REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

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1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE July 2000	3. REPORT TYPE AND DATES COVERED Final Progress Report. 4/15/96-4/14/2000

4. TITLE AND SUBTITLE
Active-Passive Hybrid Adaptive Structures for ~~Dual-Functional Multi-Directional~~ Vibration Controls – An Integrated Approach

5. FUNDING NUMBERS
DAAH04-96-1-0052

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8. PERFORMING ORGANIZATION REPORT NUMBER

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U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 34765.10-EG

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by the documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The objective of this research is to develop, validate and evaluate novel *active-passive hybrid* adaptive structures for real-time vibration suppressions. These structures could have the advantages of both the passive (stable, low power requirement, fail-safe) and active (high performance, feedback actions) systems. Two types of smart structure configurations have been investigated and advanced: structures with *enhanced* active constrained layer (EACL) treatment, and structures with *active-passive* piezoelectric networks (APPN). Accomplishments include: (a) Robust control laws have been synthesized for APPN to compensate for uncertainties. (b) Nonlinear analysis and control methods have been developed to utilize the high authority actions of APPN. (c) The integrated EACL-APPN configuration has been analyzed, it is shown that both the narrowband and broadband controls can be achieved with such configurations. (d) A detailed non-dimensional analysis on EACL performance has been developed to provide design guidelines. (e) A new hybrid constrained layer (HCL) configuration has been developed by mixing both active and passive materials to form hybrid coversheets -- such a design can outperform systems with pure active PZT coversheets.

14. SUBJECT TERMS
active-passive hybrid vibration controls, adaptive structures, piezoelectric materials, enhanced active constrained layers, piezoelectric shunt, hybrid constrained layer damping

15. NUMBER OF PAGES
16 (including this page)

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION ON THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)

Enclosure 1

DTIC QUALITY INSPECTED 4

20001122 161

ACTIVE-PASSIVE HYBRID ADAPTIVE STRUCTURES FOR VIBRATION CONTROLS -- AN INTEGRATED APPROACH

K. W. Wang
Proposal No. 34765-EG
Grant No. DAAH04-96-1-0052

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STATEMENT OF THE PROBLEM STUDIED

The objective of this research is to develop and evaluate novel *active-passive hybrid* smart structures for real-time vibration controls. This investigation is to advance the current active-passive hybrid technology (the active-passive piezoelectric network (APPN) and the active constrained layer (ACL) approaches) and to eventually achieve an optimally control-configured, high performance vibration rejection system with low power requirements and high reliability and robustness. Being an optimized hybrid structure, it will have the benefits of both the passive (stability, fail-safe, lower power consumption) and active (high performance, feedback and feedforward actions) systems.

SUMMARY OF THE MOST IMPORTANT RESULTS

The major achievements are described in the following paragraphs.

Robust control law for active-passive hybrid piezoelectric network (APPN) with uncertainties The schematics of four possible APPN networks are illustrated in Figure 1. From previous studies, it is recognized that all these networks will provide similar active authority and passive damping enhancements. Therefore, for the purpose of illustration, we have selected configuration (a) (Figure 1) in our investigation. This network consists of a piezoelectric actuator integrated with an external voltage source in series with a resonant shunt. A comprehensive analysis has been performed to provide more insights and understandings to the system. It is shown that comparing to a purely active arrangement, the shunt circuit not only can provide passive damping, they can also enhance the active action authority around the tuned frequency. Therefore, the integrated APPN design is more effective than a system with separated active and passive elements.

While the studies on APPN have indeed illustrated promising results, the previous investigations [Agnes, 1994; Kahn and Wang, 1994, 1995] have not addressed the issue of system robustness. To ensure that the concept can still perform well for complex structures under uncertainties, the technology needs to be advanced. The major challenge here is to determine the active and passive parameters simultaneously with the consideration of system uncertainties. The goal of this task is to address such issues and develop a coupled robust control (μ synthesis [Packard, 1988]) / optimization approach for APPN-based structures. The active and passive parameters are determined simultaneously with consideration of the system uncertainties. The cost function is defined to be the maximum achievable γ, reflecting the ability for disturbance rejection. Analysis shows that the passive parameters R and L (resistance and inductance) are the same for a purely passive system with different uncertainties. In an active-passive hybrid case, the optimal R and L can be quite different from those of the purely passive system. However, the optimal R and L will move toward those of the purely passive configuration to increase the system stability under larger uncertainties. It is also illustrated that the APPN approach can tolerate much more uncertainties than a purely active system (Figure 2). In this given case, the maximum structural uncertainty level the purely active system can tolerate is 0.17%, while still achieving the given performance requirement. For the APPN system, a 17.2% uncertainty is allowed - a 100 times improvement.

