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PREFACE

This collection of papers on Adaptive Structures is from the three sessions organized by the ASME Materials and Structures Committee of the Aerospace Division for the 1989 ASME Winter Annual Meeting held in December in San Francisco. The objectives of the special sessions in Adaptive Structures are to stimulate discussions between the various investigators and to collect the latest papers in this volume for use by others to evaluate the merits. Adaptive Structures will enable new exciting future missions, especially those related to precision large space structures. Unlike most designs, where the passive structure is designed, fabricated and ground tested to meet the operational requirements, Adaptive Structures allows the geometry and characteristics of the structure itself to be varied at any stage in its development including its operational state to help fulfill the mission requirements. Several definitions of Adaptive Structures in the literature are "can purposefully vary its geometric configuration as well as its physical properties" and "whose geometric and inherent structural characteristics can be beneficially changed to meet mission requirements either through remote commands and/or automatically in response to external stimulations". The concepts are equally applicable to other fields such as aircraft, robotics and buildings, although most of the papers included are related to space structures. An attempt was made to contact all the active researchers in Adaptive Structures; all the contributed papers are from the U.S. and Japan. As a result, a U.S./Japan Conference in Adaptive Structures is being planned with ASME as a cosponsor.

Recently many terms such as Adaptive Structures, Smart Structures, Intelligent Structures, Controlled Structures, and Active Structures have been used to identify areas of research; the first paper categorizes and distinguishes between the various terms which are consistent to the authors. The topics covered by the papers include the utilization of various forms of actuators and sensors, new active member concepts, structural concepts for geometric control, influence of structural uncertainties, quasi-static control, active damping, wave control, system identification, and controls.

This volume was made possible by the cooperation of all the authors who contributed their time and documented their results to meet the publication deadline.

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ADAPTIVE STRUCTURES

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Abstract

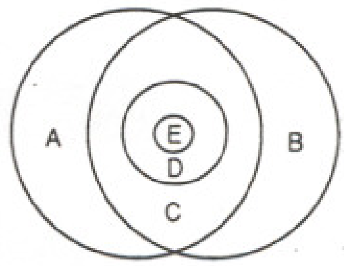
The performance requirements of advanced space systems of the future have motivated a new approach to structural design. This paper surveys the field of *adaptive structures* and proposes a general framework for categorizing the various approaches being pursued. Examples are described in each category to place the work in relative perspective and to describe the similarities and differences between the approaches.

I. Introduction

The performance required of future precision space structures has motivated a new approach to structural design, where feedback control principles and advances in sensors and actuators are applied to the design of high performance structural systems. This paper is an overview of research into such *adaptive* structures. General nomenclature will be defined to assist in categorizing the many aspects and approaches to controlling structures for space applications. Later sections will expand on the work in each category, and discuss the relationship between the approaches being taken by several teams of investigators in the United States, Europe and Japan. The authors take responsibility for any work inadvertantly omitted from this overview.

A general framework is proposed in Figure 1, which embraces a broad context of structural control approaches. The two most basic categories are the *sensory* structures, those which possess sensors that enable the determination or monitoring of system states or characteristics, and the *adaptive* structures, those which possess actuators that enable the alteration of systems states or characteristics in a controlled manner. A sensory system may possess sensors for health monitoring, but possess no actuators. Conversely, an adaptive system may possess actuators for a controlled deployment, but have no sensors.

The intersection of sensory and adaptive structures are the *controlled* structures, those with both sensors and actuators in a feedback architecture for the purpose of actively controlling system states or characteristics. It is somewhat arbitrary (and may expose the predisposition of the authors) to call such systems *structures*, since in principle a controlled structure may be composed of a conventional structure and a separate and distinct control system, such as a proof mass actuator attached to a truss structure. Perhaps the main utility in such a definition is to distinguish such conventional approaches from the next category: the *active* structure.



A ... Adaptive Structures
B ... Sensory Structures
C ... Controlled Structures
D ... Active Structures
E ... Intelligent Structures

Figure (1) Proposed Framework.

The *active* structure is a controlled structure that contains sensors and/or actuators that are highly integrated into the structure and have structural functionality in addition to control functionality. The hybrid nature of the active structure is the point of departure from conventional approaches, and characterizes a truely integrated control/structural system. Taken to the logical extreme, the *intelligent* structure contains highly integrated control logic and electronics that provide the cognative element of a distributed or heirarchic control architecture.

