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Review of seismic vibration control using 'smart materials'

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Abstract. For the potential application of smart materials to seismic structural control, this paper reviews seismic control techniques for civil engineering structures, and developments of smart materials for vibration and noise control. Analytical and finite element methods adopted for the design of distributed sensors/actuators using piezoelectric materials are discussed. Investigation of optimum position of sensors/actuators and damping are also outlined.

Key words: smart materials; seismic vibration control; finite element.

1. Introduction

Active, semiactive, hybrid and passive control schemes offer great promise for increasing the dynamic resistance of structures while maintaining desirable dynamics properties. The control of structural vibrations due to wind and earthquake loadings can be done by modifying the design to include damping devices or by providing active or passive control systems. Traditionally, the techniques available to reduce structural vibrations are isolation and suppression methods. Two well-known approaches used to isolate or suppress vibrations are provision of flexible supports and addition of active or passive damping systems. Both active and passive systems have their drawbacks. Hence, 'hybrid control system' which combines the use of active and passive systems is preferred to supplement and improve the performance of a passive control system, or, alternatively, to decrease the energy requirements of active control systems.

Several kinds of active/hybrid mass damper systems have been developed for the vibration control of tall or slender buildings in the world, mostly in Japan. The purpose of the vibration control is to improve human comfort in vibration environments of the buildings caused by strong winds and weak earthquakes. However, in a practical sense, it is almost impossible for active/hybrid mass dampers to guarantee safety of tall buildings against strong earthquakes, because of prohibitive cost necessary for mass dampers, and of the large amount of emergency energy power source to drive the control actuators. Furthermore, active/hybrid mass dampers are not suitable for the control of super high-rise buildings because required strokes of actuators for good control efficiency are too large. For the limitation of active/hybrid mass dampers, new alternative systems are required for vibration control of buildings (Caughey 1998).

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Extensive investigations have been carried out to use smart materials as potential sensors and actuators for a wide range of applications in aerospace, automotives, civil structures, machine tools and bio-medical system to actively control vibration and noise, improve performance, and augment stability (Sirohi and Chopra 1998). These materials can change their physical properties, such as stiffness, shape, position, damping, natural frequency and viscosity according to variations in electrical field, magnetic field, or temperature. The actuators made from smart materials can develop strains in response to applied stimulus such as temperature gradient, electrical field, magnetic field, and so on. The resulting strains are then used as control forces to control the shapes and mechanical properties of the structures.

This paper presents a review of structural control techniques and the development of smart materials for structural vibration and noise control. For the potential application of smart materials, analytical and finite element methods have been used for the design of distributed sensors/actuators using piezoelectric materials. A hybrid configuration, active constrained layer, and investigation of optimum position of sensors/actuators and damping are also outlined.

2. Structural vibration control

It is well recognized that active control is an effective way to alleviate the vibration of civil engineering structures under the hostile environmental loadings, such as winds and earthquakes. For the reason of heavy weight of civil engineering structures, very large control force and energy source are required to meet the need of perfect control effect. Furthermore, the external loadings related to civil engineering structures, winds and earthquakes, for instance, are highly uncertain with respect to magnitude and arrival time. And performance requirement of control systems for civil engineering structures are generally not as fine-tuned as those for other engineering areas, for example, aeronautical engineering. These make the control systems for civil engineering structures are a few differences.

The control of structural vibrations due to earthquakes or winds can be done by various means such as modifying stiffness, mass, damping and shape and by providing passive or active counter forces. In general, there are four kinds of structural control systems:

1) Passive control system: This system does not require an external power source, and works on the basis of energy dissipation for enhancing damping, stiffness and strength (Soong and Dargush 1997). This may be achieved either by conversion of kinetic energy to heat, or by transferring of energy among vibration modes. Passive control devices include: a) base isolators (Buckle and Mayes 1990, Kelly 1986): these devices can filter out the high frequencies of the ground motion and lengthen the natural period of vibration to about 2 seconds. Because of their simplicity, reliability and effectiveness, these systems have been implemented on civil structures for many years. However, this would be unsatisfactory if the earthquakes spectrum had a significant amount of energy in the neighbourhood of a 2 second period. The use of much softer materials to increase the natural frequency of the structure would be objectionable due to large amplitude motions. This technology is working good for low-rise and medium-rise structures and bridges and also to protect the fragile and important contents of buildings, but for certain structures, because of their shape, for example slender high-rise buildings, may not be suitable, b) auxiliary dampers (Shen and Soong 1995); For flexible structures such as tall buildings, these devices provide a significant increase in energy dissipation and reduction of motion, and c) tuned mass dampers (Villaverde 1994, Mita and

Feng 1994); These devices are classical dynamic vibration absorbers, consisting of an auxiliary mass on the order of 1% of the mass of the total structure, located at the top of the building and connected through a passive spring and damper. While this is a particularly effective strategy for stationary, narrow band motions such as wind, it is less efficient for broadband excitations such as earthquakes, where transient effects are dominant.

Besides these devices, there are a number of other passive control systems such as metallic yield dampers (dissipate energy through inelastic deformation of metals), viscous fluid dampers (dissipate energy through shear deformation of the viscoelastic layers), viscous fluid dampers (dissipate energy through movement of the position in the highly viscous fluid) and tuned liquid dampers (absorbs structural energy by means of viscous actions of the fluid and wave breaking). Usually these kinds of dampers are located between bracings of the building or between columns and foundation, where large relative displacement can be introduced to reduce structural vibration by increasing structural damping effect (Skinner *et al*. 1975, Makris *et al.* 1993).

There are some advantages related to passive control system: a) it is usually relatively inexpensive, b) it consumes no external energy, c) it is inherently stable, and d) it works even during a major earthquake.

Currently the most common method of isolating a structure is to build the superstructure on elastomeric bearings (base isolators), with these being positioned between the lowest floor and foundation in the case of buildings. The elastomeric bearings are very stiff vertically, being several hundreds times the shear stiffness, so as to sustain the structure's gravity loads with only minimal settlement. Bearings are either circular or rectangular with typical plan dimension between 250 mm and 1000 mm and thickness between 100 mm and 900 mm. The isolating effect and the resulting period increase are caused by the low shear stiffness of the elastomeric bearing which is (ideally) directly proportional to the shear modulus and the cross sectional area and inversely proportional to the total rubber thickness.