APPN enhancement and high-authority nonlinear action utilization It is recognized that the APPN enhanced active authority is due to the voltage amplification characteristics of the circuit around the tuned frequency. During some operating conditions, this high voltage (electric field) across the piezoelectric material will cause significant nonlinear effects, such as high order nonlinearities and hysteresis. To further advance the technology and utilize the high authority APPN actions, a controller based on sliding mode theory [Utikin, 1993] is developed for the APPN configuration, which can take care of the piezoelectric nonlinearity that deviates from the usual linear assumption at high electrical fields.

In this research, the nonlinear behavior of the piezoelectric material is investigated experimentally and analytically. Through lab tests, one can clearly see the complexity of the material property, especially at high field levels. This fact suggests that one way to utilize the high field (high authority) regime is to consider the various nonlinear phenomena as uncertainties and develop robust controls to compensate for such uncertainties. By treating the nonlinearity (or part of it) as bounded uncertainties, a constitutive relation is proposed. For example, if the linear constitutive relation is used as the basic model, the actual actuation strain at a certain field will be the linear deterministic value plus some bounded uncertainty. The modified constitutive equations can be expressed in the following form,

$$\tau = E_p \varepsilon - h_{31} D$$
$$E = -h_{31}(\varepsilon - \varepsilon_0) + \beta_{33} D$$

where τ, ε, D and E represent the stress, strain, electrical displacement (charge/area) and electrical field (voltage/length along the transverse direction) within the piezoelectric patch, respectively, and E_p, h_{31} and β_{33} are the Young's modulus, piezoelectric constant and dielectric constant of the material. Here, ε_0 represents the uncertainty in the strain-field relation, which is bounded in the following manner,

$$|\varepsilon_0| < \varepsilon^*$$

The bounds can be selected according to the maximum field level that the actuator will undergo and identified from experimental data.

Given the new constitutive equation and uncertainty bounds, a robust sliding mode control algorithm is then developed to compensate for the piezoelectric nonlinearities. The effectiveness of the proposed approach is demonstrated through experimental studies and numerical analyses on vibration control of an APPN treated beam structure. It is shown that the performance of a linear optimal controller will be serious degraded by the nonlinearity. On the other hand, when compared to the linear control approach, the proposed sliding mode scheme can achieve more vibration reduction with the same control effort (Figure 3). That is, with this nonlinear robust controller, one can fully utilize the high authority characteristics of the APPN system.

Integrated APPN-EACL configuration To enhance the control bandwidth of the APPN actuator and achieve the dual-functional (narrowband and broadband controls) effect, the Penn State researchers recently explored the feasibility of ***combining*** the APPN with the *enhanced* active constrained layer (EACL) configuration (see Figure 4).

It has been shown that the classical active constrained layer (ACL) treatment can improve the system damping when compared to a traditional passive constrained damping layer approach.

However, when compared to a purely active case (no viscoelastic layers), the ACL viscoelastic materials (VEM) layer will reduce the direct control authorities from the active source to the host structure. It is also shown that by adding the shunt circuit to a classical ACL, one cannot obtain much additional damping because of low *transmissibility* between the piezoelectric coversheet and the host structure. To address this issue, the Penn State researchers created an *enhanced* active constrained layer (EACL) configuration to improve the transmissibility and active action authority of the classical ACL treatment [Liao and Wang, 1996]. Introducing a pair of *edge elements*, the active action from the piezoelectric cover sheet can be transmitted to the host structure more directly in the EACL. On the other hand, such a configuration still has the damping ability of the passive VEM. Combining the overall active and passive actions, the EACL can achieve better performance (smaller vibration amplitude) with less control effort (lower voltage or power) compared to the classical ACL systems. Since transmissibility is increased, an APPN-EACL combination can achieve significantly more damping around the tuned frequency than the APPN-ACL combination (Figure 5). On the other hand, the EACL broadband damping ability can greatly enhance the control bandwidth of the APPN treatment. Analysis results have illustrated that the integrated APPN-EACL approach can outperform the individual EACL or APPN configurations through out a wide frequency range.

