by authors . The elements developed by

authors include the stiffness, mass and electromechanical coupling effects of various control strategies.

S. Raja, P.K. Sinha and G.Prathap, [159] have proposed a modal control approach to suppress the vibration amplitude of a laminated composite plate. The monolithic piezo crystals are employed as distributed actuators. Sensors and are surface bonded at 0/45 positions on the plate. Optimal control gain estimated off-line is converted as feedback voltage and is implemented in an analog control system. The piezo actuators placed at 45° position are found efficient in controlling the torsion mode. However 0° position crystals are observed effective in bending modes control. The displacement control is observed to be comparatively better in controlling all the three elastic modes than velocity control.

Laminated composite beams, containing embedded layers of Terfenol-D particles have been modelled as a distributed parameter system by A V Krishna Murty, M Anjanappa, Y Wu, B Bhattacharya, M S Bhat [15]. The magnetostrictive property of Terfenol-D is used by authors to control the vibration. Velocity feedback, constant gain distributed controller has been chosen to achieve vibration suppression. Simply-supported beams with symmetric and unsymmetric layers have been investigated by authors to illustrate the "vibration suppression capability through the use of magnetostrictive materials. Numerical results are presented by authors for various lay-up sequences and for various positions of the magnetostrictive layers. Their results show how the vibration suppression time, control current, and actuation forces vary with the control gain. In the general case of unsymmetric laminates, as per them the governing equations are in the form of two coupled differential equations. Noticing that the omission of in-plane inertia has negligible influence on the results, a simpler equation has been deduced by authors which can be conveniently used to study such beam problems, particularly with other boundary conditions.

P.S. Nair, S. Shankar Narayan and M.J. Samuel [164] presented studies on Vibration Control of Spacecraft Using Smart Structure Concepts According to the authors, increased size and flexibility of solar arrays and other appendages make it essential to consider the control - structure interaction in the design of spacecraft. The presence of large quantity of propellant makes the dynamics of an orbiting spacecraft more complex. The details are mentioned to understand the coupled dynamic behavior of spacecraft involving rigid body, propellant slosh and the flexible solar array vibrations. The study is carried out by authors on a model, simulating some of the major dynamic features of a spacecraft in orbit. Both theoretical and experimental studies are carried out by authors. An attempt is

made to control the vibrations of the solar arrays using piezo electric wafers as actuators and accelerometers as sensors.

The study done by A. A Ghate, P. Seshu [165] deals with the application of two different control Strategies viz. Direct Velocity Feedback (DVF) and Modified Independent Modal Space Control (MIMSC) to control the flexural vibrations of a cantilever beam mounted with piezoelectric patches. These two control strategies belong to two different categories viz. coupled control (DVF) and modal control (MIMSC). In case of DVF, the collocated system is inherently stable with respect to sensor/actuator (S/A) locations. For non-collocated system configuration, DVF is not considered to be suitable as stability of the system depends on S/A locations. With the help of root locus, it is shown that it is possible to achieve the stability of different modes provided the S/A locations are chosen properly. Also a comparison of DVF and MIMSC is carried out on the basis of two different criteria.

Analytical solutions and finite element results of laminated composite plates with smart material layers embedded in them are presented in this study by J.N. Reddy and S. Krishnan, [168] . The third order plate theory of Reddy is used by authors to study vibration suppression characteristics. The analytical solution proposed by authors for simply supported boundary conditions is based on the Navier solution procedure. The velocity feedback control is used by authors . Parametric effects of the position of the smart material layers, material properties, and control parameters on the suppression time have been investigated by authors . It has been found by authors that (a) the minimum vibration suppression time is achieved by placing the smart material layers farthest from the neutral axis, (b) thinner smart material layers have better vibration attenuation characteristics, and, (c) the vibration suppression time is larger for a lower value of the feedback control coefficient.

Mukherjee and A Saha Chaudhuri[149] Their work demonstrates the effect of axial forces on *smart* columns that have adhesively bonded piezoelectric skins on substrates. Exact solutions for the piezolaminated columns have been presented by authors . The solutions have been validated through experimental studies. The objectives of their work are (1) to show the effect of axial force on sensing and actuation mechanisms of piezoelectric materials and (2) to demonstrate the active control of column type structures using these materials. In the experimental work, polyvinylidene fluoride (PVDF) films have been used as smart skins on a plastic substrate. PVDF films are shaped corresponding to the first mode shape of the cantilever column to ensure proportional sensing and actuation.

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M. J. Schula, P. F. Pai, D. J. Inman [150], have presented new techniques under development for monitoring the health and suppressing the vibration of flexible composite structures. The techniques use piezoceramic patches bonded to the structure for actuation and sensing. Simulations and experiments are presented to demonstrate the utility of the methods for beam and panel structures. Limitations of piezoceramic materials are discussed, and suggestions are given for improving the techniques and for developing new uses of piezoceramic materials and smart structures.