2) Active control system (Soong 1988): In this system, external power source is used to control actuators that apply counter-forces to the structure in a prescribed manner. This makes such systems vulnerable to power failure, which is always a possibility during a strong earthquake. On the other hand, very high power source (in the order of tons of kilowatts) is needed to apply to actuators. Active control makes use of a wide variety of actuators including active mass dampers, hybrid mass dampers and tendon controls which may employ hydraulic, pneumatic electromagnetic or motor driven ball-screw actuations. In an active feedback control system, the signals sent to the control actuators are a function of the response of the system to external loads measured with physical sensors. Because of the difference in the nature of external loads in civil and aeronautical structures, control algorithms for these two fields are also different. The various methods of active structural control are a) optimal control, where the design involves minimising or maximising a performance measure, b) stochastic control, where the model as well as some uncertainties are described using random variables or processes for parameter errors or external excitations, c) adaptive control, where the parameters of the controller are changed in real time, d) intelligent control, which can be thought of as adaptive of self-organising systems that learn through interaction with their environment with little a priori knowledge (fuzzy logic and neural networks), e) sliding mode control (variable structural control), which is switching control method and deals with parametric uncertainties in the plant, and f) robust control, which focuses on the issues of performance and stability in the presence of uncertainty, both in the parameters of the system and in exogenous inputs to which it is subjected.

3) Semiactive control system: This system is a subclass of active control system for which the external energy requirements are smaller than typical active control systems. Based on semiactive devices, this system combines the best features of both passive and active control systems and offers the greatest likelihood for near term acceptance of control technology as a viable means of protecting civil structures. A semiactive device is defined as that which cannot inject energy into the controlled system, but has the properties that can be controlled to optimally reduce the responses of the system (Housner *et al.* 1997). Examples of such devices including variable-orifice fluid dampers, variable friction dampers, controllable friction devices, variable stiffness devices, semiactive impact dampers, adjustable tuned liquid dampers and controllable fluid dampers (Shinozuka *et al.* 1992, Ehrgott and Masri 1992, Masri *et al*. 1989).

4) Hybrid control system (Lee-Glauser *et al.* 1997): This system combines the use of active and passive control systems in a structure to take advantage of both the systems. This control system seems to offer opportunities for improving performance over either active of passive approaches taken individually. This system can lead to designs that reduce required actuator forces. On the other hand, the addition of the active control system could improve the velocity performance of the viscoelastic dampers and reduce the possibility of failure of the viscoelastic materials in case of large deformation. Also, hybrid approach is the most promising for the development of solutions for retrofit problems. Primarily, two major hybrid control systems are being used: a) hybrid mass damper system, which is the most common control device employed in full-scale civil engineering applications. This system is a combination of tuned mass damper and active control actuators; b) Hybrid base isolation, which consists of a passive base isolation system combined with a control actuator to supplement the effects of the base isolation system (Suzuki *et al.* 1994, Reinhorn and Riley 1994).

By extensive research studies, significant progress has been made in the area of structural control, and some types of control approaches has been applied successfully to protect civil engineering structures from being damaged by earthquakes. However, for the different control requirements of varieties of civil engineering structures, there are still various research topics that need further study before structural control techniques can be applied more widely in civil engineering.

3. Smart materials for strucutral control

Recently, smart materials, which are also otherwise referred as intelligent materials, high performance materials, innovative materials, adaptive materials and sensory materials, have been used for active control of vibration. Such materials can change their stiffness, shape, position, damping, natural frequency, viscosity and other properties in response to variations in electrical, magnetic or temperature fields. Induced strain actuators are material systems that develop strains in response to applied stimulus such as temperature gradient, electric field, magnetic field and so on. The resulting strains are then used to control the geometrical configurations and mechanical properties of the structure with the aim of applying controlled forces. Among such materials are piezoelectric materials, magnetostrictive materials, shape memory alloys, electrorheological fluids (ER) and magnetorheological fluids (MR).

There are two fundamental electromechanical effects associated with the piezoelectricity theory: the direct piezoelectric effect and the converse piezoelectric effect. The direct piezo-electric effect is a charge-voltage generated by an imposed force/pressure to a piezoelectric. The converse piezoelectric

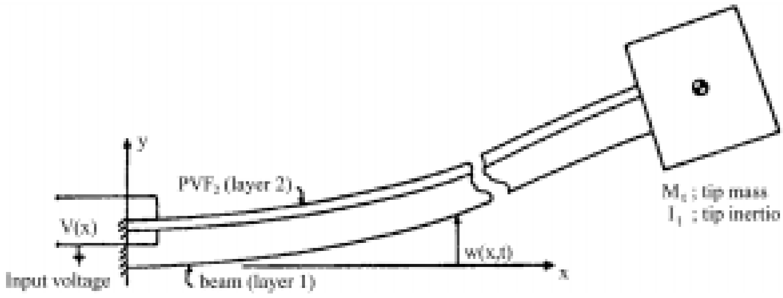

Fig. 1 Active damper configuration

effect is an induced stress/strain due to an external applied voltage/charge.

Numerous investigators have demonstrated the feasibility of the integrated concept. The use of smart materials as the distributed sensors and actuators has been studied for detecting and controlling the shape and vibration of aerospace structures (Hanagud *et al.* 1987, Wang and Rogers 1991, Kim and Jones 1991). An active vibration damper was developed by Bailey and Hubbard (1985) for the control of a cantilever beam using a distributed-parameter actuator and distributed-parameter control theory. Fig. 1 shows the configuration of the active damper. The distributed-parameter actuator was a piezoelectric polymer, ploy (vinylidene fluoride). Lyapunov's method for the distributed-parameter systems was used to design a control algorithm for the damper. Using distributed-parameter control theory and distributed-parameter actuators one can avoid the truncation of the model. This control law can theoretically control all of the modes of vibration and avoid structural problems with uncontrolled modes.

Fanson and Caughey (1987) proposed a positive position feedback (PPF) approach for vibration suppression in large space structures using piezoelectric actuators and sensors. PPF technique was verified by experimental study. Fig. 2 shows the layout of piezoelectric ceramics on beam structure. The experiments have demonstrated that one or two sets of piezoelectric actuators and sensors can control up to six structural modes. Model damping ratios as high as 20% of critical have been achieved on a uniform cantilever beam test structure.