Structures can be controlled in a number of different senses. For example, the objective of the control system may be to influence the mechanical properties of the structure. This includes the mechanical states (position, velocity, etc.), and the mechanical characteristics (stiffness, damping, etc.). A structure which uses rate feedback to an actuator to increase damping is a mechanically controlled structure. Alternatively, other types of controlled structures can be contemplated. A thermally controlled structure would include a control system to influence its thermal states (temperature), or thermal properties (conductivity, absorptivity, etc.). A structure with distributed heaters and thermocouples would be an example. One might even envision a structure whose surface optical properties (hue and intensity) were controlled, or whose surface electromagnetic properties were controlled.

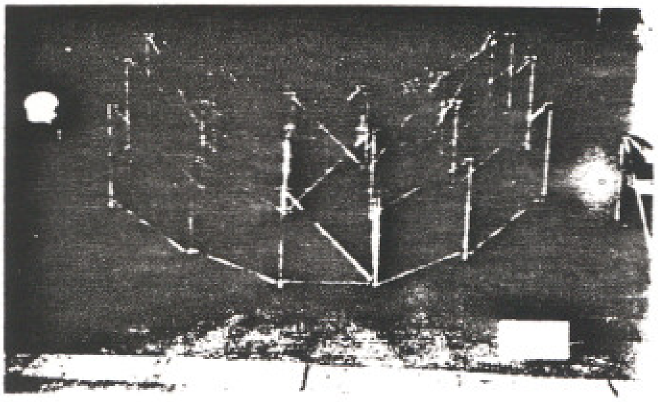


Figure (2) Planar Adaptive Truss

The remainder of the paper will expand on this classification scheme by means of examples from each category. It is reasonable to expect that the boundaries of the domains are fuzzy, and that some approaches may simply defy classification. The category of structures that are only sensory includes much of what the Department of Defense is developing as *smart structures*—those with embedded fiber optics and other sensors for health monitoring and other purposes. Such structures will not be discussed further in this paper.

II. Adaptive Structures

Adaptive structures are defined as those which posess actuators that allow the alteration of system states and characteristics in a controlled manner. Another definition of Adaptive Structures proposed by Miura (1988) is a structure that "can purposefully vary its geometric configuration as well as its physical properties." The two definitions are essentially identical. Various examples of Adaptive Structures which will not be covered in subsequent sections will now be described.

Geometry Adaptive

Deployable structures are structures that undergo large controlled geometric changes from a compact to a final distributed geometric configuration; examples include space antennas. Deployable space structures include the capability to adjust the lengths of the individual members in a controlled fashion to develop compatible configurations during the deployment, to provide for fine adjustment about the final configuration, and to establish preloads to alleviate undesireable motions which may be introduced by conditions such as loose joints. Figure (2) illustrates a deployable antenna type structure (Natori et al, 1988), where the actuators to deploy the structure can be modified to make the fine resolution adjustments of the structural surface. The actuators used to adjust the member lengths can also be utilized to make adjustments during the mission as well as to provide structural damping or isolation.

The Hoop Column Antenna (Miller et al, 1986) is an example of a deployable antenna with a mesh for the reflector surface; the mesh is then adjusted in space by applying the appropriate tension loads to a large number of surface control cables which are attached to the mesh. Similarly both static and dynamic adjustments can be made by varying the boundary conditions of structural systems (Natori et al, 1989).

Space cranes are classes of structures that are similar to

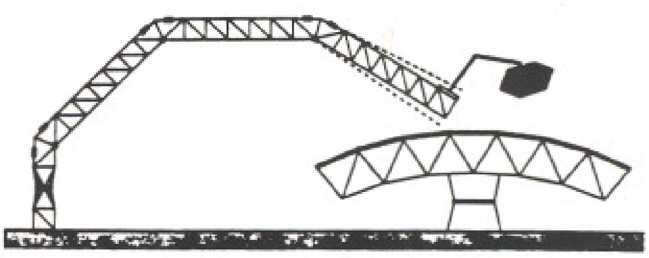


Figure (3) Space Crane Concept.

deployable structures except the final geometric position is not necessarily pre-specified. The dynamic characteristics of the structural systems may vary by orders of magnitude during its operation which may require various degrees of controls. An example of a space crane (Mikulas et al, 1988) is shown in Figure (3); the crane is currently being evaluated for the assembly of large systems in space to support the Lunar Base and Manned Mars Missions. Initial design parameters of the crane are a length of 300 feet with a capability of moving masses ranging from a few pounds up to 300,000 pounds. The work space is defined as a sphere with a radius of up to 300 feet from the base of the space crane. The actuation of the crane includes extensional members (Utku et al, 1989) which can also be utilized to provide active damping to the system.

