ACTIVE CONTROL OF RADIATED SOUND WITH INTEGRATED PIEZOELECTRIC COMPOSITE STRUCTURES

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ABSTRACT

The work investigated in this URI project is concerned with the active control of radiated sound using advanced structural systems with fully integrated actuators and sensors driven by realistic forms of disturbances. The overall goal was to demonstrate active control of sound radiated from vibrating structures with a *fully integrated, practical* active material including multiple actuators and sensors. This ultimately implies addressing the requirements for realistic active structures with integrated actuators and sensors as well as developing new sensing, control theory and design approaches so that the active material systems can be correctly and efficiently implemented.

This report summarizes three years of research work to achieve these goals. The work was evenly split between two main groups. The Materials Research Laboratory (MRL) at Penn State University addressed the development and construction of a suitable actuator system. The Vibration and Acoustics Laboratories (VAL) at Virginia Tech focussed upon developing new approaches for radiation control, system component development and integration and integrated system testing and demonstration. The work essentially followed a general theme of continual component development, system integration and testing through various phases tightly coordinated between MRL and VAL.

The two core technologies of the project were a new air piezoceramic actuator system conceived and developed by MRL and a new radiation control approach based upon a continuous active skin conceived and developed by VAL.

The report describes work by MRL-PSU on developing an constructing a new actuator called PANEL based upon using double amplification obtained from a system of orthogonal bimorph piezoelectric elements covered with an acoustic diaphragm configured in a flextensional type manner. The resultant PANEL source after many iterations of analysis, development, construction and testing was found to provide amplification ratios of around 250:1 and generate diaphragm vibration levels of the order of 500 microns (on resonance) and 200 microns (off resonance) over a frequency range of 0 to 1500Hz. The corresponding sound pressure levels generated by the PANEL source at 1m ranged from 80dB at 200Hz to 90dB above 400Hz. These performance levels were considered high enough to enable the PANEL source to be applied to a number of practical noise problems such as interior noise in aircraft and cars as well as electrical transformer noise and jet engine inlet noise. For applications below 200Hz, where the performance of the PANEL falls off, a new pseudo-shear multi-layer actuator utilizing folded multi-layer piezoelectric elements was developed and tested. The new pseudo-shear actuator was found to have significantly enhanced very low frequency performance below 200Hz.

The report also describes the new active noise control approach based upon implementing an active-skin which completely covers the structure conceived by VAL-

VPI. In the VAL part of the project, multiple PANEL actuators were integrated into a continuous skin system with independently controllable sections. A new structural acoustic sensing approach which enable the integration of sensors directly into the skin and yet allowed estimation of far-field sound radiation was developed and implemented in the active skin system. New control approaches and system optimization and design approaches were developed and used to efficiently configure and control the skin system. New active-passive approaches, which take advantage of the system natural dynamics to lower control authority requirements and increase robustness, were investigated. Finally the component technologies were integrated into an active skin approach designed to control broadband sound radiation from a test panel. The active skin system with integrated sensors was tested and found to provide total attenuation of the plate radiated sound power of 7.3dB over a bandwidth from 200 to 600Hz. This bandwidth encompasses multiple plate mode resonances. In order to handle the very low frequency region below 200Hz a new distributed active vibration absorber was implemented and tested. The work has demonstrated the high potential of an active skin with integrated piezoelectric amplifier elements and structural sensors for controlling structurally radiated sound with realistic loads.

The report is divided into two main parts. The first part summarizes work at MRL-PSU on developing the new actuator systems. The second part describes the system integration and testing performed at VAL-VPI. Throughout the report, reference is made to a set of published papers which describe the project work in detail. These papers are provided for convenience of the reader in Appendices at the end of the report.

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1. INTRODUCTION

The main theme for this ONR sponsored MURI evolved during a major snowstorm in State College, which immobilized Professor Qiming Zhang and Dr. Leslie Bowen of MSI, Inc. in the Materials Research Laboratory for a two day period of intensive thinking. The idea which evolved was to make a light flat panel high intensity acoustic source using orthogonal bimorph and flextensional amplification (see Fig. 1). The opportunity to explore the idea practically came with this URI program joining Dr. Christopher Fuller's group at Virginia Polytechnic Institute with the Penn State MRL in an aggressive program for active control of radiated sound with integrated piezoelectric composite structures. The program required just such large area flat panel piezoelectric sources.

Simple calculations for a PZT 5H bimorph driving a light flexing diaphragm, suggested a gain of 250× able to generate a sound pressure of 136 dB at 500 Hz with an efficiency of 4.5%. The initial system constructed using a simple loudspeaker paper diaphragm came very close, generating a near field sound pressure of 135 dB at 520 Hz with 2.1 kV/cm drive on the bimorph elements however, the system proved too fragile for practical use. The results were however sufficiently promising to initiate a wide-ranging search of the many new bending mode actuators evolved in recent years. This search highlighted the advantage of a folded L-shape unimorph/bimorph combination to drive the diaphragm.

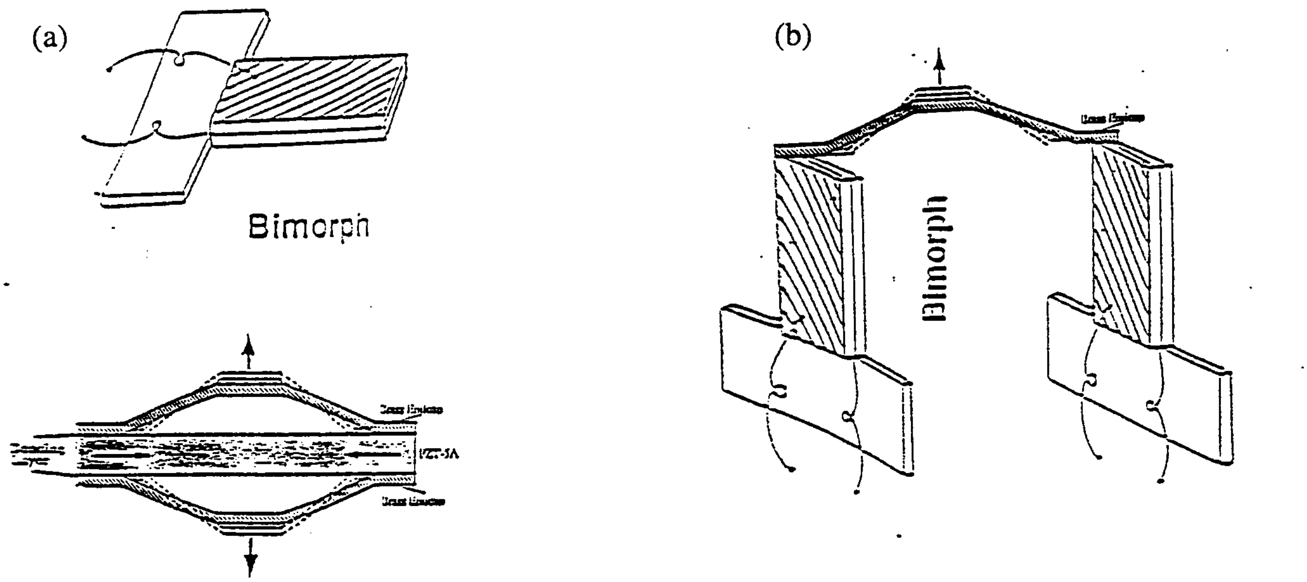


Figure 1. Actuator configurations (a) simple bimorph and flextensional amplifiers (b) orthogonal arrangement for enhanced gain.

This new L-shaped actuator is much more robust and capable of driving a high strength carbon fiber reinforced diaphragm. The resulting PANEL acoustic source has a high resonant mechanical Q, but with adequate damping, the required broadband source characteristics covering the range from 300 to 1 kHz were achieved. Six PANEL systems were constructed and supplied to Dr. Fuller's group at VPI for integration into his control system as described in the second half of this report.

Below 200 Hz, the performance of PANEL falls off rapidly and a stronger high strain element than the unimorph is required to drive a larger area diaphragm. For this purpose a new pseudo-shear model multilayer actuator has been designed which uses an effective folded multilayer configuration. The element provides higher blocking force at higher displacements than are possible with the bending mode systems. A single large area element was provided to VPI for initial evaluation. Penn State has applied for patent on the shear mode concept.

Previous work under ONR funding has developed and demonstrated the potential of active structural acoustic control or ASAC systems for efficiently reducing low frequency sound radiation from vibrating structures. In general the ASAC approach relies on applying active inputs directly to the structure while minimizing radiated sound or a related variable such as structural wave number or volume velocity. Such an approach has led to control systems with a significantly reduced complexity when used below the structural critical frequency. Much work has been carried out on developing the necessary sensing and control approaches. The actuators used were generally piezoelectric patches which could be bonded or embedded in the structural system. The combination of integrated transducers and adaptive MIMO control approach makes typical ASAC systems a part of the growing field of smart, intelligent or adaptive structures. While much progress has been achieved there is still much development that needs to be carried out to make the ASAC approach generally applicable to realistic systems. In particular problems with applying ASAC to heavy or stiff structures with a high modal density of response need to be resolved as many Navy ship systems and commercial applications are of this nature. In this project we investigate a related but new technique of coating the radiating structure with an active skin to reduce the sound radiation in order to resolve these issues. The development of the PSU PANEL source has made possible the practical realization of such an active skin for sound radiation control.

This report delineates research performed over the period 1 October 1994 to 31 March 1998 in the Materials Research Laboratory of The Pennsylvania State University and the Vibration and Acoustics Laboratories at Virginia Polytechnic Institute and State University on the ONR funded project number N00014-94-1-1140. Support for the program was through a URI to Professor Christopher R. Fuller at VPI&SU, and involved major elements at VPI&PSU, with smaller supporting programs at Material Systems Inc (MSI) and Hood Technology Corporation/University of Washington as delineated in Fig. 2.