Crawley and de Luis (1987) presented their analytical and experimental development of piezoelectric actuators as elements of intelligent structures, i.e., structures with highly distributed actuators, sensors, and processing networks. Static and dynamic analysis models were derived for segment piezoelectric actuators that were either bonded to an elastic structure or embedded in a laminated

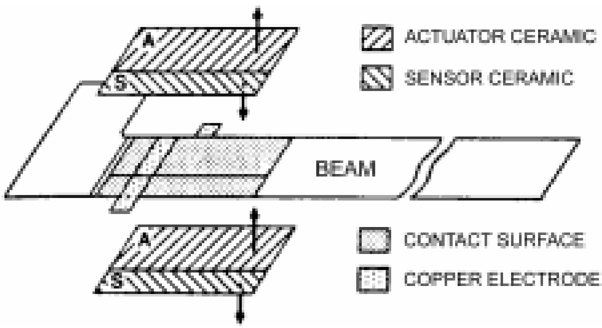

Fig. 2 Layout of piezoelectric ceramics on beam structure

composite. These models lead to the ability to predict, a priori, the response of the structural member to a command voltage applied to the piezoelectric and give guidance as to the optimal location for actuator placement. Analysis results showed that the effectiveness of piezoelectric actuators was independent of the size of the structure. And various piezoelectric materials were evaluated based on their effectiveness in transmitting strain to the substructure. Elastic models for two-dimensional piezoelectric actuators bonded to the surface or embedded into the body of a beam have been developed by Crawley and Lazarus (1991). They developed a model, namely "consistent plate model", of induced strain actuator system, which combined both the actuators and the substructures into one integrated structure. The consistent plate model relations lead to direct formulation of the plate equations of elasticity and strain energy equations. The general procedure was developed for solving the strain energy equations with a Rayleigh-Rize technique. The models and solutions were verified experimentally. Simple sandwich and more representative cantilever plates were built and the induced strains and deformations were measured. The results demonstrate the validity of the models developed, and the effectiveness of using induced strain actuation for shape control of elastic structures, as shown in Fig. 3.

In these studies, analytical solutions usually are restricted to relatively simple geometries and boundary conditions. When the geometry and/or boundary conditions become relatively complicated, difficulties occur with both theoretical and experimental models. Thus, the finite element method becomes attractive in modelling advanced flexible structures with integrated distributed piezoelectric sensors and/or actuators.

Many researchers have used the finite element method for designing piezoelectric transducers since the 1970s (Allik and Hughes 1970, Panda and Natarajan 1979, Naillon *et al.* 1983, Wu and Chang 1989, Ha *et al.* 1992, Ray *et al.* 1994, Tzou and Ye 1996, Liao and Wang 1998). In general, for modelling piezoelectric layers mounted on plate structures, either plate element or 3D solid element can be employed.

Ghosh and Batra (1994) formulated the problem for a fibber-reinforced laminated composite plate with piezoelectric ceramic (PZT) element bonded symmetrically to its top and bottom surfaces. They used a first order shear deformation plate theory, employing the shear correction factor, for modelling plate. It was shown from their studies that by applying suitable voltages to the surface

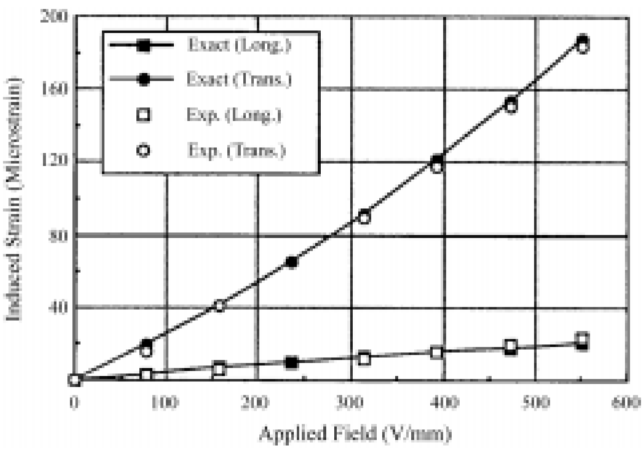

Fig. 3 Induced strain vs field for the graphite/epoxy sandwich

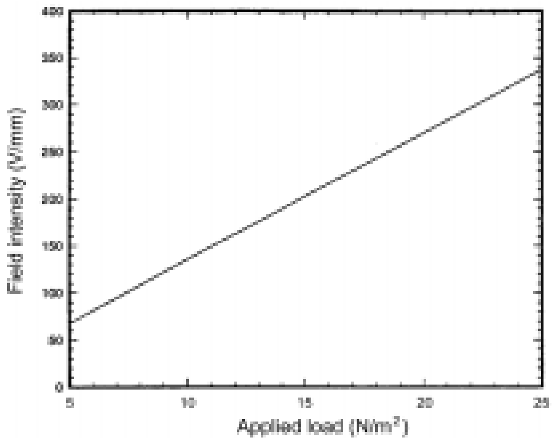

Fig. 4 Electric field intensity required to suppress the deflections of the centreline of a simply supported aluminium plate versus the applied load

mounted PZTs the deformed shape of a simply supported plate and the deflection of the midpoint of the free end of a cantilever plate achieved could be controlled. Fig. 4 shows that the electric field intensity to be applied to the PZTs in order to suppress the deflection of points on the simply supported plate varies linearly with the intensity of the uniformly distributed load.

For many practical situations, it may be possible to bond the piezoelectric elements on to only one side of the plate. In this case, the neutral surface of the plate is shifted and the deformation of the plate is a combination of pure bending and membrane deformation, which violate the assumption of the symmetry. Another point is that in a finite actuator patch, the normal stress distribution across the thickness does not lead to free edge conditions whereas equilibrium conditions require the normal stress at the actuator boundary to be zero. Furthermore, there is likely to be some warping of the cross section due to the actuation strain in the piezoelectric element and this model does not allow any twist moments because pure bending is assumed on the model and requires the plate to be bent to a special surface of curvature. To mitigate the drawbacks of classical plate theory in this case, a hybrid equivalent single layer theory has been developed (Reddy and Robins 1994). This theory is used for the mechanical displacement field whereas the scalar potential function, from which the electric field is derived, is modelled using a layerwise (discrete layer) approach. Also, it is possible to use layerwise theory in the displacement field of plate models (Heyliger and Ramirez 1994, Reddy 1995). However, to reduce the large computational time required by the layerwise theory due to the number of degrees of freedom, it is preferable to use this theory in local regions and a classical plate theory in global region. The two models can be matched at the local/global boundary.