A Variable Geometry Truss (VGT) (Miura and Furuya, 1985) shown in Figure (4) can be utilized as a space crane in which one end is fixed to a base or a baseless space mechanism, in which two masses are attached to each end of the extended structure which is then drawn together in space for assembly. Other applications include the use of VGT trusses as scaffolding for space construction or to form structural shapes such as large structural rings for antennas. Variable geometry trusses have also been developed for robotic applications by Robertshaw et al (1989), and Reinholtz and Gokhale (1987).

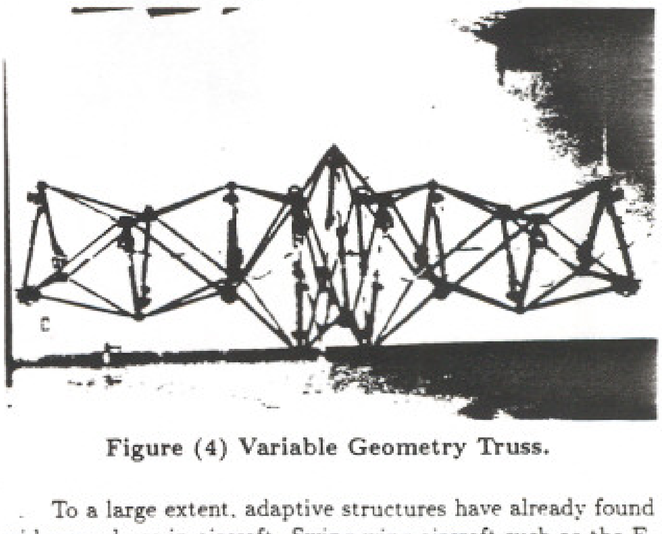


Figure (4) Variable Geometry Truss.

To a large extent, adaptive structures have already found widespread use in aircraft. Swing wing aircraft such as the F-111 fighter/bomber, F-14 fighter and the B-1 bomber; aircraft with deployable Fowler flaps; and lifting surfaces with maneuver related flap scheduling are examples of adaptive wing geometries. In addition, lifting surfaces with variable camber are employed on aircraft such as the F-111. Recently, methods of incorporating the mechanism which provides for variable geometry lifting surfaces into the wing substructure or skin, hence developing a true adaptive aeroelastic structure, has been investigated with promising results (Crawley and Lazarus, 1989).

Feedforward Control of Mechanical Properties

Temperature control can be utilized to control the characteristics and geometry of the structure. The control can be affected either by adjusting the total heat flux to the system by mechanisms such as louvers, or by other direct heating sources such as electrical heaters. For most material properties, the direct change of the material characteristics, such as Young's Modulus, due to temperature change, is insignificant. However, the change in the damping characteristics of viscoelastic materials used to enhance passive damping is dramatic. Changes of up to an order of magnitude in damping characteristics of viscoelastic materials with a ten degree change in temperature can be expected. Experiments (Wada et al. 1987) utilizing the control of the temperature of viscoelastic material embedded at various locations in a composite beam with collocated heaters and thermocouples have been performed. The modal damping characteristics of the beam were controlled by adjusting the temperature of the viscoelastic material.

Electro-rheological materials are suspensions of very fine dielectric particles in insulating mediums which exhibit controllable rheological behavior in the presence of applied electric fields. Application of electric field levels between 0 and 4,000 volts/mm results in several order of magnitude change in the complex shear modulus from which the shear storage modulus and shear loss factor can be derived. Replacing the viscoelastic materials frequently used to add damping to a structure by the electrorheological fluid, the capability exists to change and control the value of damping by applying different electric fields. Gandhi et al. (1988) and Coulter et al. (1989) have demonstrated the change in modal damping by a factor of two to three of the lower structural modes of a beam. Additionally, they have demonstrated that the lower resonant frequencies can be increased by 50–100% by increasing the shear modulus of the electro-rheological fluid which couples the face sheets of the sandwich plate.