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According to the study by Dongchang Sun, Liyong Tong, Satya N. Atluri [152], in vibration control of smart structures, piezoelectric sensors/actuators are usually bonded to the surface of a host structure. Debonding may occur between the piezoelectric sensors/actuators and the host structure, and it may decrease the control efficiency of vibration suppression or even lead to an unstable closed loop control system. This work of the authors investigates the effect of the debonding on vibration control of beams with piezoelectric sensors and actuators. They have presented a novel model, which takes into account both flexural and longitudinal displacements of the host beam and piezoelectric layers as well as the peel and shear strains of the adhesive layer. 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.

In this work , Yaowen Yang, Zhanli Jin, Chee Kiong Soh [154] the parameters of vibration control system of smart beams, including the placement and size of piezoelectric sensors and actuators (S/As) bonded on smart beams and the feedback control gains of the control system, have been simultaneously optimized for vibration suppression of beam structures. Since the sizes of the S/As are selected from a prescribed patch pool provided by the manufactures, the size design variable is then discrete, but the locations and feedback gains are continuous. Thus, the resulting optimization problem has discrete-continuous design variables which are difficult for the conventional optimization methods to solve. An integer-real-encoded genetic algorithm has thus been developed by authors to search for the optimal placement and size of the piezoelectric patches as well as the optimal feedback control gains. The criterion based on the maximization of energy dissipation was adopted for the optimization of the control system. The optimal distributions of the piezoelectric patches based on specific controlled vibration modes have also been addressed. The results showed that the control effect could be significantly enhanced with appropriate distribution of piezoelectric patches and selection of feedback control gains, and meaningful observations have been obtained for practical design by authors .

H Gu and G Song [139] Positive position feedback (PPF) control is widely used in active vibration control of flexible structures. To ensure quick vibration suppression, a large PPF scalar gain is often applied. However, PPF control with a large scalar gain causes initial overshoot, which is undesirable in many situations. Authors in this work have proposed a fuzzy gain tuner, to tune the gain in the positive position feedback control to reduce the initial overshoot while still maintaining quick vibration suppression. The fuzzy system is trained by a batch least squares algorithm based on desired input-output data so that the trained fuzzy system can behave like the training data. A specific 3.35 m long composite I-beam with piezoceramic patch sensors and actuators is used by authors to demonstrate the fuzzy PPF control. For comparison purposes, three types of control methods are used by authors in the experiment: a standard PPF control, a standard PPF control with traditional fuzzy gain tuning. PPF demonstrates that PPF control with batch least squares fuzzy gain tuning behaves much better than the other two control methods in terms of successfully reducing the initial overshoot and quickly suppressing vibration.

2.3 Literature Review in the domain of shape deformation

Following are the papers scanned in the domain of shape deformation of structures using piezo patches :

2.3.1 Shape studies on beams

V. K. Gupta, P. Seshu and K. Kurien Issac have developed [4], a finite element model piezoelectric actuated shell structures, based on Ahmad's reduced shell element. Experiments have been conducted by authors on a number of structures like straight beams, curved beams, and shells. Finite element and experimental results predicted by authors have been shown close correlation. Nonlinear behavior has been observed by authors in their experiments, particularly at higher fields, and complete hysteresis loops have been presented in their work. The finite element method has been applied by authors to study the deformation of a typical paraboloid shell (representative antenna shell) under piezoelectric actuation. It has been shown by authors that piezoelectric actuation can be used to induce desired deformation shapes in the antenna shell, which result in beam steering and shaping.

V.K. Gupta and P. Seshu and K. Kurien Issac [141] The authors have carried out research in the domain of use of piezoelectric actuators for curved beams. It is observed that despite the fact that some theoretical work has been done, but experimental studies, particularly on curved beams, are limited. In the current study, a finite element model is developed for piezoelectric actuated curved beam structures based on Ahmad's reduced shell element. Experiments have been conducted on a number of structures like straight beams & curved beams. Finite element and experimental results have been shown to match well. Nonlinear behavior has been observed in the experiments, particularly at higher fields, and complete hysteresis loops have been presented.

Arthur Ballato [157], in this paper mentions that piezoceramic cantilever beams will play a significant role in futuristic sensors, actuators and resonators. The authors has considered in this work the simple piezo-bimorph, describing the shapes taken by the beam as function of operating frequency and overtone. Two conditions are of particular practical pertinence: tip deflection without rotation, and tip rotation without deflection. Frequencies at which these conditions appear have been found by him, as these are the resulting displacements and slopes at the cantilever free end.