Lee and Saravanos (1997 and 1999) and Saravanos *et al.* (1997) presented generalised discrete layer mechanics for the analysis of smart thermopiezoelectric plate structures and addressed the problem of active thermal distortion management with smart piezoelectric plates. A corresponding finite element formulation was presented using the layer wise laminate theory and a 4-node plate element was developed. Fig. 5 shows one of the 0.83 mm thick plate with 15 piezoceramic patches bonded on each side, 0.25 thick (Saravanos *et al.* 1997). Fig. 6 shows the predicted transverse deflection of the plate induced by an applied uniform electric field of 394 V/mm, of opposite polarity at the upper and lower piezoelectric patches. The measured data in this figure were reported

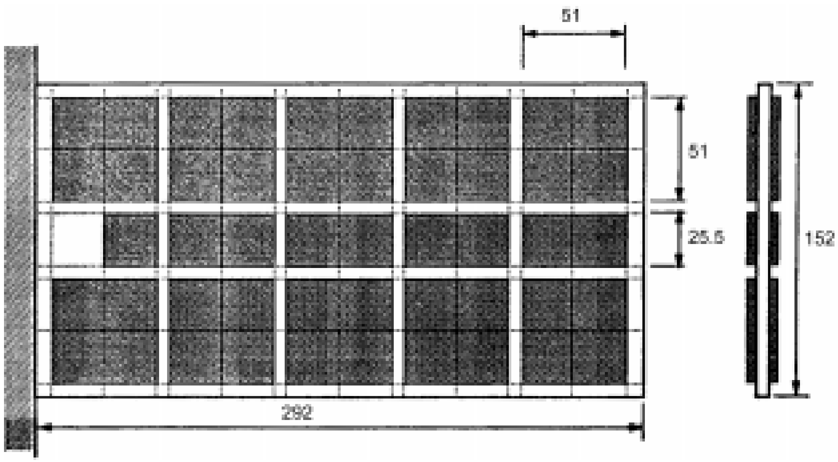

Fig. 5 Schematic configuration of cantilever beam with distributed piezoelectric patches

by Crawly and Lazarus (1989). There are good agreements between predicted and measured results. Saravanos (1997), Lee and Saravanos (1999) proposed a mixed laminated theory for the analysis of smart piezoelectric composite shell structures. The mechanics of this theory involves approximate through-the-thickness field for both displacements and electric potential and solution of the coupled equations of piezoelectricity in curvilinear coordinates. The proposed laminated shell theory is unique because it utilized different types of approximations for displacement and electric potential, that is, first-order shear type theory of assumptions for the displacements and the so-called discrete-layer (or layerwise) approximation for the electrical potential. The combination of mixed through-the-thickness approximations enables the analysis of thin and moderate thick piezoelectric shells of general laminations with reasonable computational efficiency, which maintains sufficient detail in the approximation of the electrical fields. The approach is particularly suitable for finite element formulation. It ensures direct calculation and continuity of the sensory electric potential over the shell structure, thus avoiding the drawbacks of uncoupled approaches that effectively back calculate the sensory voltage from mechanical strains.

Samanta *et al*. (1996) developed a finite element model for active control of composite plates with piezoelectric sensor and actuator layers using a high order shear deformable displacement plate theory, which is applicable for both thick and thin composite plates. An eight-node two-dimensional quadratic quadrilateral isoparametric element was derived for modelling the global coupled electroelastic behaviour of the overall structure using higher-order shear deformable displacement theory. The results show the significant reduction in vibration amplitude because of increased damping through feedback, as illustrated in Fig. 7.

Finite element methods for composite structures with integrated piezoelectric materials are described by Tzou and Tseng (1990 and 1991). Because the electric charge is distributed on both the top and bottom surfaces of a piezoelectric layer, the conventional thin plate/shell elements are difficult to model these surface characteristics. Besides, conventional isoparametric hexahedron elements are too thick for “thin” plate modelling and analysis. Thus, they developed a new “thin” piezoelectric solid element with internal DOFs to improve the accuracy in calculation by using a variational principle, and the dynamic system equation was formulated by using Hamilton’s principle. Guyan’s reduction scheme (Guyan 1965) was employed to condense the internal DOFs and the

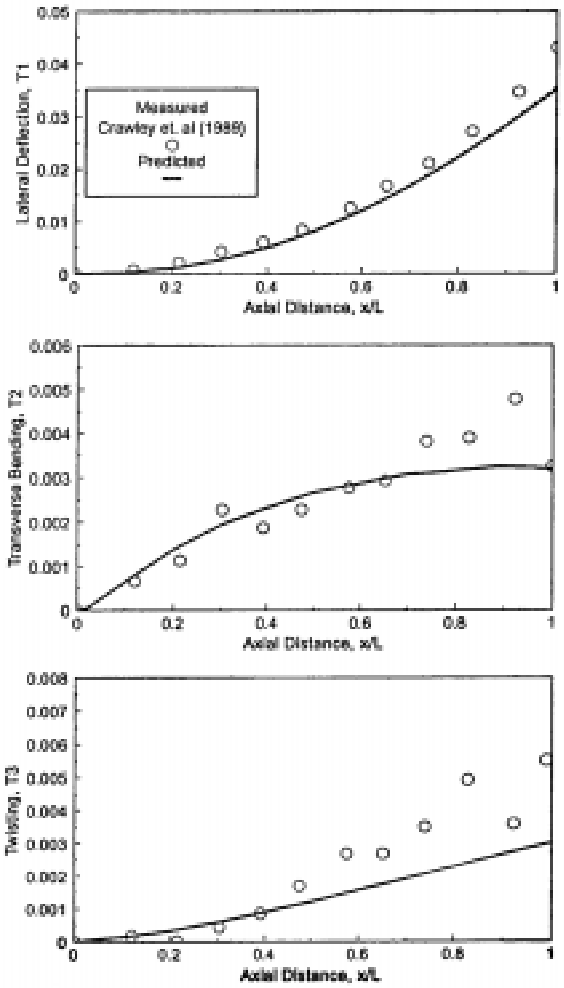

Fig. 6 Predicted induced deformation of the cantilever beam

"slave" DOFs in order to improve computation efficiency. Structural identification and control using the piezoelectric finite element were derived. The performance of a plate model was evaluated, distributed structural identification and control of distributed parameter systems (DPSs) were also studied using theoretical, experimental, and finite element techniques. They concluded that the voltage of any node was determined by the local strain, and the damping ratio of the controlled structure increases when the feedback voltage/gain increases. Fig. 8 shows a steel beam which was sandwiched between two piezoelectric ceramic PZT layers. Fig. 9 shows a free tip response with 2% natural damping. Fig. 10 shows that controlled responses by two different control algorithm. Using distributed piezoelectric sensors and actuators for distributed vibration control and identification of DPSs was demonstrated to be an effective technique. The developed piezoelectric finite element also proved to be suitable for modelling and analysis of piezoelectric/elastic coupled electromechanical DPSs.