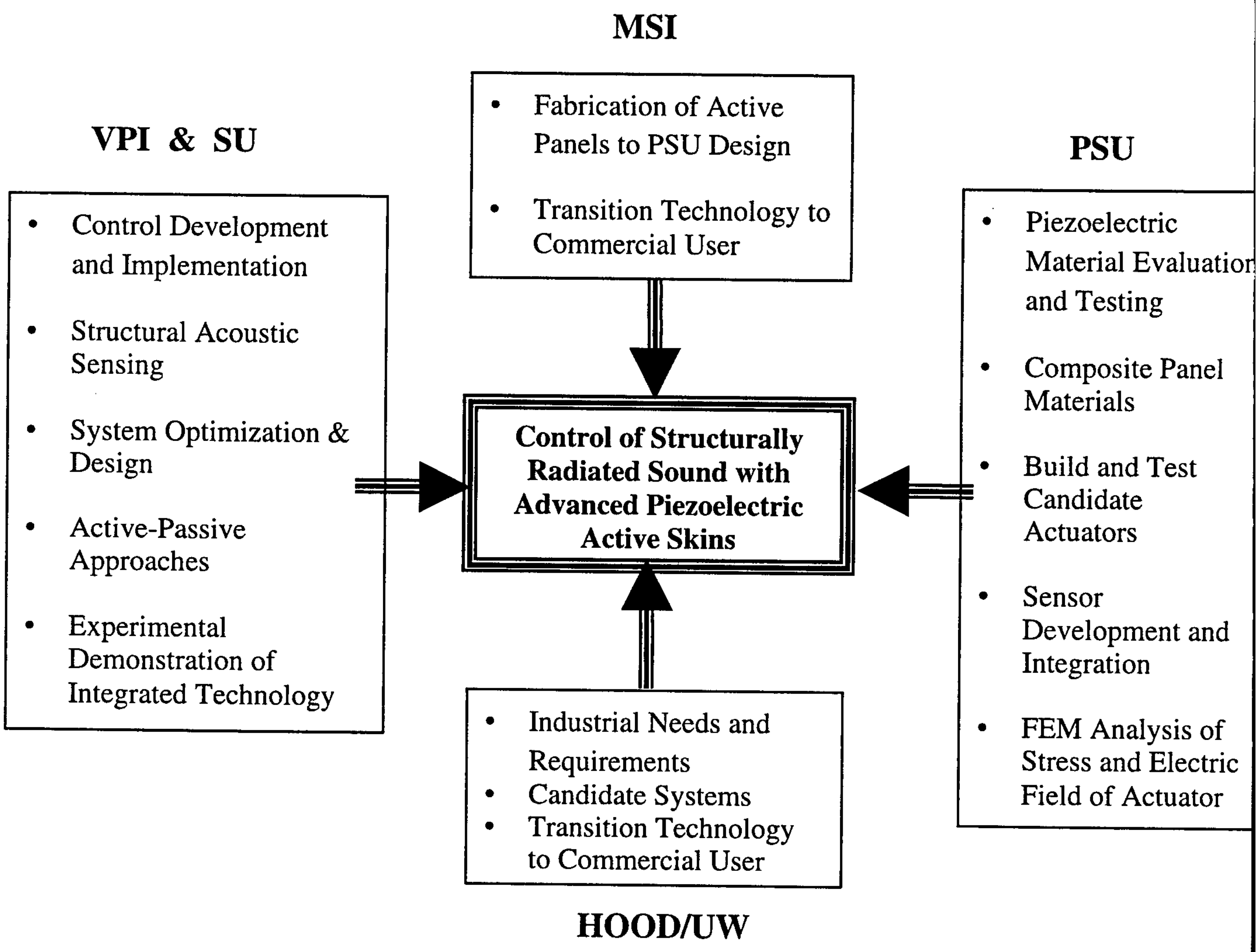


Figure 2. Elements of the research program

Following long established precedent, the report will draw extensively upon published results provided in the Appendices which will be connected by a brief narrative summary to highlight the major achievements arranged as below.

Section 3 of the report deals with the work carried out at Penn State and concerns:

- Systems requirement and proposed approach.
- Simple bimorph based double amplifier.
- Evaluation of a wide range of bending mode actuators.
- Development of the robust PANEL transducer.
- Multilayer bending mode transducers.
- New pseudo-shear mode low frequency driver.

Sections 4 and 5 deal with work carried out at Virginia Tech and concern:

- Structural acoustic sensing.
- Control approaches.
- System optimal design methods.
- Integrated active system demonstrations.
- Active-passive approaches.

2. GENERAL CONCEPTS OF AN ACTIVE SKIN FOR RADIATION CONTROL

As discussed above a promising method of controlling sound radiation from structures is the ASAC method. In the ASAC method the actuators tend to be spatially small and thus cover only a very small part of the structural surface; their effect is achieved due to the distributed elastic response of the structure. This technique has worked well for a number of applications where the structure typically has reasonable mobility and a low modal density of response. In some applications however, the structure is quite massive or stiff and it is extremely difficult to achieve the necessary control field response with practical control actuators. This effect tends to become exacerbated as the drive frequency is lowered.

In this project we investigate a variant of the ASAC approach in which the control inputs come from an *active skin* which covers all or most of the vibrating surface. Fig. 3 shows a schematic of a generic active skin. The objective of the active skin is to locally change the radiation impedance (in particular the resistive component) of the structure in order to control the total radiated sound power in contrast to ASAC which directly alters the dynamics of the base structure. Since it does not drive the base structure (only modifies the radiation impedance above it), an active skin is thus suitable for heavy or stiff structures with low mobility.

In order to successfully develop and implement an active skin, various new component technologies had to be developed and integrated together to create the required device and performance. Work had to be carried out on developing suitable actuators for the skins. Hybrid active-passive approaches needed to be investigated in an attempt to lower the control power requirements and reduce controller complexity. Since the sensors must be integrated directly into the skin, new structural acoustic sensing approaches were developed along with suitable new control approaches. New optimal design techniques will have to be developed so that all the component technologies can be integrated in efficient manner to give a high level of sound control performance. Finally the active skin concept was demonstrated on representative structural systems and disturbances.

These general topics and goals are the main aims of the work of this project and are summarized below.

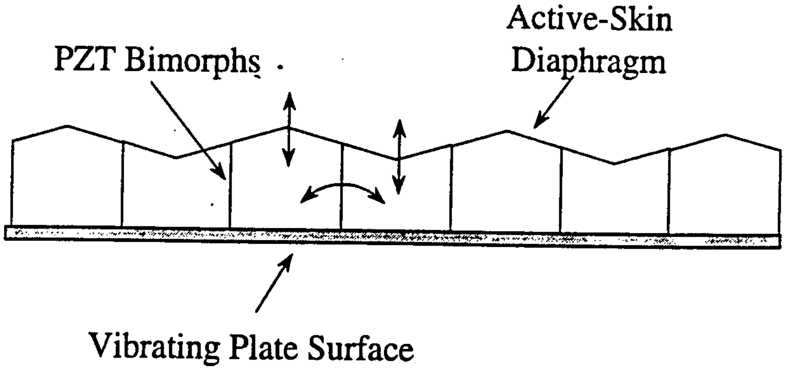


Figure 3. Schematic of an active skin for sound radiation control.

3. DOUBLE AMPLIFIER ACTUATOR DEVELOPMENT AND TESTING

3.1 Systems requirements and proposed actuator research

Following an initial one day meeting of all participants at Penn State, likely conditions of spatial scale, surface normal displacement and frequency range were delineated for the applications of a typical turbo prop aircraft, the Grumman E2C, the Douglas MD80/DC9, in turbulence (excitation of aircraft fuselages), large electrical transformers and for jet inlet (turbo fan) noise control. The resultant information is summarized in Table 1.

TABLE 1

System requirements in actuation for several relevant quieting needs

REQUIREMENTS			
Application	Spacial Scale [m]	Displacement $[\text{mm}]_{\text{p-p}}$	Frequency [Hz]
Turbo prop	≈ 1 0.5	30 10	70 - 100 140 - 200
E2C	1	1000 (≈30G)	74
MD80/DC-9	1	30-100	100
Turbulence	0.04	<1	<1000
Transformer	1.5 – 2	5	120, 240 . . .
Jet Inlet	0.03 – 0.05	250 – 500	2000 – 4000

It is clear from the data of Table 1 that in several instances the throw from a typical piezoelectric actuator of reasonable dimensions is much too small. Bimorph and flextensional amplifiers are well known but in each case the amplification is inadequate, however by combining them in an orthogonal arrangement as shown in Fig. 4 a gain of over 200 can be realized (see Table 2).

3.2 Bimorph based double amplifier actuator

A simple bimorph based double amplifier of the type proposed above is discussed in more detail in Appendix 1. The structure was realized using two short end clamped bimorphs with a loudspeaker paper diaphragm. An effective one dimensional model which uses complex dielectric, piezoelectric and elastic constants models the dynamic behavior quite well is presented in Appendix 2, and further optimization, particularly of the cover plate structure is discussed in Appendix 3 where it is clear that flexure of the very light paper diaphragm strongly limits performance even though this is adequate for most purposes. A more severe problem was the fragility of the resulting structure which proved inadequate for practical systems. The performance was however sufficiently promising to merit a much broader ranging survey of bending mode actuators which could drive a more robust diaphragm.

TABLE 2

Elementary derivation of possible gain

AMPLIFICATION FACTORS

- Bimorph vs transverse piezoceramic

Bimorph

$$\Delta_c \simeq d_{31} E_3 \left(\frac{L^2}{t}\right)$$

Δ_B	tip displacement, d_{31} transverse piezoconstant
E	applied electric field, L bimorph length
t	bimorph thickness

Transverse Piezoelectric

$$\Delta_c \simeq d_{31} E_3 L$$

Amplification

$$A_T = {}^{3}\!/_{2}\left(\frac{L}{t}\right)\left(\frac{W}{h}\right)$$

- Flextenstional element

$$A \simeq \frac{W}{h}$$

- **TOTAL AMPLIFICATION**

$$A_T = {}^{3}\!/_{2}\left(\frac{L}{t}\right)\left(\frac{W}{h}\right)$$

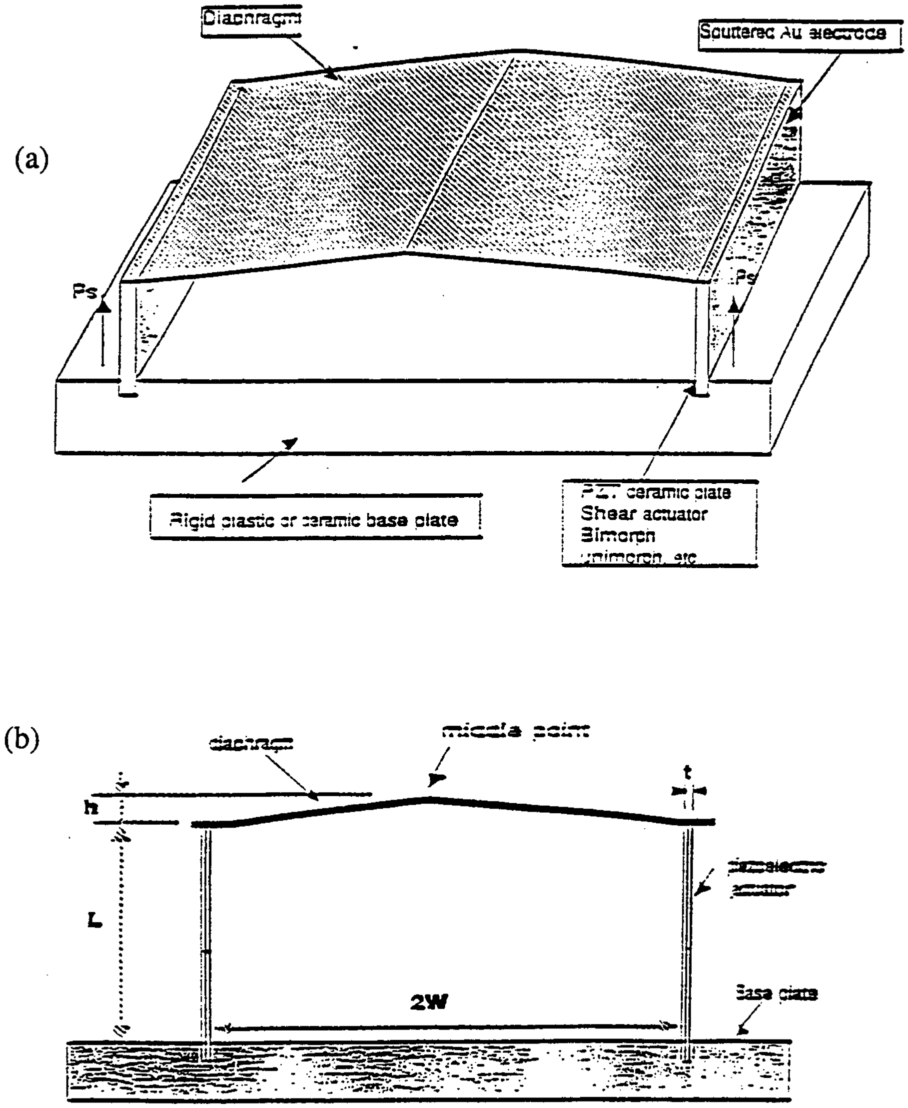


Figure 4. Double amplifier actuator (a) arrangement (b) elevation with critical dimensions.