In this work [13] Ganguli A. Jhavar S. and Seshu P have presented the shape control of curved beams using symmetric surface bonded piezoelectric actuators

excited out of phase. To predict the deflections accurately, a finite element model using a three-noded isoparametric curved beam element has been implemented by authors . To model the piezoelectric layers, coupled finite element equations have been used by authors and solved using iterative approach. Closed form expression for deflection has also been derived and compared with FEM and experimental results. The closed form solution based on linear strain variation is used by authors for the static shape control of curved beams. Shape control is achieved by authors by minimizing an objective function which takes into account the error between actual and desired shapes as well as energy consumed by the actuators.

The focus of the stuffy by Byung-Koog Jang, Ya Xu, Ryutaro Oishi, Hideki Nagai, Hitoshi Yoshida, Yoshio Akimune, Kazuhiro Otsuka and Teruo Kishi [160] is the thermo mechanical characterization and effect of damage recovery on the pre-strained SMA wire embedded CFRP composites for developing the smart composites with self-damage control of beams. The SMA utilized in their work is a Ni-45at%Ti wire with a diameter of 0.4 mm. A steel mold was specially designed by authors to embed the pre-strained TiNi wire into CFRP prepreg and prevent their recovery during the cure cycle. TiNi /CFRP Composites were fabricated by hot-pressing in the temperature range of 150-180°C by controlling the applied pressure. The study is divided into four parts: fabrication of SMA wire embedded CFRP composites, experimental characterization of thermo mechanical behavior on SMA wire by electrical heating, recovery effect of self-damage control in composites and sensing effect by detecting the electrical resistance at SMA wire. Compressive recovery force induced by the nano mechanical actuation of SMA depends on pre-strained level and volume fraction of TiNi. The hot pressed TiNi/CFRP specimens were loaded by authors under tensile test in order to induce a transverse crack or partial damage. Specially, transverse crack easily happen at 90° stacking CFRP layers. The damage degree due to generation of transverse cracks is quantified by authors w.r.t real-time measurements of electrical resistance of SMA in composites during tensile load. After electrical heating, they observed that the generated transverse cracks in composites got successfully repaired due to compressive force introduced by pre-strained TiNi wires and resulted in the self-damage recovery effect.

M Ganapathi and B. P. Patel, M Touratier, G Coffignal i.md M. Verge [170], A new element is developed by the authors for the analysis of laminated/sandwich beams incorporating piezoelectric layers. Beam theory has been employed by authors which satisfies the interlace stress and displacement continuity and has zero shear stress on the top and bottom surfaces of the beam. Piezoelectric layers can be placed arbitrarily and can act as sensors and actuators. The transverse shear deformation in the form of trigonometric sine function is incorporated by authors to

define the transverse shear strain. The displacement and stress variations along the length and thickness are presented by authors .

Coupled electro-thermo-elastic equations applicable for the analysis of smart structures have been derived by Sheikh N. Ahmad, C. S. Upadhyay and C. Venkatesan [161]. These governing equations have been used by authors to obtain the deformation of a smart beam under the action of external mechanical load and an electric potential. The results of the study have been compared by authors with those available in literature. The study brings out the essential difference between sensing and actuation phenomena by solving for the electric potential and the deformation variables in the piezo material.

Basic methods for the preparation of carbon fibres are presented by D H Bowen [163] and the relationship between fibre properties and structure is described. Carbon fibre composites with carbon, metal and resin matrices are briefly reviewed and examples of applications for resin composites in spacecraft are described. Finally, the possible course of future developments is discussed .

Dipak K. Maiti, E. Hemalatha, J. V Kamesh and A. R. Upadhyya [166] have presented the Finite Element analysis of structures with surface bonded piezoelectric patches. The objective of their investigation was to develop layered piezoelectric elements which can be combined with the plate bending elements in general purpose software such as MSC/NASTRAN as a sensor/actuator for the analysis of smart structures. After thorough validation by authors , numerical results are generated for various piezo-electric parameters.

G. R. Liu. K. Y. Dai. and V. K. Varadan [167] have summarized the studies on mesh free point interpolation method (PIM) for static and dynamic analysis of piezoelectric structures. In the PIM methods, the problem domain is represented by a set of properly scattered nodes. The displacements and the electric potential of a point are interpolated by the values of nodes in its local support domain using shape functions derived from point interpolation scheme. Galerkin's formulation is used by authors to establish a set of system equations for arbitrary-shaped piezoelectric structures. Numerical examples are presented by authors to demonstrate the validity and convergence of the present method and their results compare well with the conventional FEM results from ABAQUS as well as the experimental ones.