Ha *et al.* (1992) derived a finite element formulation for modelling the dynamic and static

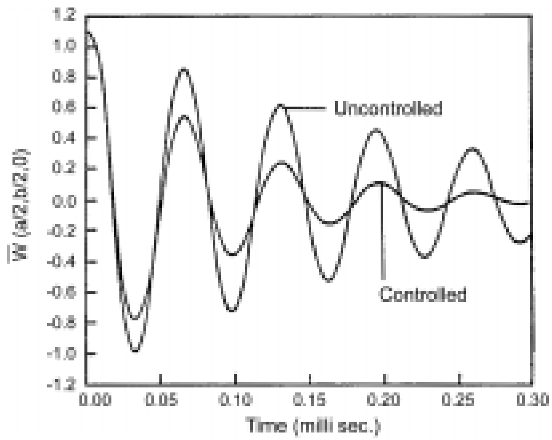

Fig. 7 Maximum axial deflection of a thick composite plate covered with piezoelectric layers

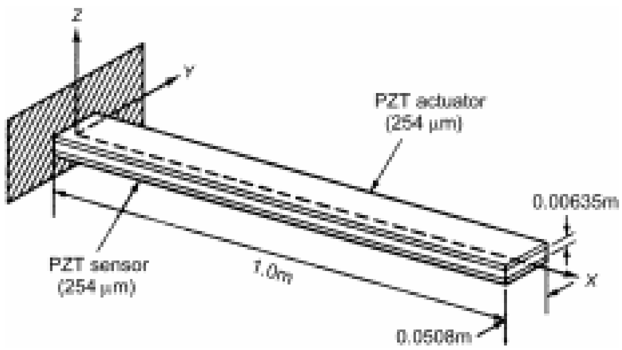

Fig. 8 A steel beam with distributed PZT sensor and actuator

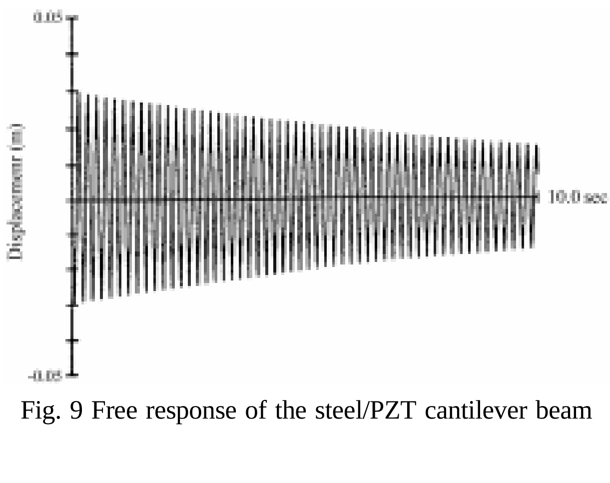

Fig. 9 Free response of the steel/PZT cantilever beam

response of laminated composites containing distributed piezoelectric ceramics from the variational principle with consideration for both the total potential energy and the electrical potential energy of piezoceramics. An eight-node three-dimensional composite brick element was implemented for the

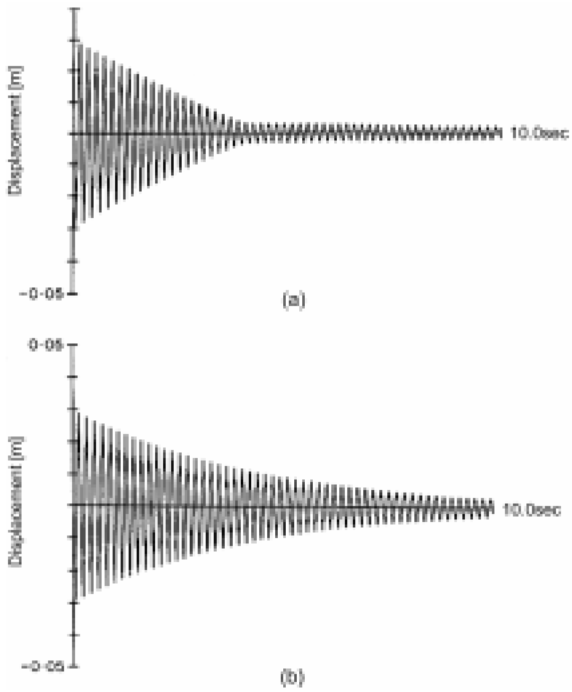

Fig. 10 Active distributed vibration control of the steel/PZT beam: (a) Constant amplitude feedback control; (b) Constant gain feedback control

analysis, and three-dimensional incompatible modes were introduced to take into account the global bending behaviour resulting from the local deformation of the piezoceramics. Experimental and theoretical results show that the proposed finite element method is valid. And the finite element formulation could be further developed as a design tool for designing large-scale structures containing distributed sensors and actuators.

Hwang and Park (1993) have developed a piezoelectric Kirchhoff type plate element with one electrical degree of freedom for a plate element together with active control system. By modelling the plate and sensors/actuators with the new four-node, two dimensional quadrilateral plate elements, the problems associated with solid element are eliminated and the problem size is much reduced, which save much memory and computation time. Fig. 11 shows the laminated composite plate with sensors and actuator layers. The sensors are attached over the whole upper surface and the actuators over the lower surface. The decay envelopes for feedback gains of 0, 40, and 80 are shown in Fig. 12a and 12b for tip displacements, in bending and torsional tests respectively. As the feedback gain increases, the displacements decay faster. In this study, they ignored shear deformations in their formulations; hence their formulation is not applicable to thick plate analysis.