3.3 Evaluation of a wide range of bending mode actuators

Detailed studies were carried forward on several of the newer types of bending mode actuators. The thermal stress biased CRESENT type unimorph is discussed in Appendix 4 for an element which used PK 1550 ceramic bonded to stainless steel at 250•C. the Reduced and Internally Biased Oxide Wafer (RAINBOW) is evaluated in detail in Appendices 5, 6, 7, and 8.

The dynamical performance was evaluated for unimorphs cut from the typical disk type RAINBOW in Appendices 5 and 6. The fascinating structure associated with the abrupt reduction front and the mechanical performance of this monolithic ceramic actuator in Appendix 7. To understand the dynamical mechanical performance completely it is necessary to know the Young's modulus of the reduced layer in the RAINBOW, and this is measured in Appendix 8.

A new type of d_{33} driven unimorph and bimorph actuator which is christened the caterpillar type is described in Appendix 9. The characteristics show excellent improvement over the normal d_{31} driven systems, but the cost and complexity make the element difficult to apply. A simple shear mode monolithic actuator driven through d_{15} was also evaluated (see Appendix 10). Here the frequency is limited by the larger compliance s_{44} and the force is compromised by the flexing of the driven beam.

To permit intercomparison of the very wide range of bending mode systems studied, all types of actuator were fabricated from the same ceramic with the same thickness, length and width and driven by the same electric field. As a figure of merit for the double amplifier application (Tip displacement) × Blocking Force/Admittance was used for a short 2.5-cm long end clamped configuration. Data for the bimorph is normalized to unity, and the Table 3 compares bimorph, unimorph, L-shaped bimorph, L-shaped unimorph, RAINBOW, CRESCENT, Thunder (A NASA design) Shear mode d_{15}, d_{33} bimorph, and d_{33} driven unimorph. Clearly the d_{33} driven systems are superior, but expensive, and for the next generation double amplifier the L-shaped unimorph was chosen because of its robust character and compact dimensions.

It may be noted that in this study, because of the field limit, the stress biased Thunder, CRESCENT, and RAINBOW are not driven to their limiting states.

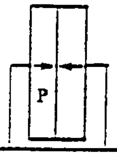
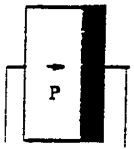
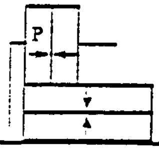
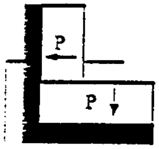
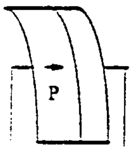
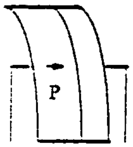
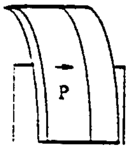
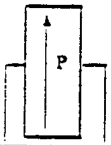
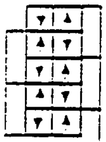
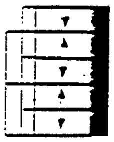
A fuller discussion of the comparative evaluation is given in Appendix 11 and the influence of higher drive levels discussed in Appendix 12.

3.4 Development of the robust PANEL transducer

From the earlier studies (Section 3.3) it is clear that the L-shaped unimorph structures have significant advantage. The incorporation in the PANEL system is shown in Fig. 5. To provide additional drive the base was fabricated as a bimorph, with the metal shim providing the robust frame for the whole structure. The final design is depicted in Fig. 5. The simple structure incorporating the higher strength very light carbon fiber reinforced composite diaphragm proved to have high mechanical Q, so that to achieve the flatter band response a damping material (A double layer of 0.045" thick GP3) was incorporated as shown.

TABLE 3

Figures of merit for short end damped bending mode actuators

TYPE OF PIEZOELEMENT		Displacement	Blocking Force	Admittance	Figure of Merit
d_{31} Bimorph (PKI550)		1	1	1	**1**
d_{31} Unimorph (SS302/PKI550)		0.41	1.8	1.0	**0.74**
L-Shape d_{31} Bimorph (l_1=l_2=0.5l)		0.75	1.5	1.0	**1.13**
L-Shape d_{31} Unimorph (SS302/PKI550)		0.31	2.7	1.0	**0.84**
RAINBOW Aura Ceramics (C3900 ?)		0.19-0.22	0.1-1.2	0.66	**0.03-0.40**
CRESCENT 250°C (SS302/PKI550)		0.44	1.75	0.91	**0.85**
THUNDER ~300°C (3Al/PZT5A/Al)		0.12	0.36-1.0	0.90	**0.05-0.13**
Shear- mode (d_{15}) (3203HD)		<0.1	?	1	**-**
d_{33} Bimorph (PKI550)		**2.5**	**1.52**	**~1**	**3.80**
d_{33} Unimorph (SS302/PKI550)		**0.72**	**3.5**	**~1**	**2.52**

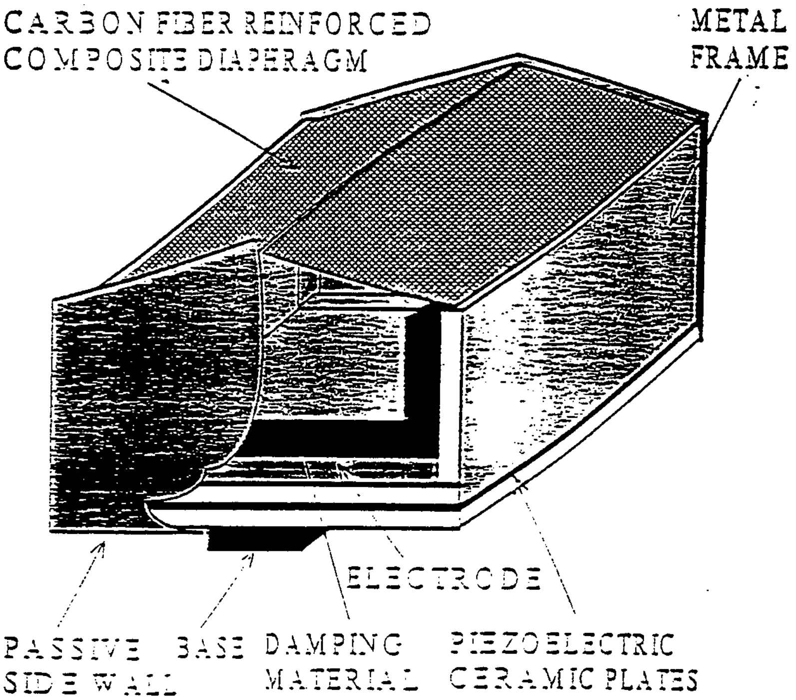


Figure 5. PANEL double amplifier using L-shaped shim actuators.

Dynamical characteristics for the damped structure are shown in Fig. 6a-c which shows that the Q can be reduced to 3.8 without significant loss of quasi-static performance.

Calculated sound pressure for a single device based on the model of a baffled piston is depicted in Fig. 7 for two reasonable drive levels. Over the range from 300 Hz to 1,000 Hz, sound pressure levels of over 90 dB are achieved.

3.5 Multilayer bending mode transducer

A brief examination of the possibility to use multilayer bimorph elements to reduce the driving voltages and increase driving currents was carried forward. The idea is depicted schematically in Fig. 8. Bending of the two vertical elements takes place about the central metal shim, the multilayer on one side elongating and the one on the other side contracting.

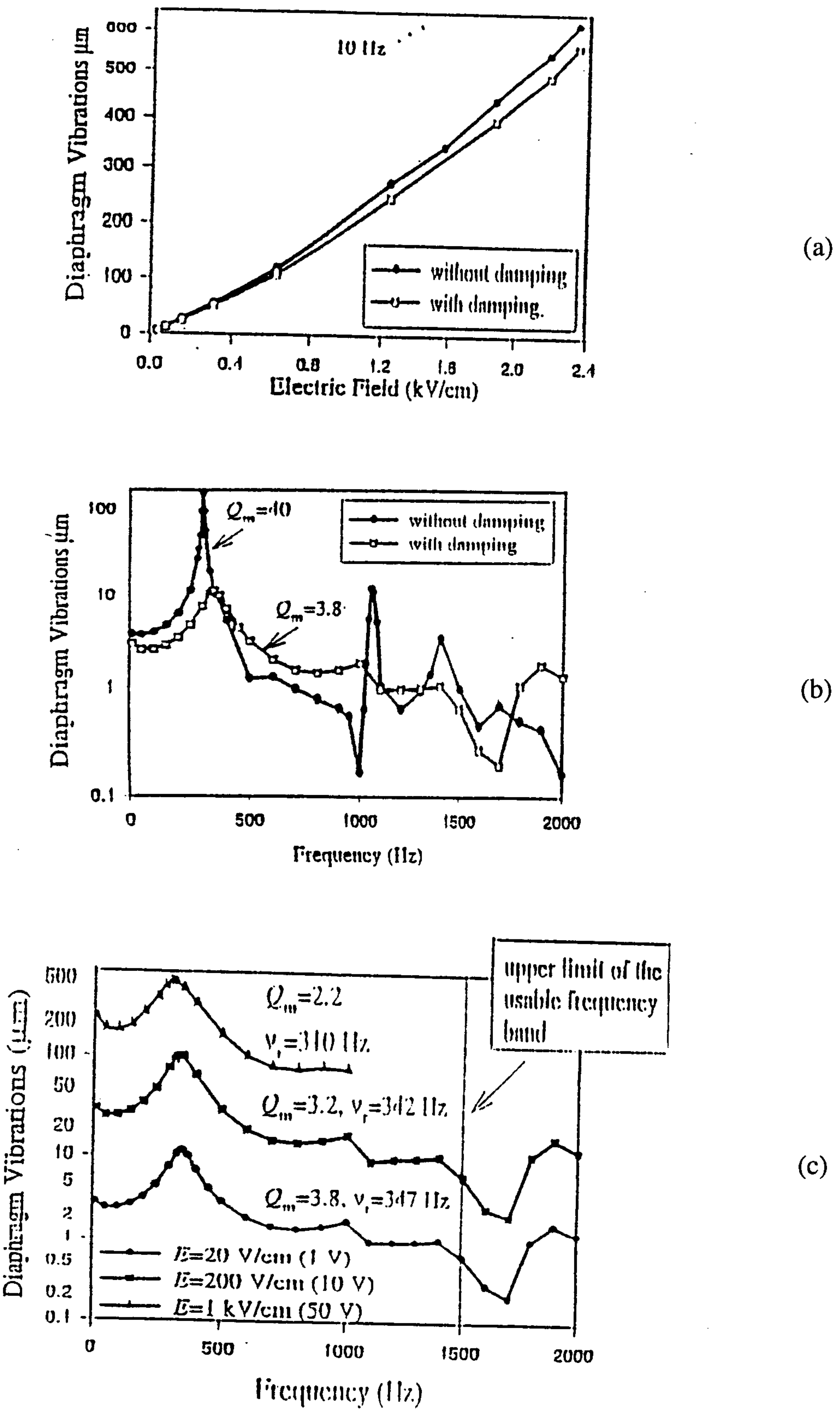


Figure 6. Performance of PANEL with (a) effect of damping on quasi-static response (b) effect of damping on dynamical response(c) dynamical response at higher drive field levels.