A numerical technique to estimate the dielectric constant and loss factor of a homogeneous dielectric material placed in an arbitrary shaped cavity has been developed by. The values of S-parameters are measured by Kailash P. Thakur and

Wayne S. Holmes [171], experimentally by placing the sample in the cavity. Starting with a trial set of permittivity values, the computation is carried out using the finite element technique (FEM) to match the S - parameters around the fundamental resonance frequency. The FEM routine is run several times by authors, while optimizing the values of dielectric constant and conductivity of the sample. During the process of optimization, eight different measures of error between computed and experimental values of complex S-parameters are examined by authors. It is found by authors that there is no single measure of error which can be minimized to estimate two parameters (dielectric constant and the loss factor) but the combination of errors has to be minimized to get the exact solution. The computer program can generate the solution with an accuracy of less than 0.01% in few hours on a Pentium based PC.

C.Venkatesan and C.S.Upadhyay, [172] have presented a comprehensive description of the physical interactions in a piezoelectric material used in development of smart structures. The governing electro-thermo-elastic equations for the analysis of smart structures have been developed by authors from the fundamental laws of conservation and thermodynamic principles. A brief description of the application of smart technology to rotorcraft is also presented.

Ho-Jun Lee, Dimitrios A Saravanos of Lewis Research centre & Ohio Aerospace Institute [144] have worked on finite element modeling aspects of piezos and thermal effects on them. Their work concentrates on the fact that Layer wise finite elements enable modeling of responses of smart piezoelectric composite structures.

In the paper entitled ,`Simulation of an ultrasonic piezoelectric transducer',by David H. Johnson, P.E., Dharmendra Pal, [143] the authors have presented the piezoelectric, coupled field capability of the ANSYS / Multiphysics product in both linear and nonlinear simulations. A piezoelectric transducer assembly is modeled, including a discussion of vendor-supplied property data as it relates to the ANSYS material input requirements. A cylindrical geometry is treated as an axisymmetric model using the PLANE 13 element type. The transducer model is used in modal and harmonic analysis solutions to understand its mechanical behavior and to aid in design modifications to optimize its weight, performance, and electrical power consumption. Experimental measurements made by authors with a Philtec optical sensor are compared to harmonic analysis amplitude results. According to the authors , this sensor device, using a light source, fiber-optic transducer and an oscilloscope display, can measure the high frequency (~22 kHz) vibrations of the transducer assembly.

R. P. Shimpi and Ainapure [145] in this paper, have used, variationally consistent layer-wise trigonometric shear deformation theory and extended this theory to deal with free vibration of two-layered laminated cross-ply plates. Governing differential equations are derived by making use of a displacement field which allows a sinusoidal variation of the in-plane displacements through the laminate thickness. In this displacement based theory, constitutive relations between shear-stress and shear-strains are satisfied in both the layers, and therefore, shear correction factor is not required. Compatibility at the layer interface in respect of in-plane displacement and compatibility in respect of transverse shear- stress is satisfied by authors , yet present theory contains fewer unknown variables than that of the first order shear deformation theory. Effects of rotary inertia and other inertias are also included by authors. Efficacy of the present theory is demonstrated through illustrative examples by authors.

2.3.2 Shape studies on curved reflectors

Gregory Washington [71] has reported that recent studies have shown that reflector surface adaptation can achieve performance characteristics of the order of phase array antennas without their complexity and cost. The study develops a class of antennas capable of variable directivity (beam steering) and power density (beam shaping). The actuation for these antennas is employed by attaching polyvinylidene fluoride (PVDF) film to a metallized Mylar substrate. A voltage drop across the material will cause the material to expand or contract. This movement causes a moment in the structure which causes the structure to change shape. Several studies of flexible structures with PVDF films have shown that cylindrical antennas can achieve significant deflections and thereby offer beneficial changes to radiation patterns emanating from aperture antennas. In the study, relatively large curved actuators are modeled and a deflection-force relationship is then employed in simulations where the far-field radiation patterns of an aperture antenna are manipulated.

In this paper, Su Huan Chent, Cuo Feng Yao and Hua Dong Lian [19], have proposed a new three-dimensional piezoelectric thin shell element containing an integrated distributed piezoelectric sensor and actuator. The distributed piezoelectric sensor Layer monitors the structural shape deformation due to the direct effect and the distributed actuator layer suppresses the deflection via the converse piezoelectric effect. A finite element formulation is presented by authors for static response of laminated shell with piezoelectric sensors/actuators. An eight-node and forty-DOF shell element is built by the authors . The performance of the shell element is improved by reduced integration technique. The static shape

control of structure is derived by authors & the shell element is verified by authors by calculating piezoelectric polymeric PVDF bimorph beam. Their results agreed with those obtained by theoretical analysis, Tzou and Tseng (1990) and Hwang and park (1993) fairly well.