Varadan *et al.* (1996), Lim *et al.* (1996) and Kim *et al.* (1997) used three dimensional elements to model the piezoelectric devices and flat shell elements to model the plate structure and to connect the three dimensional solid elements to the flat shell elements. For modelling the dynamical response of smart structures with embedded piezoelectric ceramic devices subjected to transient loading, Lim *et al.* (1996) developed a finite element formulation based on a variational principle using the concept of virtual work. Kim *et al.* (1997) employed full three-dimensional elements in

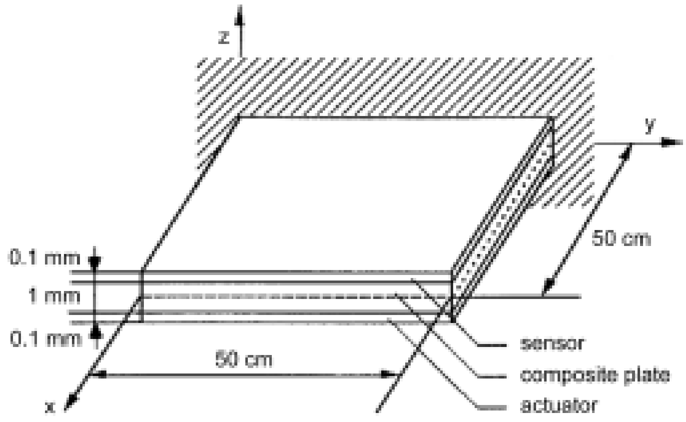

Fig. 11 Laminated plate with piezoelectric sensor/actuator

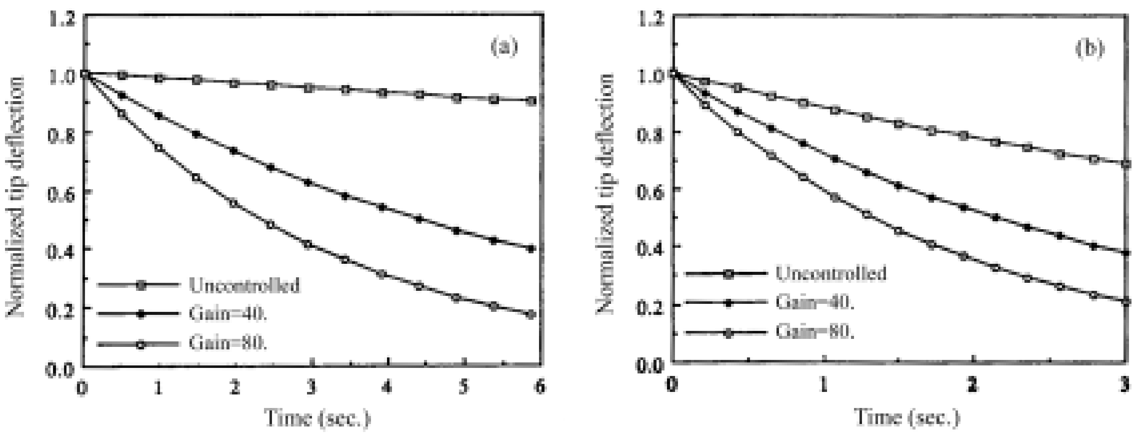

Fig. 12 Decay envelopes for bending and torsional test θ=90 deg: (a) First bending mode and (b) First torsional mode

the piezoelectric regions and flat-shell elements for the structure to model the plate structures on which piezoelectric active devices were mounted. To connect three-dimensional elements and plate or shell elements, transition elements were used. From the study, it was found that the use of transition and flat-shell elements is more accurate and converges faster than the use of three-dimensional elements only. And the model combined with quadratic flat shell and transition elements has advantages in terms of accuracy and computation speed relative to a model that uses a combination of linear elements. While Kim *et al*. (1997) and Lim *et al*. (1996) used piezoelectric for active control, Varadan *et al*. (1996) adopted hybrid active/passive arrangement as an active constrained layer damper (ACLD) including a control algorithm (constant gain feedback controller) to close the loop between the sensor and the actuator to control the structure. Viscoelastic material (VEM) layer acts as a passive damper. For better transmitting of the control force from the piezoelectric actuator to the structure, they used a bench shaped model surrounded VEM.

The active constrained layer (ACL) system generally consists of a piece of viscoelastic damping material (VEM) sandwiched between an active piezoelectric cover sheet and the host structure. Such

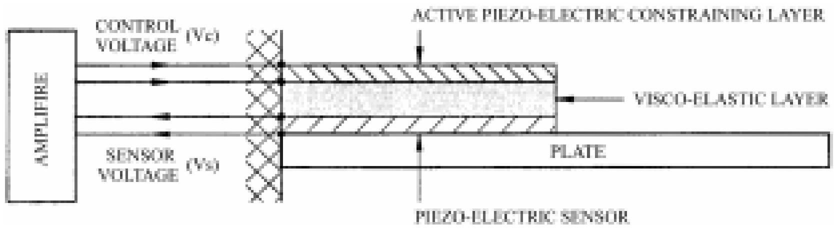

Fig. 13 Schematic drawing of the active constrained layer damping

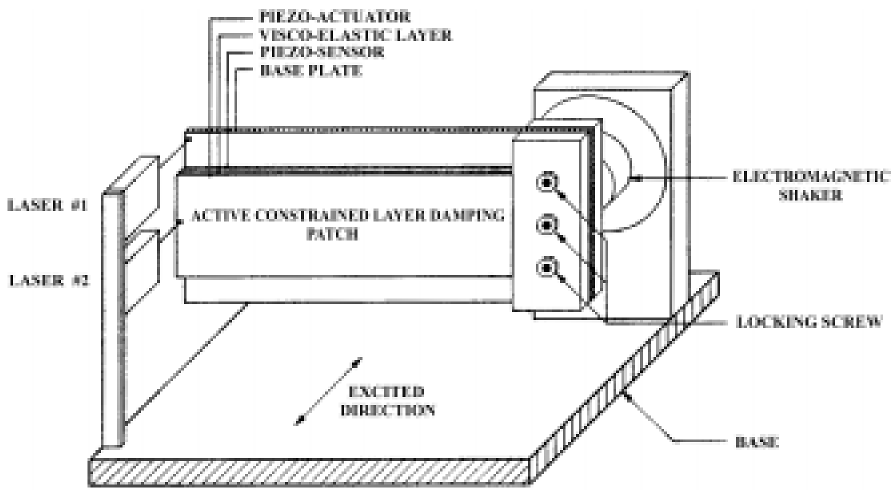

Fig. 14 Experimental set-up

a configuration (or similar types) has been studied by various researchers (Agnes and Napolitano 1993, Shen 1994, Van Nostrand *et al*. 1994, Huang *et al*. 1996, Lesieutre and Lee 1996).