<u>A detailed non-dimensional analysis on EACL performance</u> The purpose of this task is to advance the work on the enhanced active constrained layer (EACL) damping treatments. We want to provide more comprehensive results that can be better generalized for the design of such system. For given strain distributions in the host structure and utilizing a self-sensing control law, closed form solutions to the longitudinal motion of the active cover sheet of the EACL are derived. Active, passive, and hybrid (total) loss factors are examined to discuss the damping properties of the treatments. The active loss factor (η_a) and passive loss factor (η_p) of the treatment are defined as $\eta_a = \frac{W_a}{2\pi W_s}$ and $\eta_p = \frac{W_p}{2\pi W_s}$. Here, W_s is the maximum strain energy stored in the PZT, VEM (viscoelastic material), the edge elements, and the host structure. W_a and W_p are the energies dissipated per cycle by active control and by passive damping, respectively. The total system loss factor (η_s) is a sum of η_a and η_p.

With a non-dimensionalized formulation, this research identifies and examines the major factors that affect the EACL damping characteristics. These factors are: the bending stiffness ratio between the host structure and the constraining layer, the offset distance of the constraining layer from the host structure, the strain distribution in the host structure, the active control gain, the characteristic length of the EACL, the viscoelastic material (VEM) loss factor, and the stiffness distribution of the edge elements. The effects of these factors on open and closed-loop damping characteristics of the treatment are discussed. Results confirm that the edge elements can significantly improve the active action transmissibility of the active constrained layer damping (ACL) treatment. It is found that the effect of the edge element stiffness distribution on the EACL damping treatment is closely related to the strain distribution of the host structures (see Figure 6). When the strain field being treated is not anti-symmetrical, EACL with sufficiently stiff and symmetric edge elements could greatly improve the damping property of the system by increasing the active control transmissibility. When the strain field is anti-symmetrical, such configurations will have no active authority but could provide high passive damping. Unsymmetrical EACL, on the other hand, will not have the problem of active action uncontrollability for anti-symmetrical field. However, the overall performance of unsymmetrical EACL is not as high as that of the symmetrical EACL. If maximizing hybrid damping action is the most important factor in one's application, it seems that symmetrical and stiff edge elements will be the best choice (Figure 6). Nevertheless, unsymmetrical EACL could be desirable in many applications where a better mix of active and passive damping is required. The insights obtained from this investigation could be used to provide guidelines for EACL designers.

Hybrid constrained layer (HCL) configuration development To further advance the state of the art in active constrained layer (ACL) and enhanced active constrained layer (EACL) research, the Penn State researchers recently explored the feasibility of the hybrid constraining layer (HCL) configuration (see Figure 7). That is, combining both the active and passive materials into the constraining layer (coversheet).

In both the ACL and EACL treatments, the constraining layer (coversheet) is completely made of piezoelectric materials (e.g., PZT ceramics or PVDF polymer) because of their active action capabilities. PZT materials are in general much better than PVDF polymers for this purpose. Nevertheless, having a density similar to steel (relatively heavy) and a modulus close to aluminum (moderate stiffness), PZTs are not ideal as constraining materials. Because of the limited selections of active materials, it is difficult to find one with both features - good material property for constraining purpose and strong active action.

Recently, the Principal Investigator and his students developed a hybrid constrained layer (HCL) configuration (Figure 7). In this design, the viscoelastic material is constrained by an active-passive hybrid constraining layer. The active part is made of piezoceramics and the passive part can be designed differently for different purposes. It is shown that by selecting a passive material stiffer than PZT, the HCL could obtain higher open-loop damping (fail-safe ability with no active action) than the treatment with a pure PZT cover sheet (ACL or EACL). Furthermore, when the active constraining length and passive constraining length are optimally designed, the overall closed-loop damping of the HCL is also higher than that of the configuration with a pure PZT coversheet (Figure 7). Experimental efforts are also performed to verify the new hybrid damping concept. The experiments are conducted on cantilever beams. One aluminum beam is treated by the hybrid constrained layer (coversheet with 60% PZT and 40% aluminum oxide). The second beam, with the same material and dimensions as the first one, is treated by an active constrained layer with a pure PZT coversheet. The treatments are of the same overall size and at the same location of the beams. The self-sensing control law is implemented using the bridge circuit proposed by Dosch et al. [1992]. A four-pole Butterworth dual electronic filter is used as the low pass filter with a cutoff frequency of 80 Hz (the first resonant frequency of the system is about 30 Hz). Figure 8 shows the impulse responses of the two systems under closed-loop control. In this case, the same amount of impulse is generated to excite the beams. The damping ratios (derived using the logarithmic decrement method [Rao, 1995]) for the treatment with the hybrid coversheet and that with the PZT coversheet are 8.3% and 5.6%, respectively. From these results, the benefits of the HCL treatment are clearly demonstrated.