In this research according by Marc R. Angelino and Gregory n. Washington [146], an antenna's far field radiation pattern is controlled by controlling the shape of a sub reflector in a cassegrain antenna system. The antenna is actuated using multiple point actuators in contact with the reflector surface by the authors. A PZT stack coupled with a friction-based compliant mechanism gives the point actuators used in this design an advantage over similar studies using PZT bimorph or PVDF actuators. The main advantage stems from the fact that the displacement can be maintained without the continuous application of voltage. An electromechanical model is used by authors to describe the motion of the stack, and the friction based compliant mechanism is modeled similar to power screw-type actuators. A combined finite element-electromagnetic analysis code is used by authors to determine the desired shape of the reflector and the corresponding actuator displacements. The final shape of the reflector is verified using stereo photogrammetry by the authors.

2.3.3 Active shape control

Hwan-Sik Yoon and Gregory Washington [3] , have demonstrated that aperture antennae can have their performance improved by employing shape control on the antenna surface. The antennae previously studied by authors were actuated utilizing polyvinylidene fluoride (PVDF). Since PVDF is a polymer with limited control authority, these antennae can only be employed in space based application. In the study carried out by authors , they have examined more robust antenna structures devised of a thick metalized substrate with surface bonded piezoceramic (PZT) actuators. In this work, piezoceramic-actuated adaptive antennae of cylindrical-cut shape are studied by authors . When a PZT actuator is attached to the reflector surface, the converse effect develops a bending moment in the structure making the reflectors bend inward or outward. This bending can be employed in antenna beam steering and shaping. In order to effectively construct the antenna, the piezoceramic-actuated antenna surface was modeled by authors using classical curved beam theory and Newton's method. The deflection versus voltage relationship has been then experimentally verified by authors , and the resulting far-field radiation pattern has been simulated on computer. The results emphasize two major points: firstly, the far-field radiation pattern can be altered in a positive

fashion, and secondly the first two radiation modes of the antenna correspond to the first vibration mode shapes of the structure.

Fukashi Andoh, Gregory Washington, Hwan-sik Yoon and Vadim Utkin [1] have proposed a novel approach to the shape control problem with a limited number of discrete actuators. In optimizing the actuator locations, first the reference input has been expanded with a representative set of eigen functions. From the expansion coefficients, the dominant modes in the reference input have been identified. Next the distributed parameter system was rewritten in modal coordinates and the irrelevant modes were truncated. Finally, the actuator locations have been selected such that the singular values of the controllability matrix of the truncated system were maximized. The steady state actuation forces have been optimized such that a cost function based on the absolute value of the steady state error is minimized. To improve the transient response, a hybrid of dynamic modal control algorithm and the optimization method has been developed. Four discrete linear actuators for the one-dimensionally curved reflector and eight actuators for the two-dimensionally curved reflector have been utilized. The structures are controlled and assessments for experimental implementation are made.

Hwan-sik Yoon and Gregory Washington have proposed [68] an approach for modeling, design and testing of a doubly curved piezoceramic strip actuated antenna has been proposed by the authors at Ohio University. A doubly curved aperture antenna was modeled as shallow spherical shell actuated by four curved PZT patches bonded on the back surface of the reflector in 90 degree intervals. The study is supported by experimental as well as theoretical work.

Gregory Washington from Ohio University, Ohio [2] has worked on Design, Modeling and Development of Precision Apertures. His work concentrates on Smart Ku band antennas which have futuristic applications in antenna beam steering and beam Shaping as shown in Fig 2.5.

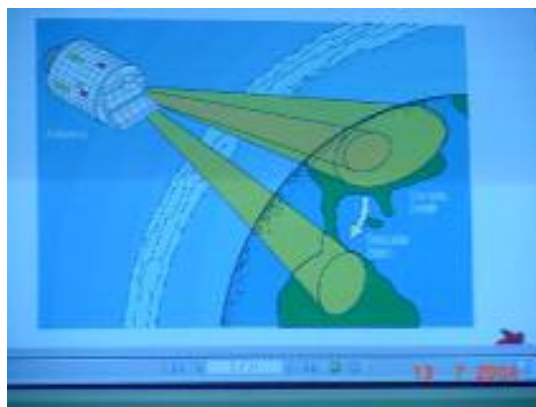


Fig 2.5 : Smart Ku band antenna demonstrating beam steering in USA

A.D. Monk, P.J.B. Clarricoats [140] report how a reconfigurable mesh reflector antenna can be used to generate nulls in its radiation pattern while closely maintaining the original pattern in regions away from the null. The theory is developed and theoretical results are presented by authors for a typical antenna of a size for spacecraft applications. Experimental results, which are in close accord with theory, are given for an offset mesh reflector which is scaled to approximately 30 wavelengths in diameter and is fed by a corrugated horn. It is shown by authors that deep nulls can be formed both within the main beam and within the side-lobe region. Applications of the offline mode of operation lie where there is a priori knowledge of the location of the interfering source which could be the case in civil scenarios, including those of some deep-space missions requiring communication with an earth-based transmitter. A typical NASA's Inflatable Antenna Experimental reflector is shown in Fig 2.6.