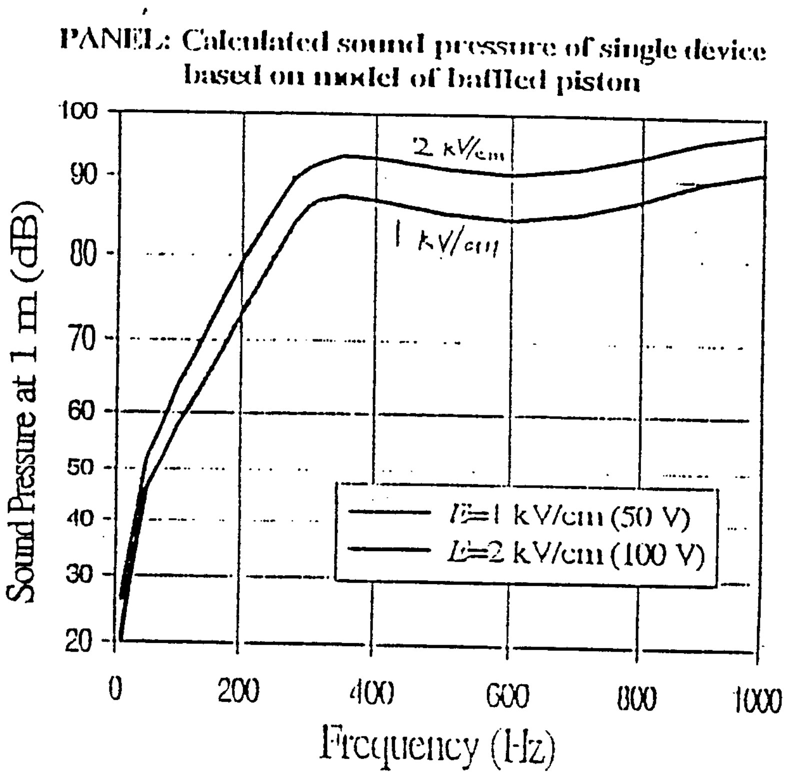
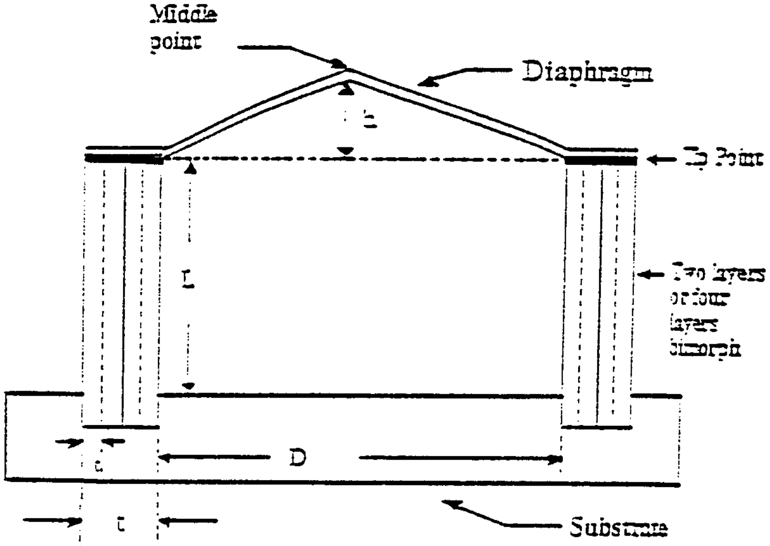


Figure 7. Calculated sound pressure from the model of baffled piston representation of PANEL.



t_l : Layer thickness, t: Bimorph thickness
h: Height of diaphragm, L : Length of bimorph
D: Distance between bimorph
L=20 mm and D=50 mm for all device in this report.

Figure 8. Schematic of possible multilayer bimorph driven double amplifier.

Quasistatic amplification factors for the multilayer devices look most attractive (see Table 4), but the resonant frequencies are reduced for the loaded device of Fig. 8. It appears most probable that the reduced frequency is due to the soft epoxy used to bond the multilayer structures for this experiment and that, by using co-fired multilayer elements, the enhanced performance could be achieved without loss of bandwidth.

TABLE 4

Quasi-static displacement for 2-layer and 4-layer bimorphs and. quasi-static amplification for diaphragm loaded 2-layer and 4-layer actuators.

(a) Quasi-static displacement of unloaded device

Bimorph Design	Layer Thickness cm	Tip Displacement μm	Driving Electric Field kV/cm(10Hz)	Voltag Applied Vrms
2 layer	0.075	3.64	0.35	26.25
4 layer	0.035	3.66	0.35	12.25
2 layer	0.1	2.997	0.35	35
4 layer	0.05	3.13	0.35	17.5

(b) Quasi-static amplification factor loaded with different height diaphragm

Bimorph Design	Layer Thickness cm	Driving Electric Field kV/cm.10Hz	Height of Diaphragm mm	Middle Point Displacement μm	Tip Point Displacement μm	Amplification Factor
2 layer	0.1	0.35	3	15.89	0.998	15.92
			2	17.22	0.896	19.21
			1	10.51	0.967	10.868
2 layer	0.05	0.35	4	29.5	3.346	8.82
			3	31.76	3.009	10.56
			2	31.7	3.23	9.81
			1	13.81	2.36	5.85
4 layer	0.05	0.35	3	21.44	2.4	8.93
			2	25.34	1.59	15.93
			1	25.43	1.17	21.735
			0.5	19.56	0.97	20.16

3.6 New Pseudo-shear mode low frequency driver

The newly designed multilayer pseudo-shear mode actuator is discussed in Appendix 13 and in Appendix 14. The advantage over the bending mode devices is the combination of large displacement with higher blocking force, the disadvantage is the lower resonant frequency which comes from the long (folded) length. This combination of features is however just what is required to drive a larger low frequency panel (see Appendix 15).

4. ACTIVE SKIN SYSTEM COMPONENT DEVELOPMENT AND INTEGRATION TESTING

4.1 Structural acoustic sensing

In order to develop a fully integrated active skin approach for reducing structurally radiated sound it is necessary develop structural sensing approaches. In order for ASAC or an active skin to be efficient, the sensing approach must give estimates of the radiated sound. However for an integrated skin approach the sensors must be included into the skin or structure and not in the radiated sound field. In addition the form of control algorithm which is to be employed in the system integration experiments is the time domain filtered x LMS approach. Thus the pressure estimates which will be the control error signals must also be in the time domain. These important aspects dictated the development of a new technique, called *Structural Acoustic Sensing (SAS)* which provides time domain estimates of far field radiated sound pressure from discrete measurements of normal structural acceleration.

The SAS approach is based upon a discretization of Rayleigh's integral. Fig. 9 shows a schematic arrangement of the SAS approach applied to a simple beam.

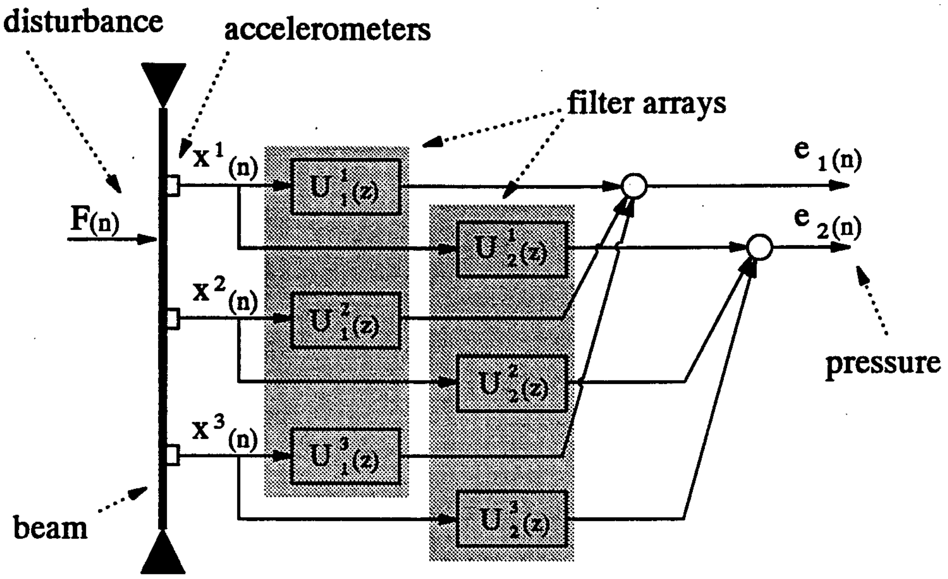


Figure 9. SAS configuration and components for a 1-D beam.

The beam normal acceleration is measured at a number of discrete points using standard accelerometers. The signals from the accelerometers are passed through FIR filters whose outputs are summed together. If the impulse response of each filter is chosen to closely match the radiation Green function related to the radiation from each accelerometer to the chosen field point, then the summed output will be a discrete approximation of the Rayleigh integral. The summed output is thus proportional to the radiated far field pressure at the same field point. The SAS technique can be applied to a variety of structures as long as the appropriate Green function is available (calculated or measured) for that structural system. Work under a previous ONR project outlined the theory, design and accuracy aspects behind the SAS approach applied to 1D-beam systems. In this project the SAS approach was extended to 2D planar systems. Appendix 16 discusses the theoretical and experimental work of applying the SAS approach to plate systems. Finally, Appendices 17 and 18 outline extending the SAS approach to cylinder systems. Appendices 16-18 outline the appropriate theory, application aspects and accuracy of estimates for each structural system. Fig. 10 presents a typical FRF plot of sound radiation from a plate towards a particular radiation angle. The figure shows both actual and SAS estimated pressure over a large bandwidth encompassing many plate modes. Twelve accelerometers were used and the FIR filters had four coefficients. The agreement between the estimated and actual pressure can be seen to be excellent. The figure presents the results for a particular wavenumber and this is because radiation at a discrete angle is proportional to a particular structural wavenumber. The SAS approach is thus also a time domain wavenumber sensing approach.