Shunted piezoelectric damping or passive electronic damping was introduced by Forward, (1979) and extended by Hagood and Crawley, (1989) to add passive damping to specific modes of vibration. Passive damping is added to a mode by coupling the piezoelectric transducers by proper matching of the mechanical and electrical impedances and tuning the electric circuit to the frequency of the mechanical system. The electrical resistance is coupled with the mechanical system through which energy is dissipated. If damping is required in several modes, several shunted piezoelectric damping circuits are required; one for each of the modes.

Buehler and Wiley, (1965) received a patent on a series of shape memory materials often referred to as Nitinol. The unusual characteristics of the shape memory materials is that when the material is plastically deformed below its phase change transition temperature, the material has a "memory" and will return to its original position when heated above its transition temperature. Plastic strains up to two percent can be recovered and restraining the material from returning to its original position can result in stresses up to 100,000 psi. By changing the composition of the material, the transition temperature can be changed to temperature ranges of interest to most space applications. Usually the material is heated electrically.

Rogers et al, (1989) have utilized the properties of the shape memory alloy (SMA) to change the properties of structures. He has embedded eight SMAs into a composite beam and through appropriate boundary conditions increased tension in the material system through heating the SMAs. The increase in the lateral frequency of the beam ranged from 18% heating two SMAs, to 73% heating six SMAs. Additional theoretical work has been performed to show that, by distributing the SMA wires in a grid fashion in a composite plate, the mode shapes of the plate can be changed by adjusting the strain energy distribution through controlled actuation of the SMA wires.

III. Controlled Structures

Controlled structures are those with both sensors and actuators, connected through a feedback architecture. They are a subset of adaptive structures, distinguished by the presence of the sensors used in a feedback loop. Controlled structures include active structures as a subset where the distinction between active structures and other controlled structures is made by what kind of, and how, the actuators and sensors are used. In general, active structures use relative actuators or sensors which are highly integrated into the structure and/or have structural functionality. Such active structures will be described in Section IV. In general, controlled structures which are not active tend to use inertial sensors and actuators in a less distributed and integrated sense. This section will review the objectives of controlling the mechanical properties of a structure, and give examples.

The most fundamental type of controlled structure is one in which the states to be controlled are the attitude and/or position of the overall structure, the so-called rigid body control. In the classical problem, when the bandwidth of the controller is much less than the fundamental flexible frequency, the structure can be considered a rigid body. However, when the bandwidth of the attitude/position controller exceeds the fundamental frequency, the flexibility of the vehicle must be considered. From the perspective of controlled structure design, the objective is to exert as little authority as possible on the flexibility of the structure. This problem of controlling the attitude/position of a vehicle at moderate bandwidth without destabilizing the flexible modes arose early in the design of unmanned launch vehicles (Gevarter, 1970) and manned spacecraft (Widnall, 1968), and continues today in the design of attitude controllers for spacecraft with flexible appendages (Spanos, 1989).

A more advanced type of controlled structure is one in which the states, or properties, to be controlled involve relative motion, i.e., shape and dynamic response. This type can be further subdivided into vibration control and shape control. In vibration control, the objective is to change the dynamic (as opposed to static) properties of the structure, such as damping, propagation and rejection characteristics. To do this, relatively small forces can be exerted on the many flexible modes by a relatively small number of actuators. The most common form of vibration control entails the addition of active damping by the feedback of measured or inferred rate to actuators (Skidmore and Hallauer, 1985) and (Schaefer and Holzach, 1985). In a number of cases, the increases in the effective damping of the structure have been up to five to seven percent of critical. The purpose of such active damping is to reduce the response and, a priori, the regulator characteristics of the structure, and to robustly further shape control.

The workhorse of active damping has been the proof mass actuator, in which a captive mass is used to react forces created by an electromagnet against the structure itself (Zimmerman et al, 1984). Attention has been focused on optimizing the design of such devices (Juang, 1984) and their passive spring and damper characteristics. A common approach is to create a low authority control loop by feeding back the collocated relative rate between the structure and actuator. This can be done alone, or as part of a low authority/high authority approach (Aubrun et al, 1984). When it is necessary to use control at lower frequencies or larger strokes, it is desirable to hybridize a proof mass scheme with an expendable mass gas jet system (Hallauer and Lamberson, 1989).

Wilson et al, (1989) also used SMA wire as actuators and sensors to actively damp a vibrating beam. SMA wires were placed on both sides of the beam; thus during lateral vibration the wires alternated between tension and compression. Heating of the wires in their compression state provided the forces to actively damp the beam. Difficulty in rapidly cooling the heated wires in the test limited the frequency response of the SMA system to a few Hertz.