Fig 2.6: A typical NASA's Inflatable Antenna Experiment reflector during ground tests

Brij N Agrawal and Kirk E Treanor [14], in this paper, present the analytical and experimental results on optimal placement of piezoceramic actuators for shape control of beam structures. The objective was to determine the optimum piezoceramic actuator locations and voltages to minimize the error between the desired shape and the achieved shape. The analytical model for predicting beam deformation due to a piezoelectric actuator is based on the Euler-Bernoulli model. The cost function has fifth-order polynomials in the actuator locations and second-order polynomials in actuator voltages. This difference resulted in difficulty in simultaneous optimization of actuator locations and voltages. Using embedded Nader and Mead simplex algorithms to separately optimize actuator locations and voltages was found by authors to produce reliable results, converging to the same optimum solution for a variety of initial conditions. The experimental results show that the analytical model provides a reasonable prediction of actuator performance

at low input voltage, but does not account for the nonlinear behavior of the piezoceramics and effects of hysteresis.

Saravanan, Srinivasan M Sivakumar and V Kalyanaraman [147], in this paper, have presented a methodology to control the surface error on a Doppler antenna using the concept of a variable geometry truss structure. A genetic algorithm is used by authors to find the optimal location and number of actuators with the objective to minimize the construction and runtime costs. The optimization also takes into account the limitations in actuation. A piezoceramic based actuator is used by authors to demonstrate the effectiveness of the methodology. A simple illustration of 2d trusses, which could form a part of a Doppler antenna structure, is used to show the efficacy of the method. An analysis of the effectiveness of such a design is presented by authors . The influence of the variables in the problem is examined by authors and observations are made. This study concludes that the smart antenna concept is a viable, feasible and effective option in design.

A general purpose design scheme of actively controlled smart structures with piezoelectric sensors and actuators is presented by S.X.Xu, T. S. Koko [148] in this study. Their proposed scheme makes 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. Subsequent details of designing state/output feedback control are addressed . For the purpose of demonstration, a commercial finite element code complemented with output feedback control law is employed to design a set of structural systems for active vibration control. The present scheme can be adapted to the design of actively controlled smart structures with non-piezoelectric sensors or actuators.

2.4 Literature Review in the domain of thermal distortion aspects

The literature survey in thermal distortion domain has been carried out as follows :

2.4.1 Thermal distortion aspects

W L Lehn [142] in the present study has worked in the development and evaluation of transparent conductive coatings, conductive bulk materials and grounding techniques for application to high resistivity dielectric spacecraft materials to eliminate or control spacecraft charging is discussed by the author. Techniques for the application of thin transparent conductive indium oxide, indium/tin oxide and other metal oxide coatings to Kapton, FEP Teflon, OSR and solar cell cover glasses are presented . The development of conductive bulk glass and stable low out-gassing fabric type thermal control coatings as spacecraft charging control materials is presented .

Maintaining the surface shape of precision structures such as spacecraft antenna reflectors has been a challenging task. Surface errors are often introduced by thermal distortions due to temperature differences. In this work, Song, X Zhou and W Binienda [153] present numerical and experimental results of active compensations of thermal deformation of a composite beam using piezoelectric ceramic actuators. To generate thermal distortion of the composite beam, two film heaters are bonded to only one side of the beam using thermally conductive materials by authors. To correct thermal deformation caused by the film heaters, PZT (Lead Zirconate Titanate), a type of a piezoelectric ceramic material, is used in the form of patches as actuators. These PZT patches are bonded on the other side of the beam.

First, finite-element analyses are conducted with consideration of the coupled effects of structural, electric and thermal fields on the composite beam. These analyses include static coupled field modeling of the beam deformation with PZT actuation, transient modeling of the beam under thermal loading, and static coupled field modeling of the composite beam with thermal distortion and simultaneous PZT actuation to correct this distortion. Then, experiments are conducted by authors to study the thermal effect, the PZT actuation effect and active thermal distortion compensation using PZT actuators with a proportional, integral and derivative feedback controller. The Finite element modeling and experimental results agree well and demonstrate that the proposed method can actively perform structural shape control in the presence of thermal distortion.