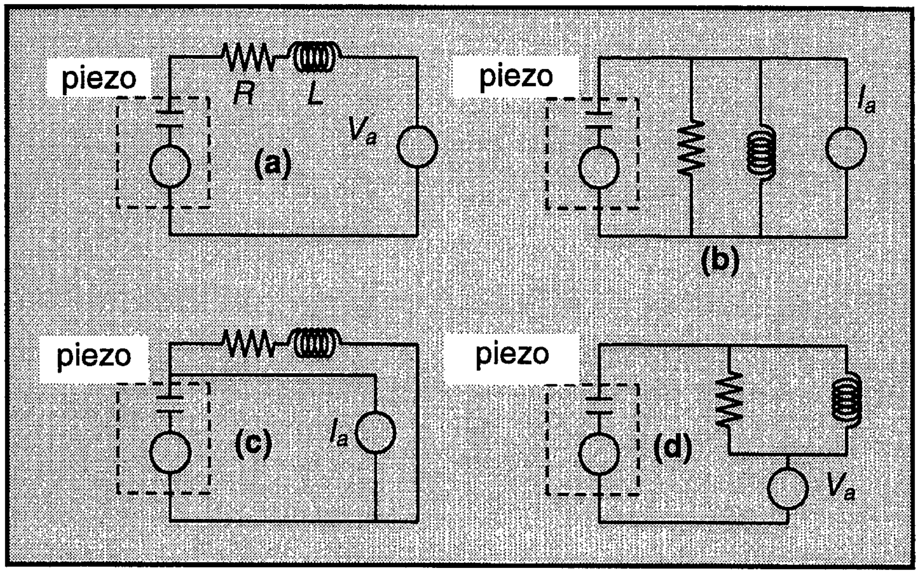

Figure 1. The various Active-Passive Hybrid Piezoelectric Network (APPN) configurations. V_a = voltage source. I_a = current source. R = resistance. L = inductance.

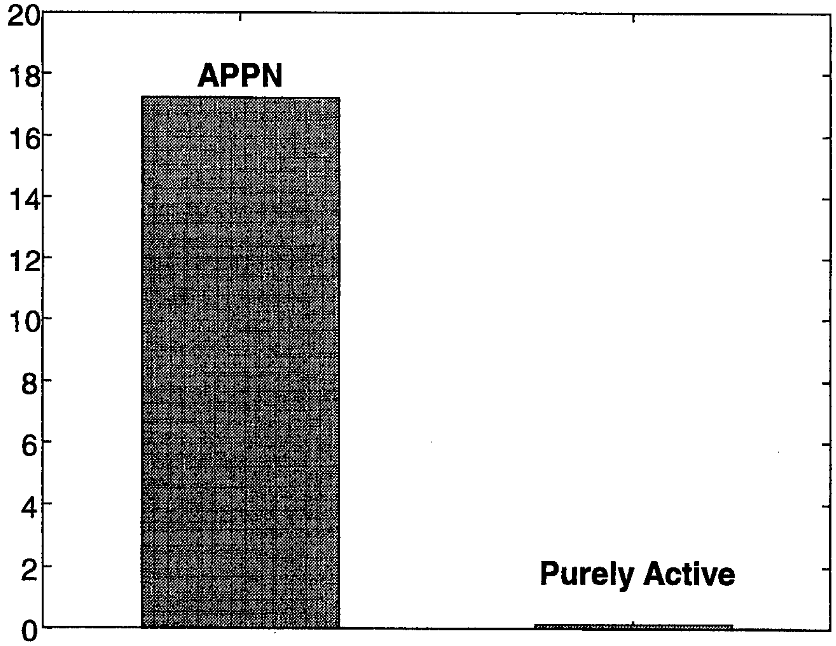

Figure 2. The maximum structural uncertainty level that a system can tolerate while still achieving the given performance requirement.