Closely related to active damping are the concepts of active isolation and wave propagation control. Isolation is a scheme to reduce disturbance transmission, usually at the source or at a critical measurement point. In the classical approach, a soft mount is used such that the isolation resonance is below the disturbance frequency. In the hard mount approach, the transmission characteristics must be actively controlled to reject the desired frequency (Sievers and von Flotow, 1989). In wave propagation control, the structure is considered a wave guide, and impedance concepts are used to shunt or absorb waves, with the net effect of making the structure damped (von Flotow and Schaefer, 1985) or, in the case of a perfectly matched termination, non-reverberant (Miller and Hall, 1989).

Another concept closely related to active damping is active stabilization, in which initially unstable modes are stabilized by the closed loop control. Although applicable to a large class of problems, active stabilization is most developed in the suppression of aircraft flutter (Noll et al, 1989), (Zieler and Weisshaar, 1986). The applications of active damping are also not restricted to spacecraft. Gust alleviation in aircraft (Liebst et al, 1986) is an application of controlled structures using aerodynamic control. Likewise, the isolation of noise by controlled structures techniques is an important area of research for commercial and defense applications.

In addition to vibration control, the second form of control of structures is generally known as shape control, in which the shape, position or alignment of some number of points on the structure are controlled so as to track a desired value. Shape control usually implies control down to d.c., or, at least, quasi-static control, although it can also include dynamic shape control. A common application of shape control is in the control of optical surfaces. Various schemes for the control of multiple segments of a segmented optical system have been examined, as well as the deformation of single optical surfaces (Chiarappa and Claysmith, 1981). In an interferometric device, the position and alignment of the optical collectors must be closely maintained (Mozurkewich et al, 1988). An example of dynamic shape control is in the slew and realignment problems. In such a problem, the structure must be rapidly moved, and then the final position/alignment established. Challenges exist both in the shaping of the control input (Singer and Seering, 1989) and in the closed loop control (Juang et al, 1986).

IV. Active Structures

By active structures, we mean those controlled structures that integrate the control sensors and actuators with the structure to such a degree that the distinction between control functionality and structural functionality is blurred. Integral sensing and actuation combines controls and structures at the hardware level, and seeks a more optimum design through shared functionality. The development of active structures has centered on the incorporation of materials and devices that can measure or induce forces and strains within the structure's load bearing volume. Applications to date can be divided by functional form into those in which the actuators are widely applied to the surface or are embedded, and those where discrete components of the structure are active. For the distributed/embedded actuation approach, actuation materials are required.

Materials that can induce forces and strains require some sort of coupling between their mechanical behavior and a controlled quantity. Some materials in use are electromechanical in nature, including piezoelectrics and electrostrictors, where mechanical strain is coupled to an applied electric field. Other materials couple strain with magnetic fields (magnetostrictors), or with temperature (shape memory alloys). Much research has been devoted to the embedding of these materials as composite laminates in planar and tubular structures. When the embedded material is stimulated, it attempts to strain against the constraints of the structure surrounding it, thereby inducing a strain in the structure itself. This *strain* actuation approach is described in detail later in this section.

Significant research has also been devoted to the control of truss structures by replacing truss elements by discrete *active-members*. The active-members may be comprised of materials such as piezoelectrics, in which case the actuation is of the *strain* actuation type; or more conventional approaches can be taken. The truss members can be displacement actuators (screwjacks), where the length of the member is controlled, or force actuators (voice coil), where the load in the member is controlled. Truss control experiments will also be detailed in the following.

Distributed Strain Acutation

In distributed strain actuation, the actuation materials are bonded to the surface (Forward and Swigert, 1981) or embedded within a composite structure (Crawley and de Luis, 1987). The actuation material used can be any material in which actuation strain can be commanded by application of a non-mechanical stimulus (i.e., thermal, electrical, or magnetic). Thus, the constitutive relations for such materials have the form

$$\epsilon = \frac{\sigma}{E} + \Lambda \tag{1}$$

where Λ is called the actuation strain, which may be due to any of the above non-mechanical stimulus, and enters into the equation in a manner analogous to thermal strain.

For a given geometry of the structural components and induced strain actuators, the strain induced in the structure can be calculated, and is usually of the form

$$\epsilon = \frac{\alpha}{\alpha + \psi} \Lambda \tag{2}$$

where ϵ is the strain induced in the host structure as a function of the commanded actuation strain Λ. ψ is a measure of the relative mechanical impedance of the structure to actuator, and α depends only on the geometry. Equation (2) indicates that the desirable properties of induced strain actuators include: being capable of developing a high actuation strain, and having a mechanical impedance comparable to the host structure (Crawley et al. 1988).