The details of the ISRO's technical report [181] referred w.r.t the thermal distortion of spacecraft reflectors are reproduced as follows :

The communication performance of the spacecraft depends on the Thermo-mechanical behavior of its antenna reflectors. Diurnal and seasonal solar variations can cause temperature extremes and gradients, which mechanically distort the reflector and degrade its communication signals i.e. performance. Thermal control using Sun Shield, Thermal paint and Multi Layer Insulation (MLI) blanket can reduce the temperature variation to certain extent but cannot be totally avoided. Thermal distortion on shaped reflector is much more felt than conventional offset parabolic reflector.

The on orbit performance of the reflector is assessed using the theoretically estimated temperature distribution data obtained using the TMG-IDEAS (Integrated Design Engineering Software-Thermal module) software. The thermal distortion

analysis of the reflector for (Beginning of Life) BOL & End of Life (EOL) cases, 1 to 24 hours is studied and the minimum & maximum distortions are estimated using NISA FE Analysis software.

The C-band reflectors on the east & west side of the spacecraft are insulated using thermal paint on the front side and five layers of MLI on the backside. The expected on orbit temperature and its gradient distribution at BOL & EOL conditions for 1 to 24 Hrs. on the dish & ribs in the deployed mode are generated theoretically using TMG -IDEAS thermal analysis module.

The thermal distortion analysis of East 2m dia. C-Band reflectors of INSAT-3C show the maximum resultant out of plane z- displacement of the dish is 0.5021 mm at T=14 hour for East reflector for BOL case. The thermal distortion analysis of west 2m dia. C-Band reflectors of INSAT-3C show the maximum resultant out of plane z- displacement of the dish is 0.2759 mm at T=14 hour for East reflector for EOL case. The comparison of maximum thermal distortion of the typical East & West spacecraft reflectors at Hold down is shown in Table 2.1.

Table 2.1: Comparison of Maximum Thermal Distortion of the typical East & West Spacecraft reflectors at Hold down

BOL		EAST		WEST
	δZ mm	δZ mm (Resultant)	δZ mm	δZ mm (Resultant)
T=1Hour	0.125	0.2965	0.1358	0.2369
T=5Hour	0.1662	0.3828	0.1596	0.3828
T=14Hour	0.2093	0.5021	0.1846	0.4989

EOL		EAST		WEST
	δZ mm	δZ mm (Resultant)	δZ mm	δZ mm (Resultant)
T = 1Hour	0.171	0.2201	0.1832	0.1894
T=14Hour	0.23505	0.27597	0.2264	0.2688

Root mean square thermal distortion alone for EOL case for 2m dia. Spacecraft reflector is the to the tune of 200 microns .

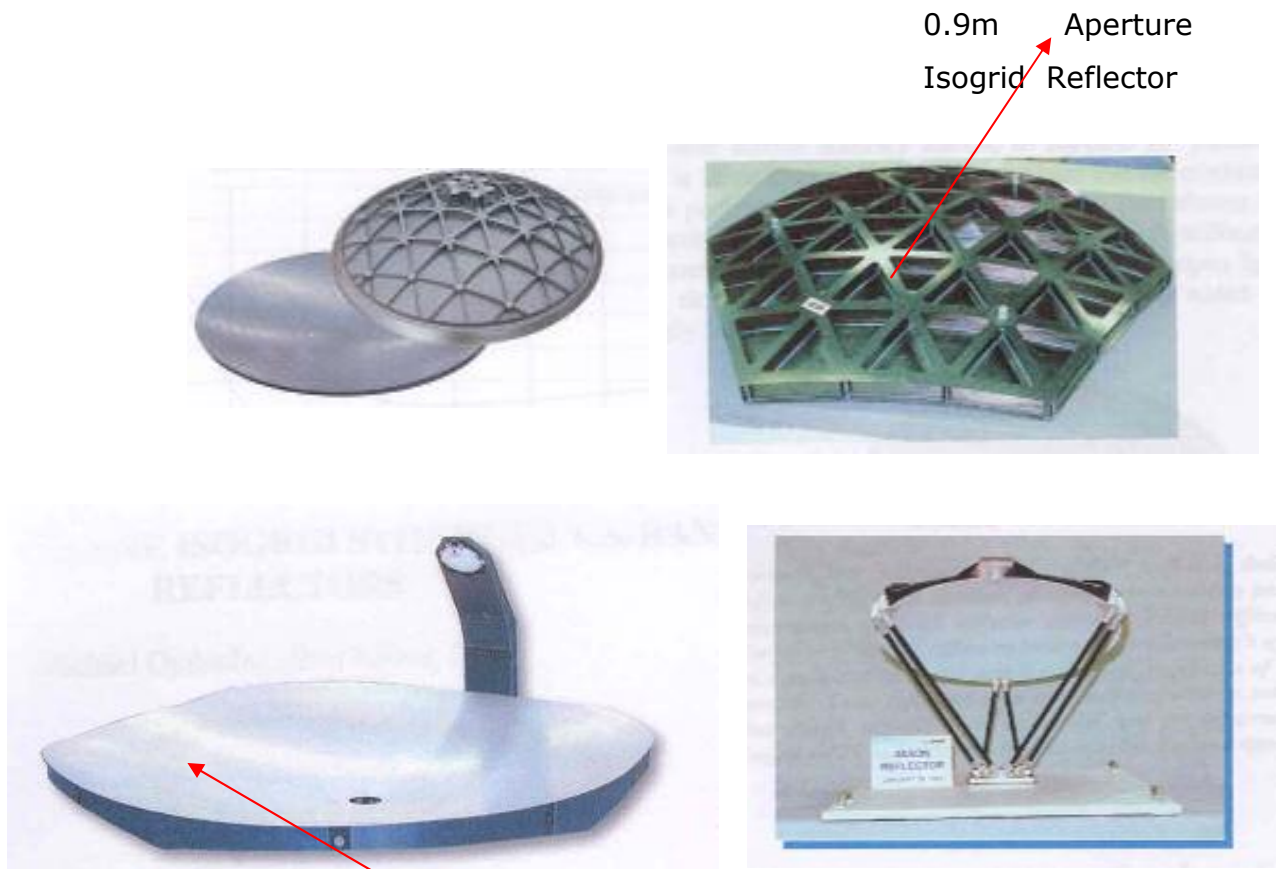
2.5 American Standard Test Methods (ASTM)