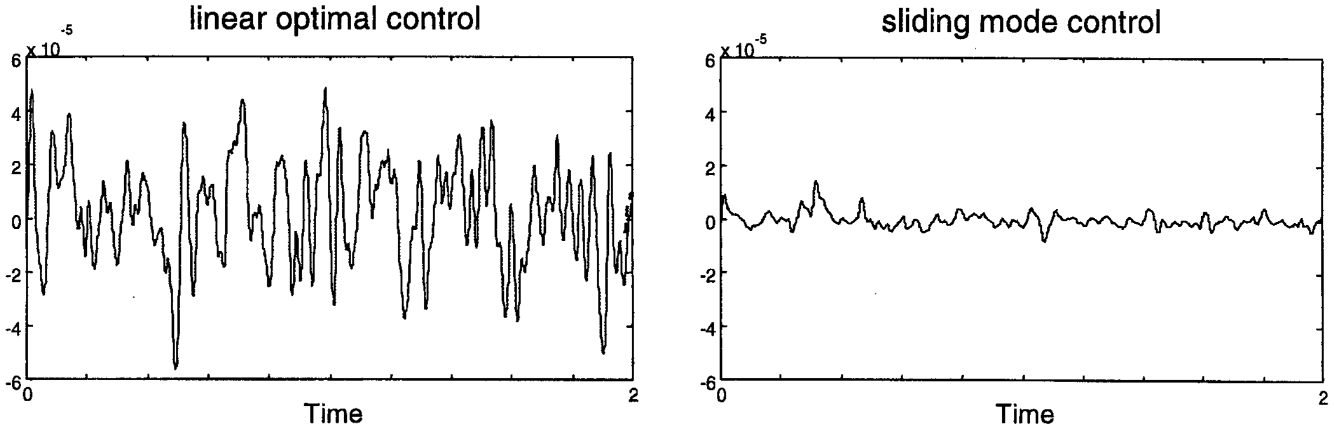

Figure 3. Comparing vibration control results (non-dimensionalized structural vibration amplitudes) between linear (optimal control) and nonlinear (sliding mode control) controllers for APPN under high electric field operations. For a fair comparison, the two controllers are so designed that they have the same RMS value of control power input.