In principle, there are a number of physical coupling phenomena which give rise to a controlled actuation strain in a material. Piezoelectricity, a linear relation between applied electric field and strain, was among the first to be exploited. Piezoelectrics come in the form of natural crystals, polymers (Burke and Hubbard, 1987), or ceramic materials (Jaffe et al. 1971). Piezoelectric devices are relatively linear and bipolar, but exhibit hysteresis. Electrostrictive materials have a monopolar nonlinear relation between applied field and strain and no hysteresis (Uchino, 1986). Similarly, magnetostrictive materials couple applied magnetic field and strain (Butler, 1988). Relatively small strains, but large bandwidths, can be achieved with the electromagnetically commanded actuating materials. Thermal input can also be used to command actuation strain. In shape memory metals, heating or cooling will cause a martensitic/austenitic phase change, with a resulting cyclically recoverable strain in the metal (Rogers et al, 1989). Alternatively, by differential heating, coefficients of thermal expansion have been used in beam applications to induce strain in the structure (Edberg, 1987). Relatively large strains, up to eight percent in the case of shape memory alloys, can be achieved with thermally induced strains. However, second law limitations on the ability to move heat place some limitations on the bandwidth with these approaches.

In practice, there are a number of different actuation strain materials and geometries that have been analyzed and tested. Among the most common has been the application of segmented piezoceramics to the surface of a beam. Various analytical models of this have been developed (Crawley and Anderson, 1989), such that the *a priori* predication of induced strain is possible. Such induced strain actuation has been used as part of output feedback (Bailey and Hubbard, 1985), (Hanagud, et al, 1986) and (Lee et al, 1989) and positive position feedback (Fanson and Caughey, 1987), for the introduction of active damping, and in the modification of wave propagation properties (Pines and von Flotow, 1989). Quasi-static shape control of plates, with surface mounted piezoelectrics, has also been demonstrated (Crawley and Lazarus, 1989).

An alternative to surface bonding of the actuation strain material is to embed the material inside a composite laminate.

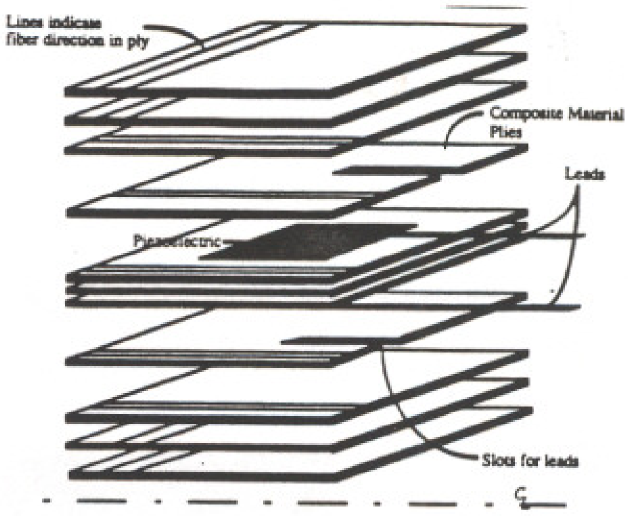


Figure (5) Piezoelectric Embedded Inside a Laminate Structure.

Piezoelectrics have been embedded in beams, plates, and tubes. The advantage of such embedding is that the load transfer from the actuation material to the host structure is enhanced and the surface of the structure is free of fragile components and connections. In addition, embedding affords the designer more options for finding the optimal geometry. However, the complications include electrical insulation and manufacturing of the ceramics and electrical leads into the laminate. Such embedded and highly distributed actuators have been used in beams for active damping experiments based on analytically derived beam controllers (Crawley and de Luis, 1987) as shown in Figure (5). Segmented piezoelectrics of cylindrical geometry have also been fabricated into tubes for uses as passive dampers and active elements of a truss (Hagood and Crawley, 1989).

The use of other materials which produce actuation strains has also been reduced to practice. Electrostrictives have been widely used in shape control of mirrors and other optical surfaces. Such materials are normally placed between the mirror surface and a load bearing structure (Ealey and Wellman, 1989). Likewise, surface mounted and embedded shape memory metal fibers have been used for active damping (Rogers et al, 1989) and shape control of laminated plates (Chen et al, 1989).