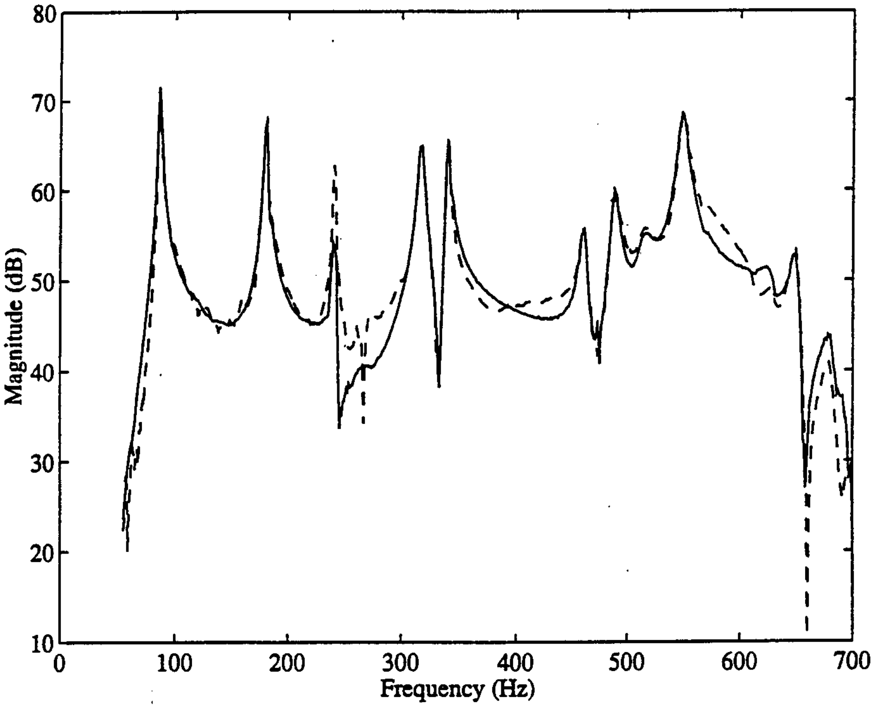


Figure 10. Actual (———) wavenumber/pressure component and measured (- - - - -) pressure in direction of radiation (ν=36°,Φ=0°).

The work demonstrates that very good estimates of time domain sound radiation can be made with the SAS method over a wide frequency bandwidth using a low number of structural sensors and low order FIR filters. The SAS approach can also be implemented in software and thus be resident on the same DSP chip that is used for the control implementation. It is interesting to note that the radiation Green function described in Appendices 16-18 has a significant delay component. Since the SAS will provide error signals for the ASAC controller this delay, relative to the primary accelerometer, can be removed from the FIR filters thus making them much more compact. In essence the SAS then provides estimates of pressure *before* it reaches the far-field.

Appendices 16-18 also present analytical and experimental testing of ASAC approaches applied to plates and cylinders with either microphone error sensors or SAS. The performances of the two sensing approaches for a number of different applications are compared and it is shown that SAS provides very comparable sound attenuation performance to the use of the conventional microphone error sensors.

Appendix 19 discusses a particular aspect of the SAS approach. It might be asked "why not just simply sum the accelerometer signals to provide an estimate of the volume velocity of the structure?" This would be much simpler since it would eliminate the need for the FIR filters. The work described in Appendix 19 compares the characteristics and ASAC performance of a SAS and a volume velocity approach. It shows that the volume velocity sensor is equivalent to a SAS estimate normal to the structure. The results show much improved performance when using the SAS sensor. This will be discussed in more detail in Section 4.4.

4.2 Control approaches

A critical part of developing an active skin is the form of the controller to be used. In this project we chose to employ the well know feedforward approach called the LMS Filtered x algorithm. The reasons for choosing this approach is that it has proved suitable in past ASAC work when a relatively complex, fully coupled controller is needed (i.e. a controller that is adaptive, with multiple control channels, that has a large operational frequency bandwidth and requires fast convergence times). As part of the project new and improved versions of the Filtered X algorithm were developed and implemented. The work is described below.

a. Stabilized Fast A-posteriori Error Sequential Technique (SFAEST).

One of the problems faced by the LMS Filtered X algorithm is that convergence is dependent on the statistical properties of the reference signals. Another problem is that the Filtered X algorithm commutes the estimations of the control and error paths. This assumption tacitly hold if the signal are steady state and the system is LTI. However the adaptive nature of the Filtered X algorithm is inherently non-steady state especially under fast convergence conditions. Both of the above problems often lead to reduced convergence speed and a reduction in the amount of cost function attenuation achieved. Appendix 20 describes work to overcome these problems. A new LMS code called the Stabilized Fast A-posteriori Error Sequential Technique (SFAEST) was developed. This approach calculates and adjustment to the error signals, which compensates for the error introduced by exchanging the filter operations. The SFAEST also utilizes the shift invariance properties of the autocorrealation matrix to derive a fast converging algorithm independent of the statistics of the reference signals. Appendix 20 describes in detail the SFAEST algorithm and compares it performance to the standard Filtered X under a variety of test conditions. The results show a significant improvement in convergence speed and amount of attenuation realized.

b. Multiple reference feedfoward control approaches.

In many applications there are multiple uncorrelated or partially correlated noise sources. This implies that the feedforward active approach must employ multiple reference sensors and signals for each noise source. However if the standard Filtered X is used with multiple reference signals which are partially correlated then poor performance can results since the calculation of the gradient is essentially ill conditioned. Appendices 21 and 22 describe work performed to correct this problem. The technique involves pre-processing of all the reference signals to ensure that they are completely uncorrelated before they are used in the Filtered X algorithm. Fig. 11 shows a schematic arrangement of the adaptive decorrelation filter (DCF) which is used across all reference channels. The DCF uses the LMS approach to cancel all correlated information between the reference channels. Full details are given in Appendices 21 and 22.

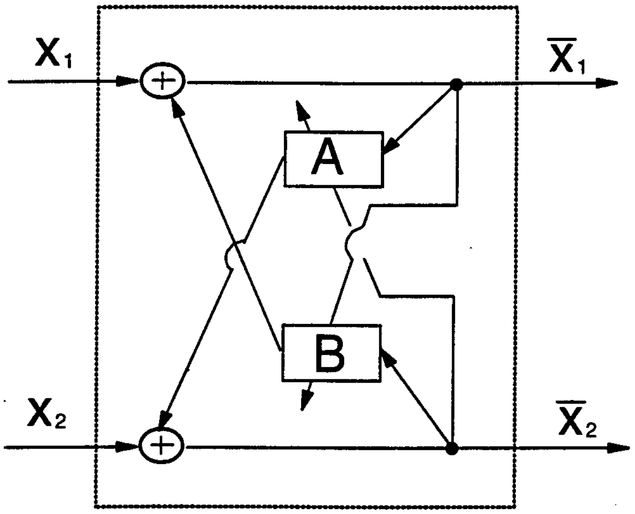


Figure 11. Adaptive decorrelation filter for two reference channels.

Figure 12 shows a typical convergence curve for an experiment utilizing a two reference signal LMS approach. The reference signals are partially correlated as described in Appendix 22. The results clearly demonstrate that when the reference signals are pre-processed with the DCF's that the convergence speed and amount of achievable attenuation are markedly increased. This was found to be even more so when there was noise on the error signals.

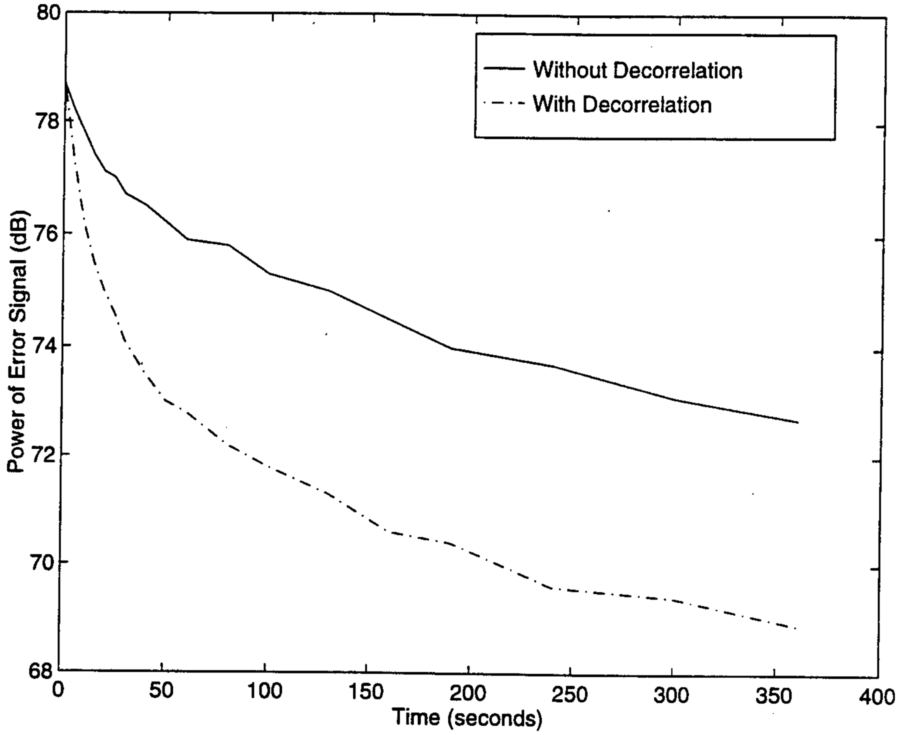


Figure 12. Comparison of experimental measured convergence curves.

4.3 System optimal design methods

Previous work has demonstrated the importance of optimal design in ASAC systems. One of the biggest impediments to the commercial success of active systems is cost. Thus it is important to keep the number of control channels as small as possible. In addition a large number of control channels often leads to an ill-conditioned controller with a resultant poor performance. A part of the project was thus directed towards developing and applying new improved optimal design approaches for ASAC systems and the active skin transducer system.

a. Nonvolumetric eigenproperty assignment design approach

Previous work has been directed towards developing an eigenproperty design approach for feedforward controlled ASAC systems. Appendix 23 describes how this technique is extended to enable the design of ASAC systems in terms of their actuator and sensor configuration so that the closed loop modes are all nonvolumetric and are thus weak radiators below the structure critical frequency. The main advantage of such an approach is that the design is independent of the disturbance characteristics (i.e. type, position and frequency content) and does not require sensors in the radiation field. The approach is thus very robust to disturbance changes and is efficient in the use of actuators and sensors. The mathematics and the methodology behind the approach are described in detail in Appendix 23 which also has results demonstrating that the approach is very efficient at reducing sound radiation at low frequencies. Later experimental work has also verified these aspects.

b. Multi-level optimization of ASAC systems

A different approach which is more suitable for systems in which modal information can be numerically or experimentally obtained is described in Appendices 24 and 25. The formulation takes advantage that both the structural response and the acoustic radiation from a controlled structure can be completely defined in the modal domain. The optimization approach is split into two levels for efficiency. The upper level of the optimization solves for the optimum modal parameters that minimize the radiated acoustic power. Then, these optimum modal parameters are used in a set of lower level or physical domain optimization problems to determine the physical characteristics of the actual actuators and sensors. Since the response of the system is evaluated in the upper level using a modal approach, the formulation permits the use of numerical or experimental data in the optimization method. The method is thus, as described in Appendices 24 and 25, is efficient for the design of ASAC approaches applied to complex or realistic structures. Appendices 24 and 25 illustrate the application of the multi level technique to control of radiation from plates and cylinders. The work clearly demonstrates the improvement in performance achieved by optimal design and illustrates the efficiency of the approach. Other work has applied the multi-level approach to a plate with the added complexity of an attached masses and a mass-spring system and experimentally verified the design methodology.