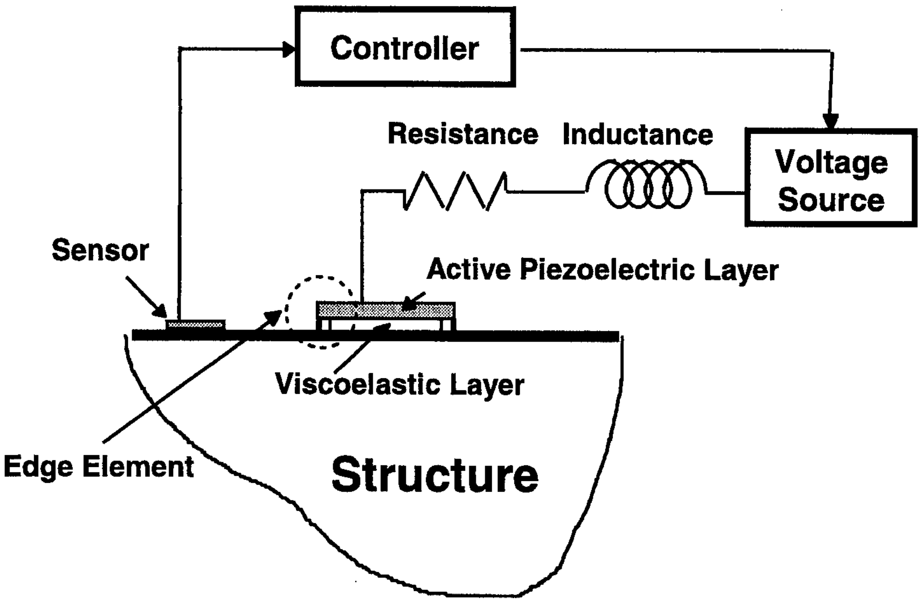

Figure 4. Combined APPN-EACL configuration for dual-functional applications

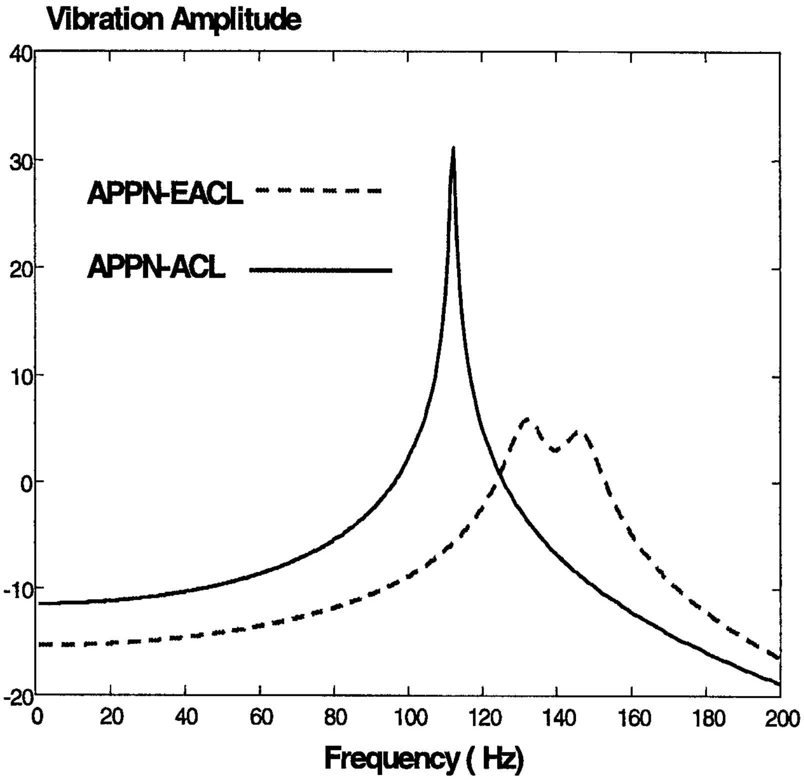

Figure 5. Vibration amplitude in frequency domain of the APPN-EACL and APPN-ACL systems. The APPN-EACL system can outperform the APPN-ACL system (more vibration reduction) due to high *transmissibility*

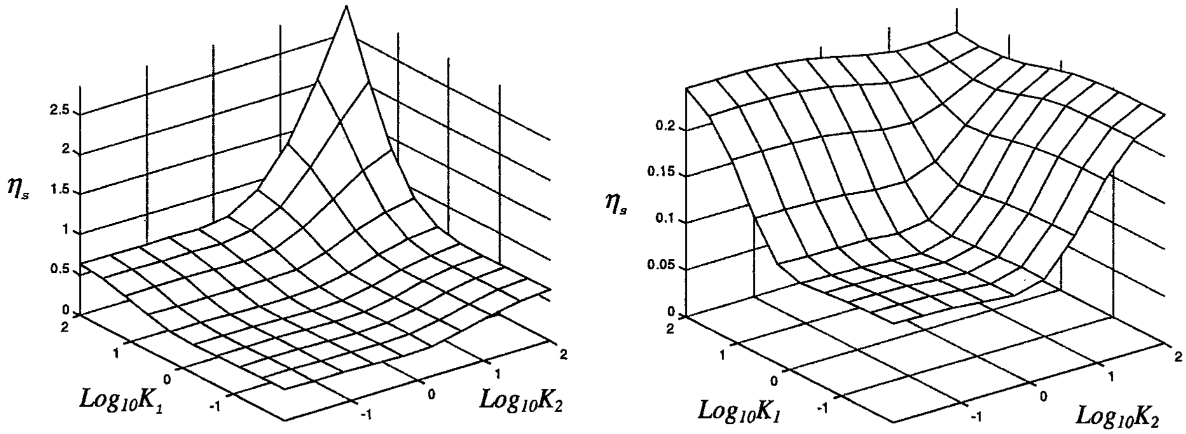

Figure 6. Total system damping loss factorη_s versus edge element stiffness distribution, K_1 (left edge element) and K_2 (right edge element) for symmetric (left plot) and anti-symmetric (right plot) strain fields in the host structure