Discrete Active Structures

Active truss experiments have been performed by several teams of investigators. Generally, an active element has been substituted for a passive strut in the truss. Depending upon the type of actuator incorporated in the member, the actuation can be force control, displacement control or in between, what has been called strain actuation. The strain actuation approaches are described first.

At the Jet Propulsion Laboratory, two truss structures have been constructed that make use of active-members with piezoelectric motor elements, and built-in displacement and force sensors. The piezoelectric ceramic is placed directly in the load path with a compressive preload applied to ensure that no tension loads are seen by the ceramic motor. The testbed structures are shown in Figures (6) and (7).

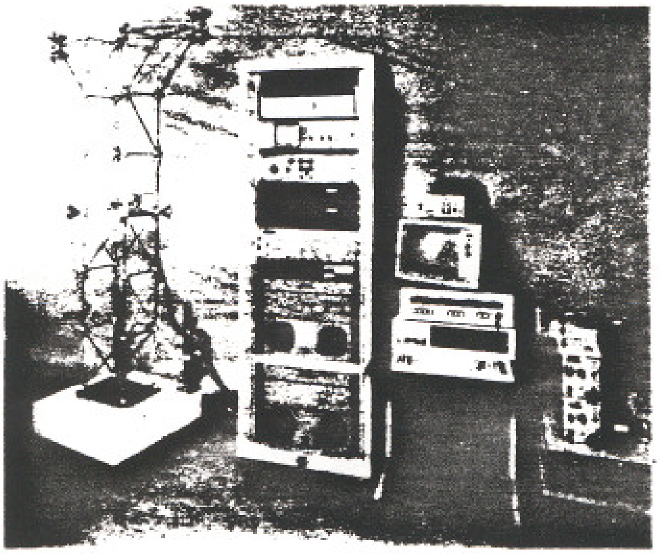


Figure (6) JPL Precision Truss.

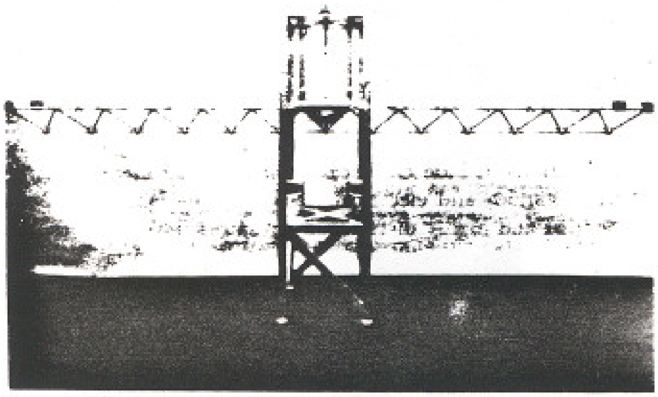


Figure (7) JPL Free-Free Truss.

Fanson et al, (1989) have experimented with collocated and noncollocated digital control of a cantilevered four longeron aluminum truss. G-S. Chen et al, (1989) make use of a similar three longeron truss in both cantilevered and quasi-free conditions, using collocated analog control. These experiments also include static shape control tests and incorporation of passive damping. Both structures have achieved significant levels of active damping ($\zeta > 5\%$) with low order controllers.

At Sandia National Laboratory, Peterson et al. (1989) have tested a cantilevered polycarbonate truss that utilizes piezoelectric material bonded to the outer surface of the truss element (Figure (8)). Piezoelectric polymer film forms a strain sensor on nearly collocated members. Digital LQG and Optimal Projection controllers were designed to minimize a line-of-sight error. Preumont et al, (1989) at the Free University of Brussels have experimented with a cantilevered truss using piezoelectric motors and collocated force transducers. Linear and nonlinear digital controllers were implemented achieving modal damping ratios as high as three percent.