4.4 Integrated active skin system demonstrations

A significant part of the project was dedicated towards implementing the PSU double amplifier device (whose development is discussed in Section 3) into an integrated active skin demonstration. This involved taking the transducer technology described in Section 3 and synthesizing it with the sensing, control approaches and optimization techniques described in Sections 4.1- 4.3. The integration was done in two steps. Appendix 26 describes an analysis of the active skin used for structural sound radiation control while Appendix 27 details experimental investigations and validations of the skin technique.

a. Analysis

Appendix 26 describes an analytical investigation of the use of the active skin to control broadband plate radiation. The active skin is comprised of a number of independently controllable double amplifier piezoelectric cells as shown in Fig.13.

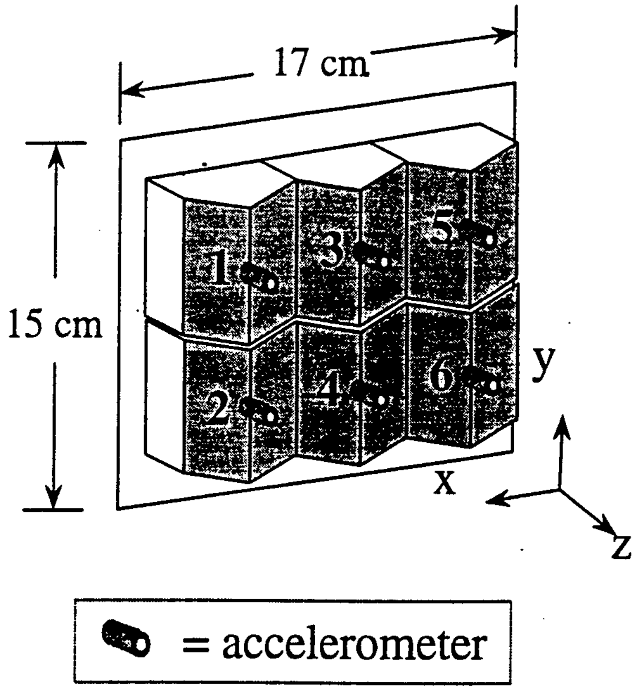


Figure 13. Schematic of a plate covered with an active skin composed of active cells and accelerometers for SAS.

The cells are configured to completely cover the radiating plate are their physical control effect is to de-couple the plate vibration from the radiated field. Fig. 13 also shows the use of accelerometers in a SAS approach. The control approach is a MIMO feedforward approach using either the SAS estimates or pressure calculations in the far-field. A numerical model describing the structural acoustic behavior of the skin cells was constructed using the Finite Element Method while the radiation from the plate and cells was modeled by a Boundary Element Method. Fig. 14 shows the FEM nodal discretization used while Figs 14 and 15 also present the calculated first and second vibration modes of the cell.

Time domain dynamics were obtained by constructing causal filters to represent the system control and plant path dynamics. These filters were then used to simulate the skin used in an active implementation under broadband random disturbances. Fig. 16 shows the calculated radiated power from an aluminum plate with and without control for a 6I6O controller (i.e. six cells and six error sensors were used) implemented with simulated microphones in the far-field. Excellent reduction is seen over the complete simulation bandwidth of 250 to 750Hz. The total power reduction is nearly 12dB,

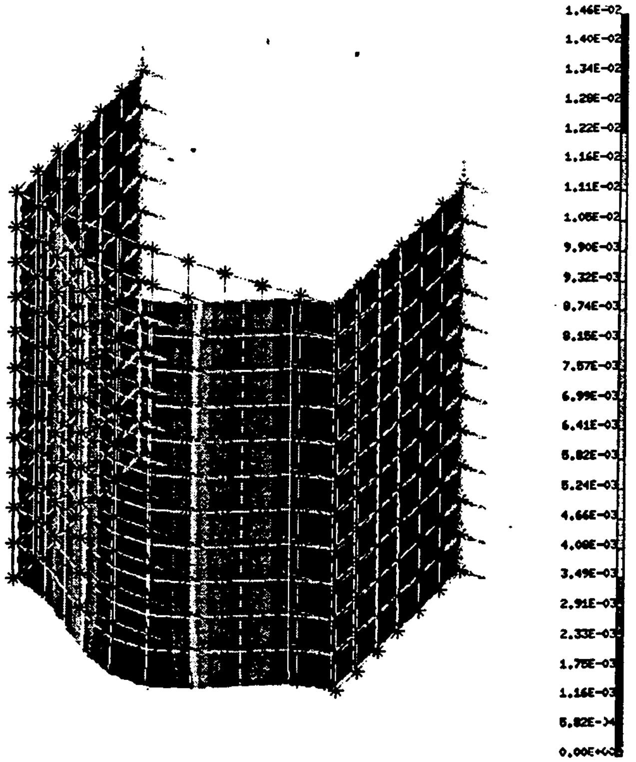


Figure 14. FEM of double amplifier cell and resultant response at the first mode.

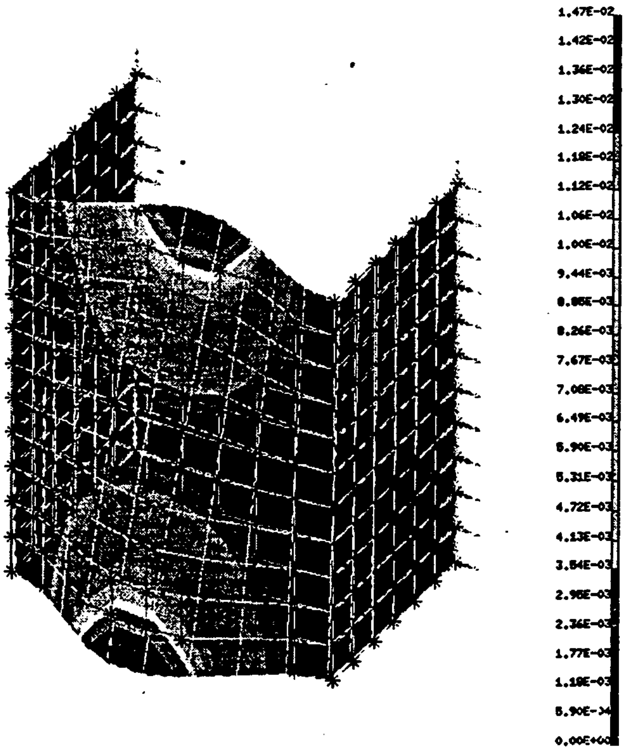


Figure 15. FEM of double amplifier cell and resultant response at the second mode.

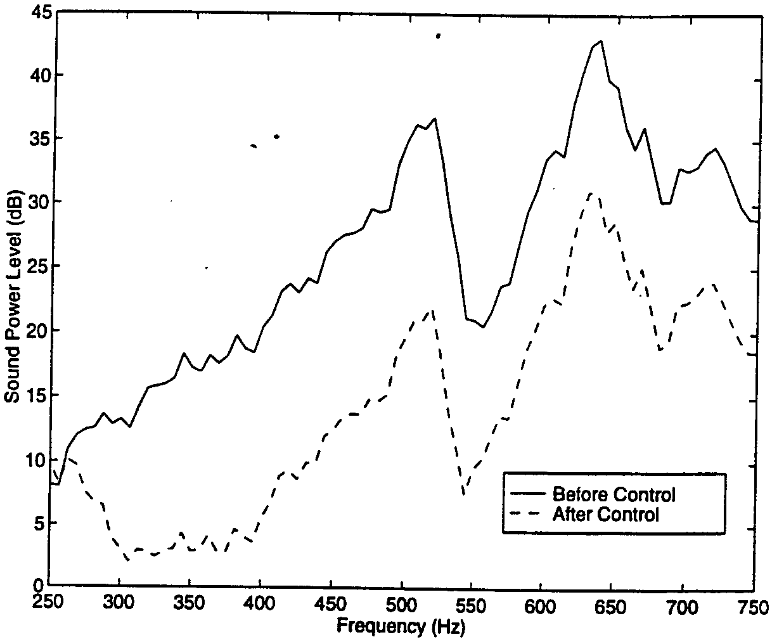


Figure 16. Predicted control performance of the active skin with far-field microphone error sensors.

Excellent reduction is seen over the complete simulation bandwidth of 250 to 750Hz. The total power reduction is nearly 12dB,

Fig. 17 shows the predicted control effect for the same situation as Fig. 16 except now SAS has been used by implementing six accelerometers on the top of each cell surface.

The amount of attenuation achieved is seen to be reduced when SAS is used but is still very good, with a total power reduction of nearly 8dB. The results indicate that the active skin approach using the PSU double amplifier cells has very good potential for control of structurally radiated sound. Full details are given in Appendix 26. The experimental validation will be described in the next section.

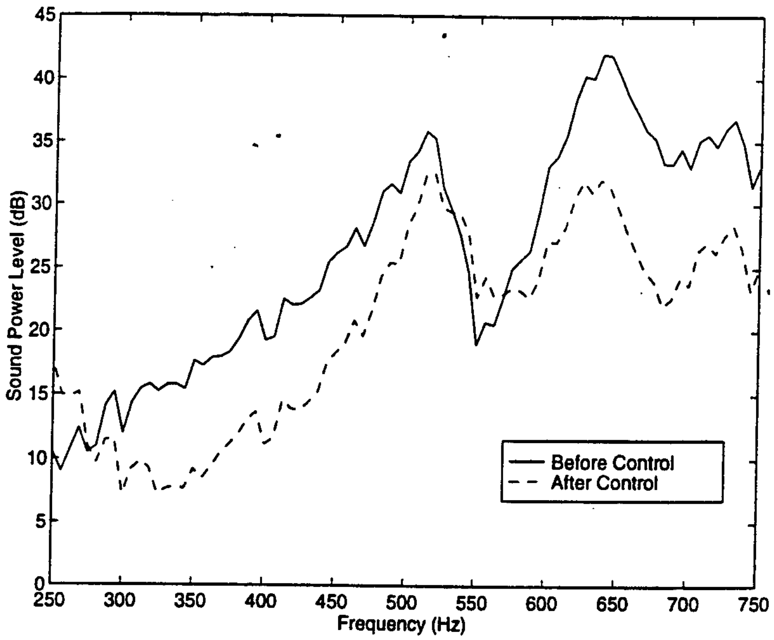


Figure 17. Predicted control performance of the active skin with SAS approach for error signals.

b. Experimental validation

Appendix 27 describes the experimental validation of the use of the PSU cells in the active skin approach to control structural sound radiation. As described in Section 3 three different cell prototypes were constructed and experimentally tested at Va Tech in the system integration program. Appendix 27 describes the use of the Phase III or PANEL prototype which was the most promising and successful version. Six PANEL cells were constructed at PSU and shipped to Va Tech. The six PANEL cells were attached to a test panel which was mounted in a rigid baffle positioned in the Va Tech anechoic chamber. Fig 18 shows a schematic of the skin/plate system and the feedforward control implementation. The plate is excited by a broadband signal driving a shaker and error signals are taken from either microphones in the radiated field or a SAS approach using accelerometers.