A new class of active-controlled constrained layer damper (ACLD) has been proposed by Baz and Ro (1995a and 1995b) to vibration control of beams and plates using beam and plate elements, respectively. The proposed ACLD consists of a conventional passive constrained layer damping which is augmented with efficient active control means to control the strain of the constrained layer, in response to the structural vibrations as shown in Fig. 13. The three-layer composite ACLD when bonded to the rotating beam acts as a "smart" constraining layer damping treatment with built-in sensing and actuation capacities. The ACLD combines the attractive attributes of both the passive and active controls to achieve optimal vibration damping. In particular, it provides an effective means for augmenting the simplicity and reliability of passive damping with low weight and high efficiency of active controls to attain high damping characteristics over broad frequency bands. For the bending vibration control of plates using patches of ACLD treatments, a finite element model was developed using two-dimension elements bounded by four nodal points. The predictions of the finite element model have been validated experimentally. Fig. 14 shows the schematic drawing of the experimental set-up used in testing the effectiveness of the ACLD for the vibration control of plates. As one of the experimental results, the amplitude of vibration of the plate at the mid-width point of its free end is shown in Fig. 15 when the plate is subjected to sinusoidal base excitation. It is evident that activation of the ACLD treatment as resulted in effective attenuation of the plate

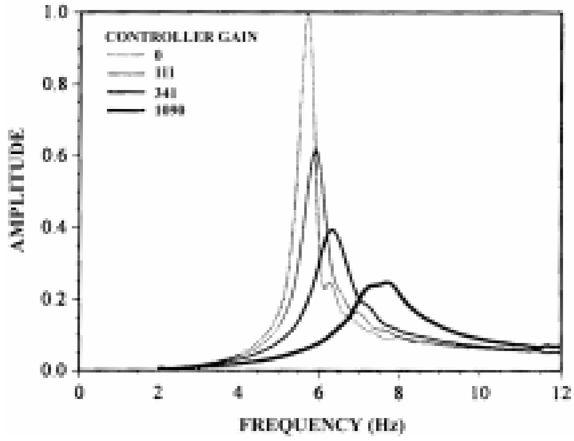

Fig. 15 Comparison between the amplitude of vibration of the uncontrolled and controlled plate at different control gains

vibrating, and increasing the control gain has resulted in improving the vibration attenuation characteristics of the ACLD treatment.

Liao and Wang (1997) investigated the effect of the active constrained layer configuration on the system vibration performance and the control effort requirement with a linear quadratic regular (LQR) control algorithm. A mixed Golla-Hughes-McTavish method was employed to discretize and analyse the model in time domain. Fig. 16 shows the schematic of the ACL treatment. Analysis illustrated that the active piezoelectric action with proper feedback control will enhance the damping ability of the passive constrained layer, as shown in Fig. 17.

It has been shown that ACL treatments can enhance the system damping when compared to a traditional passive constrained layer (PCL) system. However, it is also recognized that the viscoelastic layer will reduce the control authorities from the active source to the host structure. The significance

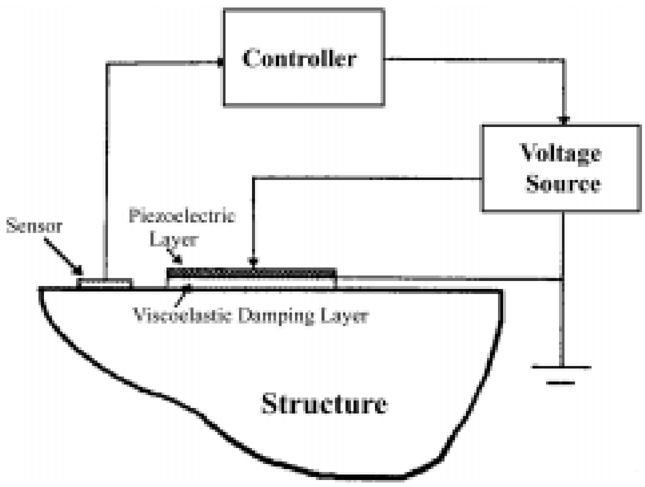

Fig. 16 Structure with ACL treatments

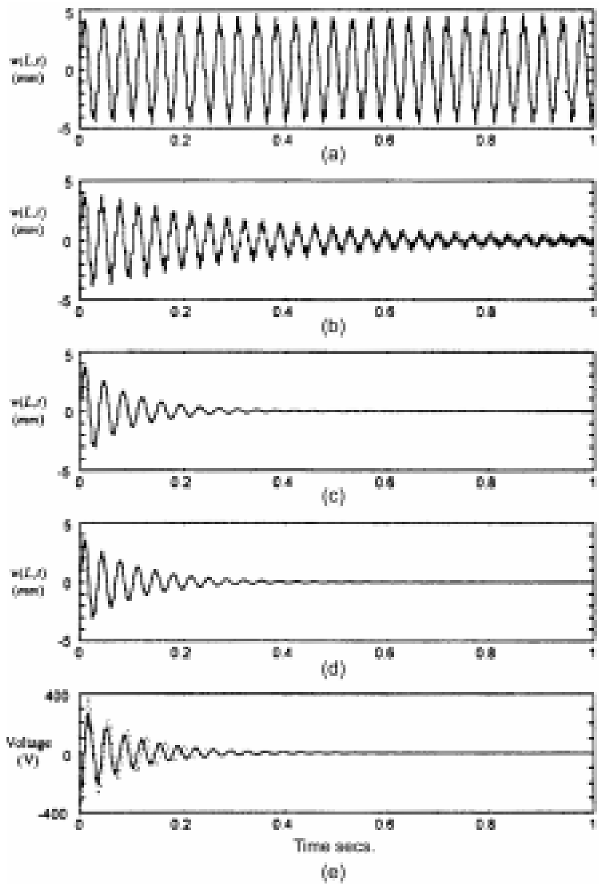

Fig. 17 The time responses and required voltage (a) beam with no control and no VEM (b) PCL (c) purely active (d) ACL (e) required control effort (solid line: ACL, dashed line: purely active)

of this effect depends very much on the viscoelastic layer configuration and material properties. Therefore, under some conditions, the ACL configuration could require more control effort while achieving less vibration reduction when compared to a purely active system (zero VEM thickness). To reduce the negative effects of VEM on active action transmissibility and enhance the actuator authority, Liao and Wang (1998) created a new enhanced ACL (EACL) configuration by adding edge elements to connect the boundaries of the piezoelectric coversheet and the host structure, as shown in Fig. 18. Such elements will increase the active action transmissibility of the ACL, and enhance the system performance and robustness.