Several structures have been built with force actuation. These generally take the form of voice coil actuators in the members. Balas et al, (1989) at Caltech have built a two

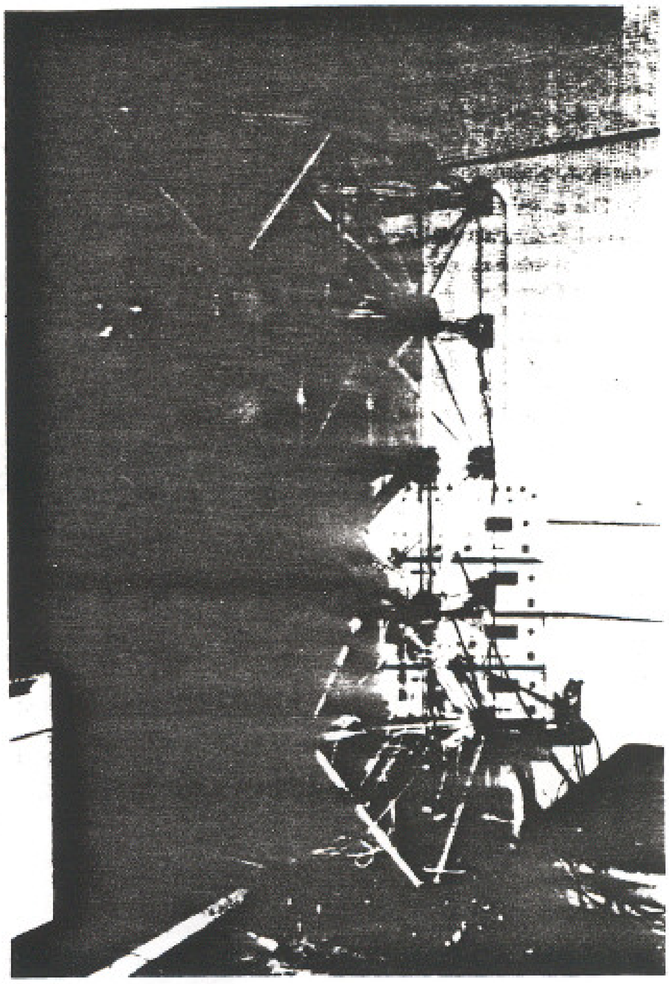


Figure (8) Sandia Gamma Truss.

bay aluminum structure and have implemented digital μ-synthesis controllers using noncollocated accelerometers as sensors. This testbed was developed primarily to study robust control methodologies. Dailey et al, (1989) at TRW tested a one bay structure using voice coil actuators and a noncollocated laser diode line-of-sight sensor. This experiment was also intended primarily to study robust control design. Some passive damping experiments were also performed. Natori et al. (1988), at the Institute of Space and Astronautical Science (ISAS) in Japan, has experimented with a suspended four longeron truss with custom voice coil actuators and noncollocated displacement sensors that were not attached to the structure. Digital control experiments on this structure achieved closed loop damping of up to eight percent. Force actuation using voice coil actuators tends to result in soft structural members because the actuators rely on a field interaction between a magnet and a coil.

Truss structures have also been built using displacment actuation in the form of screwjack type actuators and are capable of large displacements. The lengths of the members are controlled by turning a machine screw or ball screw via a small motor. Robertshaw et al. (1989), at Virginia Polytechnic Institute and State University have built two and three dimensional variable geometry truss structures and have performed digital vibration control experiments as well as robotic manipulator studies. Natori et al. (1987) of ISAS in Japan have built linear and planar truss structures where every member is controllable, and has experimented with altering the shape of the truss from a stowed configuration to flat and then parabolic (Figure (2)).

V. Intelligent Structures

The most exclusive subset of the diagram of Figure (1) is that of *intelligent* structures, which are differentiated · · m active structures by the presence of a highly distributed control system. This involves distribution and integration of not only the sensing and control elements but also of the electronic components involved in signal conditioning, computing, and power regulation.

Such a high degree of distribution lends itself to the implementation of a similarly structured control architecture. Progress has been made on the problem of a distributed control logic for the shape control of an intelligent structure. Both hierarchic (Hall et al. 1989) and still more decentralized (Young, 1983) schemes have been proposed as a means of decreasing the computational burden and distributing it among a number of processors.

As "smart skins" are developed for non-structural control applications involving radar and other avionics, work has been performed on the issues involved in physically embedding the necessary electronics in composite structures. Systems level analysis on the choice of embedded vs. surface mounted computing components is underway at such companies as Hughes, Rockwell, and Westinghouse. The feasibility of embedding microelectronic devices, or at least of one of the fundamental building blocks, the field effect transistor, has been demonstrated in a sensor for monitoring the cure of composites (Bidstrup and Senturia, 1988). With additional possibilities in the areas of dynamic reconfiguration and fault-tolerance, intelligent structures will certainly be a field of intense effort in the years to come.

Acknowledgements

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