The experimental plate/skin system with SAS sensors mounted on top of the cells is shown in Fig.19. The six independent active skin PANEL cells and the SAS accelerometers are clearly apparent.

The adaptive feedforward control approach was implemented on a Texas Instruments C40 DSP as shown in Fig. 18. The reference signal was taken from the signal driving the shaker. Fig. 20 presents the measured radiated power with and without control using microphone error sensors. Good attenuation is achieved over the whole disturbance bandwidth of 200 to 600Hz. The total reduction is 9.5dB.

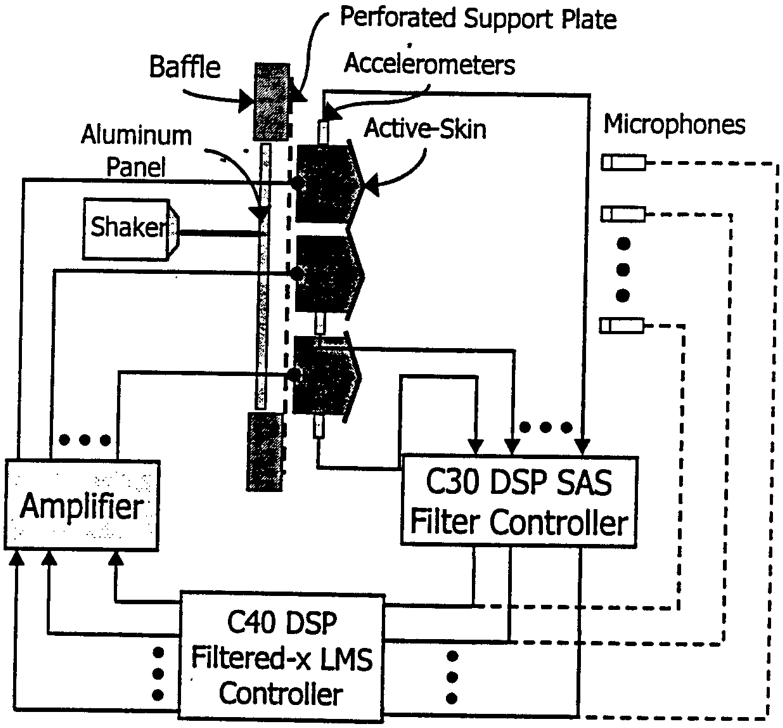


Figure 18. Arrangement of experiment to test performance of the active skin.

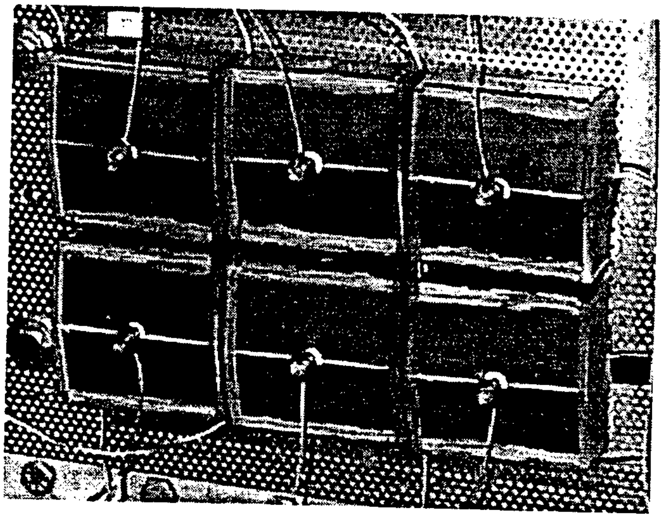


Figure 19. Active skin composed of six PANEL double amplifier sources and SAS accelerometers.

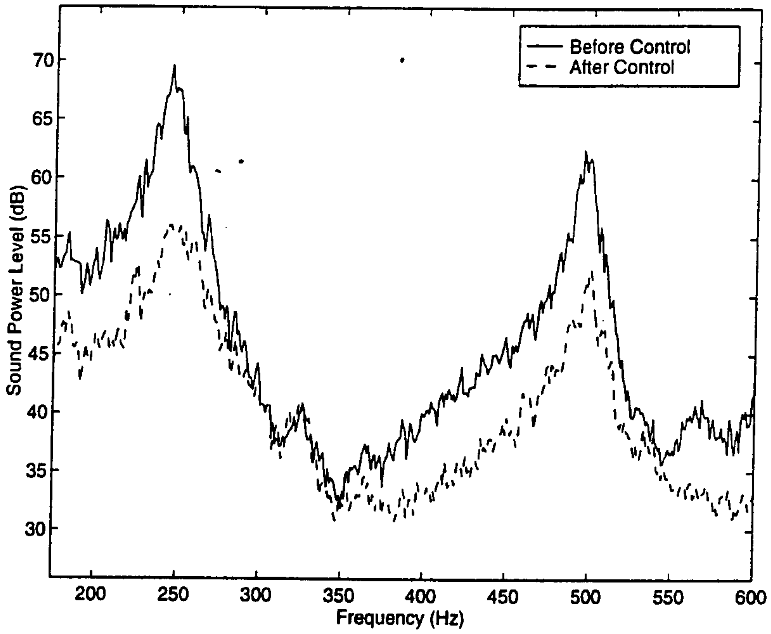


Figure 20. Experimentally measured performance of the active skin with microphone far field error sensors.

The performance achieved using SAS is given in Fig. 21. In this case the total power reduction is slightly reduced to 7.3dB but is still very good with across the band reductions achieved.

The experimental results confirm the analytical model and clearly demonstrate that an active skin with integrated piezoelectric actuators and structural sensors can be used to give very good structural sound control. Full details of the experiments can be found in Appendix 27.

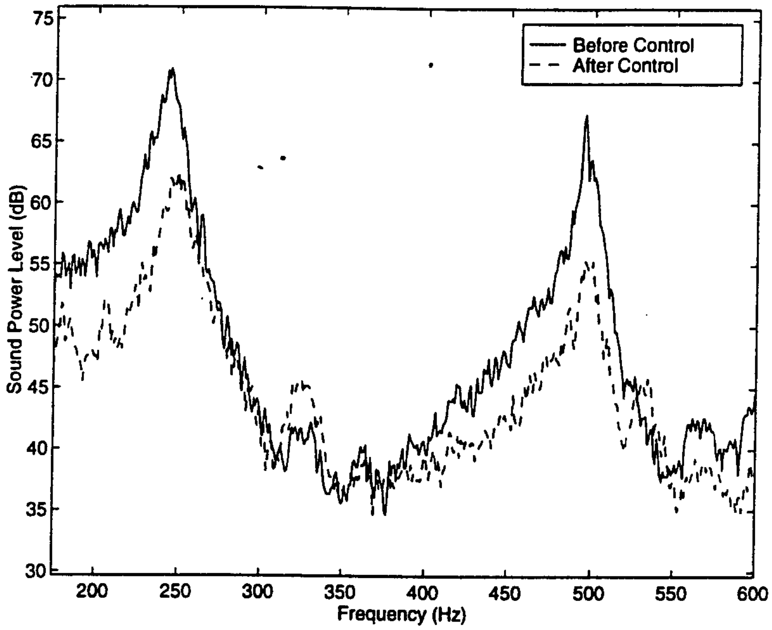


Figure 21. Experimentally measured performance of the active skin with SAS approach for error signals.

5. ACTIVE-PASSIVE METHODS

The previous section describes work on implementing a fully active approach. One of the important requirements of actuators is that they provide enough control authority for the application. For ASAC or active skin applications the main requirement is generation of enough control volume velocity at the low frequency limit. For piezoelectric devices this need usually translates into very high control voltages which dictate expensive and bulky high voltage power supplies. Another aspect is that at high frequencies, the system modal density rapidly increases requiring the use of a very large number of control channels. The high frequencies also require high digital sampling rates and thus expensive and powerful DSP's.

In an effort to overcome these problems, the use of active-passive control approaches was investigated. As the name suggests the active-passive control approach is a hybrid of the two (usually) separate techniques. Generally passive approaches work well at high frequencies while active techniques are best applied at low frequencies. Thus if the passive approach is designed with the active in mind, the active implementation can be limited to the low frequency region. In addition if the passive aspect of the actuator-substructure dynamics are cleverly chosen, then it is often possible to take advantage of natural passive effects such as resonance and damping phenomena to lower the active control authority requirements.

In this part of the project we investigated the potential of four active-passive approaches to achieve these goals.

5.1 Active-passive inserts for control of power flow in beams

Appendices 28 and 29 describe an analytical and experimental investigation of an active-passive insert to reduce extensional and flexural power flow in beam like structures. The passive control device consisted of a hard rubber insert between two beam sections and was meant to simulate a typical passive isolation section in beam and pipe systems. Piezoelectric patch type actuators were bonded to the beam-insert system in three locations; just upstream of the passive insert, directly on the passive insert and just downstream of the insert. The efficiency of the different locations in controlling total power (sum of extensional and flexural) when the beam was excited by a narrowband disturbance was investigated. It was found that the best location for the actuators was directly on the passive insert. In this configuration high attenuation of power flow with a much lower control voltage requirement was found. The results suggest the design of an active-passive insert with integrated actuators and sensors.

5.2 Adaptive vibration absorbers

In this project a limited amount of work was performed on the use of adaptive vibration absorbers (AVA) to reduce structural vibration and sound radiation. The work summarized in Appendices 30 and 31 was done in conjunction with another project with Hood Technology Corp. funded under an ONR SBIR program. The main concept is to use the natural reactive force of the vibration absorber (the name "absorber" is misleading since the devices function by exerting a reactive force and not damping) to apply an equivalent active control force to the structure. Since the impedance of the absorber can be adjusted by adapting its properties (or detuning it relative to the excitation frequency) it is possible, within a limited range, to adjust the relative magnitude and phase of the reactive force. As the force occurs due to the natural dynamics of the absorber, this can be achieved with a very low electrical voltage needed only to adapt the properties.

Appendix 30 is an analytical study of a number of such devices used to control interior noise in fuselages. It demonstrates that the best performance is achieved when the properties (in this case stiffness) of the AVA's are adjusted to minimize a radiation cost function. This result can be seen to be analogous to what is achieved with the fully active ASAC approach.

Appendix 31 describes experimental work to realize such AVA's. The design approach consists of a stepping motor suspended between a Y shaped support on the motor drive shaft. The stepper motor acts as the active mass of the AVA and the stiffness of the AVA can be adjusted by operating the stepper motor to lengthen or shorten the suspending shaft. Experiments were performed using the AVA's to reduce sound radiation from a large plate and confirmed the analytical results of Appendix 31; the best reduction was achieved when the multiple AVA's were globally detuned from the excitation frequency. Attenuations of total radiated power of the order of 10dB at 118Hz were achieved with adaptation voltages of the order of a few tenths of a volt necessary to drive the stepper motor.