Because proper selection of number and location of the piezoelectric sensors/actuators is critical to control flexible structural vibration efficiently, determining the optimum placement of piezoelectric sensors/actuators for vibration control is one of the key issues to address. Several studies regarding placement of the actuators for vibration control were presented (Crawley and de Luis 1987, Kirby *et al*. 1994, Main *et al*. 1994, Wang *et al.* 1994). A common feature of all these studies is ignorance of the inherent damping of the structure when using piezoelectric sensors/actuators in the formulation. When a piezoelectric sensor is used as a strain-rate sensor, the piezoelectric actuator increases the damping of the entire system. Therefore, the damping must be taken into account in

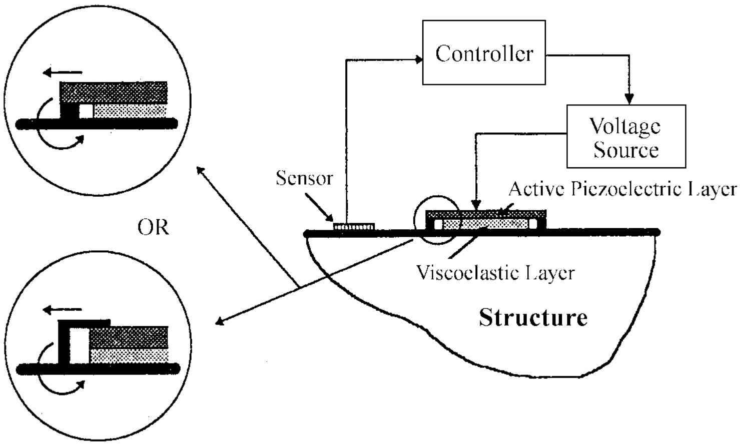

Fig. 18 Structure with new EACL treatments

the formulation of optimal placement of the sensors/actuator. Most of the research using piezoceramics sensors/actuators have taken into account only the stiffness of the adhesive layer and the piezoceramics at the same time (Ha *et al*. 1992). Ignoring damping by the adhesive layer and the piezoceramics leads to discrepancy between measurement and prediction. Kang *et al.* (1996) investigated numerically and experimentally the optimal placement of a collocated piezoelectric sensors/actuator for vibration control of laminated beams. The damping and stiffness of the adhesive layer and the piezoceramics were taken into account in the process of finite element modelling. The structural damping index (SDI), which has taken into account the modal damping and the contribution of each mode, was selected as the performance index. The numerical and experimental results show that the SDI depends on the stiffness of the host structure, the location of the sensor/actuator, and the size of the sensor/actuator. The SDI was proved to be a good criterion for determining the optimum location of the sensor/actuator because it is based on the inherent damping of the structure.

In order to achieve significant weight reduction and/or to control the response of structures, Franco Correia *et al.* (1999) developed a gradient based optimization procedure where the object is to minimize the weight/mass of the structure or maximize the piezoelectric actuator performance subject to behaviour constraints. The design variables are ply angles in orthotropic layers, thickness of the substrate and piezoelectric layers and the electric potentials applied to the actuators. The gradients of the objective function and constraint equations with respect to the design variables are evaluated analytically or semi-analytically. Analytical results show that important improvements in the structural performance and/or weight savings could be achieved.

For the optimum control design of structures, Veley and Rao (1996) compared three different damping treatments (passive constrained layer damping, active constrained layer damping and active damping) to control the vibration of beams. The problem was modelled using a two dimensional finite element based on the QUAD4 element which is modified to include viscoelastic and piezoelectric layers in the composite lay-up. By the illustrations of both beam and plate structures, they concluded that the best damping treatment to be used on a structure depended on the relative importance of mass and damping ratio as well as the structure itself and possibly the algorithm used to generate the control system gain matrices. These results show that all three damping techniques can be appropriate and that the hybrid method should be considered along with the passive and active damping techniques when designing a damped structure.

The use of smart materials in aeronautical structures is well known. But the application of this concept in civil structures is limited, and particularly this concept has not been adopted so far in the design of structural foundations. However, efforts have been put into the potential application of smart materials for the active control of civil engineering structures. Kamada *et al.* (1997) proposed a stack-type piezoelectric actuator for active vibration of frame structures of shear and bending type. A kind of magnetostrictive actuator also was developed for control of frame structures (Fujita *et al.* 1998). In both these control schemes, the piezoelectric/magnetostrictive actuators were adopted at the bottom parts of each columns of the base floor. By controlling the bending moment and axial force in the columns, the response of the entire structure can be reduced effectively.

4. Concluding remarks

In view of the operating characteristics, induced strain materials are mainly used in aeronautical engineering structures as distributed sensors and actuators for active control of noise and vibration. Taking into account the characteristics of civil engineering structures, an innovate configuration is need to be proposed for the application of smart materials to control structural vibrations in an effective way.

Considering the limitation of magnitude and stroke of generated control force of actuators, piezoelectric materials are seemly suitable to be used as a cooperative part of base-isolated structures for further response reduction of upper-structures of base-isolated structures by increasing the damping effect of the entire structural systems undergoing earthquakes in small or medium magnitudes.

Three-dimensional finite element method can be employed in the analysis and design of such kind of hybrid system. For piezoelectric materials, eight-node brick element with 4 degrees of freedom at each node (three mechanical degrees of freedom, one electrical degree of freedom) will be used in the design. The internal degrees of freedom can be used as "slave" DOF to improve the calculation accuracy. The electrical DOF for the piezoelectric materials can be eliminated from the global system matrix, and then recovered after each time-step analysis.

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