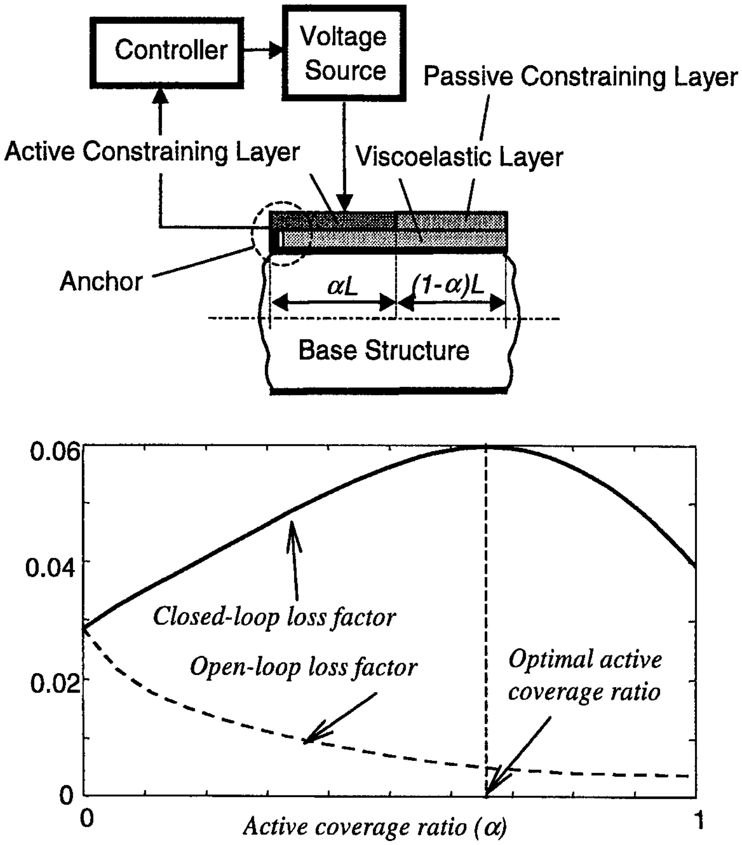

Figure 7. Upper figure: Hybrid Constrained Layer (HCL) damping treatment. Lower figure: Loss factor plot showing with proper selection of the constraining layer materials and active-to-passive length ratio, the HCL treatment could provide better (larger loss factor) open-loop damping (no active action, fail-safe ability) and closed-loop damping (total damping under control) than a system with purely active coversheet. Here, α=1 means purely active coversheet, and α=0 means purely passive coversheet.

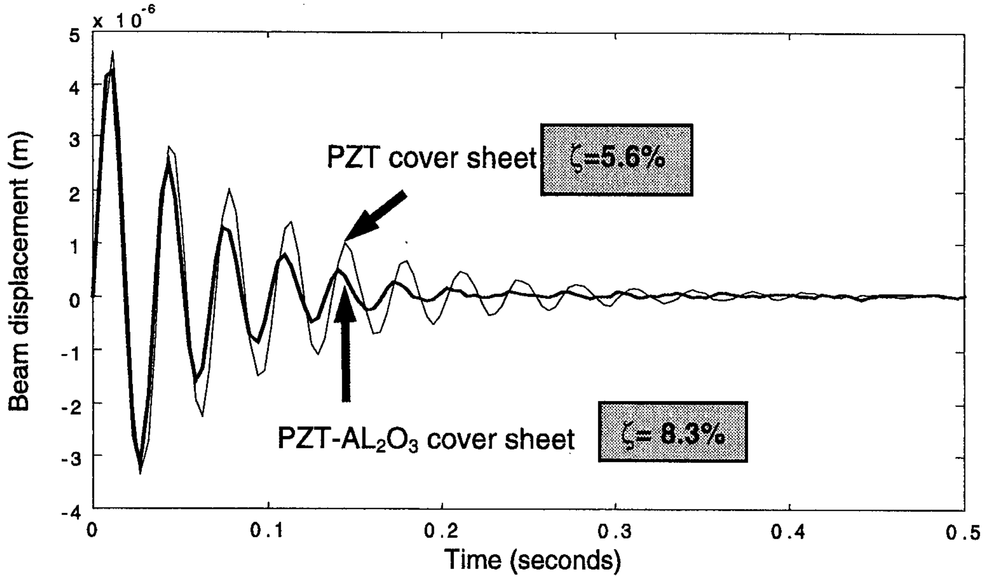

Figure 8. Experimental results (closed-loop) comparing HCL (with PZT- Al_2O_3 coversheet) versus system with pure PZT coversheet. ζ is the damping ratio.

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PARTICIPANTS AND DEGREES AWARDED

Personnel supported: K. W. Wang (PI), W. H. Liao (graduate student - partially supported by this grant), M. S. Tsai (graduate student- partially supported by this grant), Y. Liu (graduate student).

Degree awarded: W. H. Liao, Ph.D., 1997. M. S. Tsai, Ph.D., 1998. Y. Liu, Ph.D., 2001 (expected).

REPORT OF INVENTIONS

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