Following two American Standards have been referred for theoretical estimation of damping values and for estimation of the size of the specimen :

- American Standard Test Method – Designation ASTM E-756-98, Measuring Vibration damping Properties of materials.
- International Vehicle recommended practice - SAE J1637, Laboratory measurement of the composite Vibration damping properties of materials on a supporting steel bar.

Details of these ASTM Codes are given in Appendix A .

Fig 2.6 shows a few typical ultra light weight high precision spacecraft reflectors with isogrid concept [188] developed by M/S ATK Composites, CA, United States of America.



vapor deposited Aluminum (VDA) coated graphite reflectors

Fig 2.7 : Typical ultra light weight reflectors with isogrid concept

2.6 Feasibility Report – Potential Areas of the Applications of Smart Materials at SAC

A Feasibility report [192] presents the extensive study carried out by the author on the Applications of smart materials in antennas at SAC [182]. After conducting the Literature survey, visiting various premier institutes across India, studying wide gamut of smart material options and their availability & suitability finally the feasibility report was compiled highlighting some of the following potential areas of the applications as described in detail in the Section 1.8 as aim of the present investigation:

- Passive vibration damping on CFRP / KFRP spacecraft reflectors at elevated space domain temperatures using thin hybrid Piezoceramic powder coatings on CFRP, KFRP and Graphite composites sandwiched with Kevlar flexcore have not been tried.
- Micro vibration is still an unexplored domain for the composite (Carbon / Graphite / Kevlar) spacecraft reflectors (of diameter $< 2\text{m}$) of INSAT / GEOSAT satellites. It is also not understood fully what happens to the modal damping of these composites at the varying temperatures in space.
- Literature talks of Magnetostrictive coatings on cantilever beams developed from various materials for achieving active / passive vibration damping but these magnetic materials can give Electromagnetic interference and Electromagnetic coupling for micro wave antenna applications for various high Radio Frequencies signals. It is felt that, this part needs to be explored further by trying out hybrid coatings of different Ferroelectrically hard & Ferroelectrically soft viscoelastic materials on different type of high Specific stiffness composites with embedded Kevlar flexcore .
- It is felt that contemporary dielectric RF transparent materials for Spars of the Parabolic Prime Feed Fed type reflectors (Spars act as structural load carrying members for supporting the feeds at the focal points of the reflector) need to be tried out along with the smart materials from the point of view of reducing the blockage of the RF signals for the parabolic reflectors to improve their Gain and Efficiency .

- Keeping in view the requirements for the development of futuristic Smart / Mechanically Active Antenna reflectors for INSAT / GEOSAT programmes, preliminary shape deformation studies in the domain of spacecraft reflectors have also been proposed to be carried out w.r.t the spacecraft reflector parabolic profiles, particularly concentrating on usage of different types / layouts of piezoceramic patches on the reflector surface for exploring possible applications in the domain of compensating thermal distortions in futuristic ultra high precision transmit / receive frequency antennae.

The Finite Element modeling aspects of smart structures are described in Chapter 3.