5.3 Distributed active vibration absorber (DAVA)

The work described in the previous section shows that multiple vibration absorbers with varying properties can be located on a structure to globally control its vibration and/or sound radiation. If one considers an infinite number of small vibration absorbers the concept of a *distributed* vibration absorber with locally varying properties is suggested. Furthermore if an active element is introduced into the stiffness part of the distributed absorber then a *distributed active vibration absorber (DAVA)* is created as shown in the schematic of Fig.22. The goal is to achieve global sound or vibration reduction over a wide band of frequencies with a device that is of comparable weight to a classical point vibration absorber and has a low control voltage requirement. This should be contrasted to the characteristics of a classical vibration absorber which attenuates vibration at a single point a single frequency.

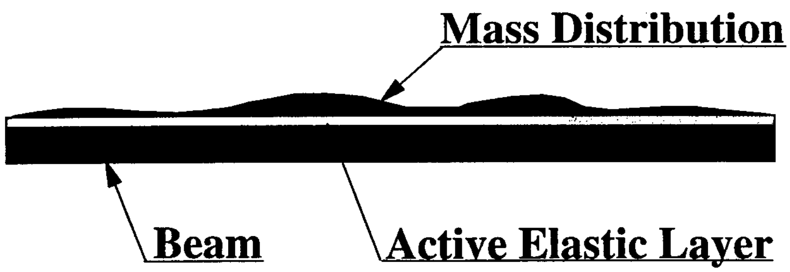


Figure 22. Schematic of arrangement of a distributed active vibration absorber (DAVA).

One of the toughest challenges to realize a useful DAVA was to construct a suitable active stiffness distributed layer. Since the total active mass of the DAVA needs to be similar to a comparable point vibration absorber and must be spread over an extended area, the local mass of the DAVA is very small. Thus in order to keep the resonance frequency of the device in a practical range, it was necessary to have a stiffness layer with a very soft local stiffness. The solution found was a sinusoidally curved sheet of PVDF which is glued to the base structure and the active mass at the maximums of the curved sheet. The stiffness of the elastic layer can be adjusted by varying the amplitude and wavelength of the curved section. When an electrical voltage is applied to the PVDF the in-plane strain is translated into normal motion by the curvature of the sheet. Thus an active input can be applied to the system which is effectively in parallel with the spring stiffness. Fig 23 shows an example sheet of the active spring layer constructed from PVDF.

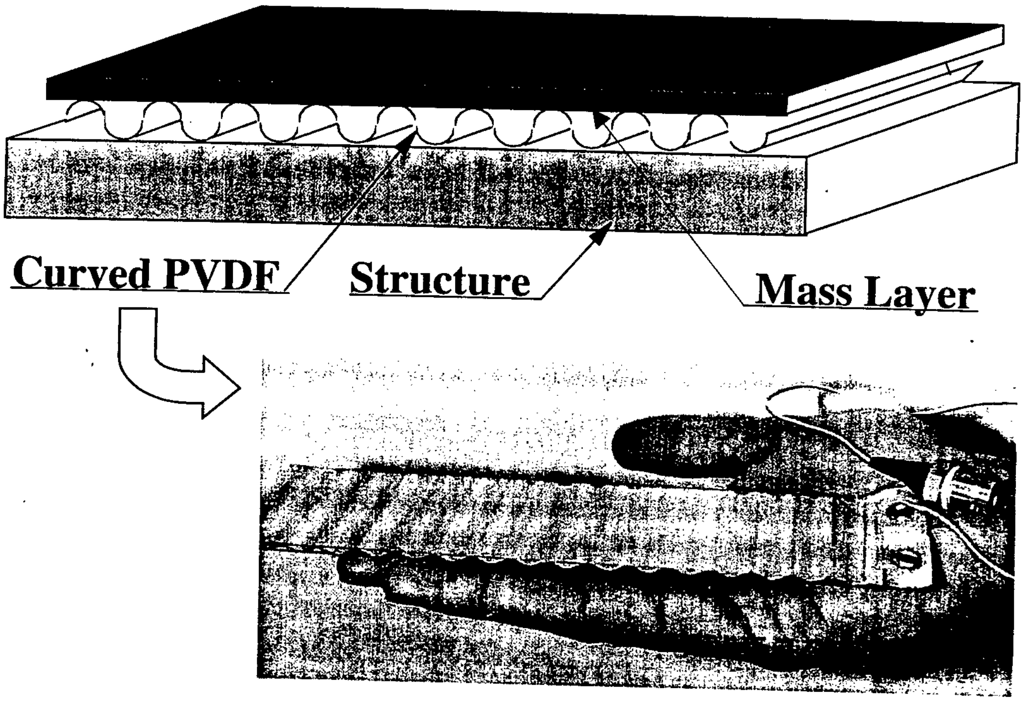


Figure 23. Active distributed spring layer constructed from sinusoidally curved PVDF.

Testing confirmed that the device had a natural resonance frequency which could be chosen in the range 300 to 1200Hz. It should be noted that although the local stiffness is soft, when installed under the distributed active mass, the global stiffness is high (i.e. the system is very stiff globally when the active mass is deformed). Thus when installed on a structure a very robust device which is conformal with the base structural system results.

An analytical model of the DAVA based upon a variational approach was constructed and verified by experiments. The analytical model was used in conjunction with a Genetic Algorithm (GA) approach to optimally design the mass distribution to achieve a required control objective. Fig. 24 shows experimental results of a typical DAVA applied to a 6mm thick beam system with the goal of reducing broadband total beam energy of vibration over 800 to 1200Hz frequency range. The beam weighed 1.5Kg while the DAVA weighed 100gms giving around 7% percent weight of treatment which is typical of what is used in practice with classical vibration absorbers.

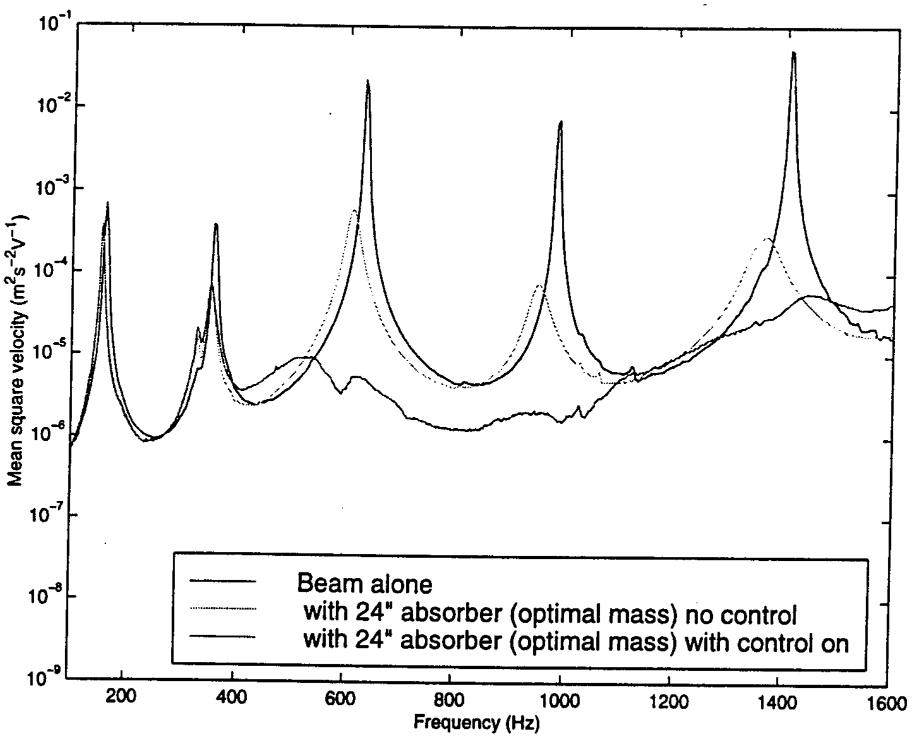


Figure 24. Experimentally measured broadband passive and active-passive performance of DAVA on controlling beam total vibrational energy.

The results show that that passive control effects of the DAVA easily outperform the classical point vibration absorber with large attenuation obtained over a range of frequencies. The point vibration absorber is seen to only reduce the beam energy at its design frequency of 850Hz. When the active signal is turned on a further significant attenuation of beam total energy is seen to occur over a broad frequency range (corresponding to the target design frequency range). Control voltages are typically around 30 to 50V rms with beam vibrations of 20 to 50 microns being controlled. Further testing also confirmed that the DAVA easily outperformed two passive treatments consisting of sheet lead or a constrained layer damping material of the same weight. The results are thus extremely promising in that the DAVA has demonstrated control of a heavy, realistic beam with a device which is conformal (less than 3mm high), physically robust and requires low control voltages if the active component is needed.

5.4 Active-Passive Vibration Isolation and Sound Control

The work at the University of Washington/Hood Technology Corporation was focused on two primary areas of application of active-passive control of noise and vibration. These two are: a) vibration isolation via six axis active hexapods and b) sound attenuation via an acoustic grillage. The six axis active hexapod is a Stewart platform configuration with each strut containing a single actuator and multiple sensors. The acoustic grillage is an array of sound sources and microphones forming an acoustic barrier in a large duct. Laboratory devices representative of both applications have been built and tested. Both applications have current and future potential for significant industrial production systems, provided that certain technical advances can be realized. Both applications presently utilize voice coil technology as the active control element and thus are scaled accordingly. The sensor mix differs, however, both prototype systems are set up to investigate the performance and robustness tradeoffs of single input – single output versus multi input – multi output control strategies. In addition, the systems allow rapid evaluation of the computational requirements for different control strategies. If (and when) new smart materials development reaches a level of maturity sufficient for design of repeatable performance sensors and actuators of smaller scales, such sensors and actuators can readily be integrated into the basic prototype hexapod and acoustic grillage configurations, thus enabling devices scaled for various potential applications.

6. MAJOR PROJECT ACHIEVEMENTS

The major achievements of the project are summarized as:

- Exploration of acoustic source needs for active skin acoustic control.

- Demonstration of the need for sources with surface displacements beyond the capabilities of current simple piezoelectric systems.

- Design of a new flat panel piezoelectric acoustic source using orthogonal bending mode and flextensional amplification.

- Evaluation of a preliminary design using short bimorph elements driving a loudspeaker paper flexing diaphragm.

- Proof of concept both by theory and experiment.

- Broad ranging study of all types of short bending mode transducers including d31 and d33 driven unimorphs and bimorphs, rainbow and thunder, pure shear and L-shaped systems to decide optimum driving elements.

- Design of the PANEL acoustic source using L-shaped bimorph: unimorph combination and a carbon fiber reinforced flexing diaphragm.

- Construction and evaluation of seven PANEL sources to provide six independent elements for a thin flat panel source covering the frequency range 300 Hz to 1,500 Hz for testing at VPI.

- Design, construction, evaluation and patenting of a new pseudo-shear mode piezoelectric amplifier element for lower frequency high drive level applications.

- Construction and delivery of a larger flat panel low frequency acoustic source using pseudo-shear mode driving elements.

- Developed and demonstrated the use of new time domain structural acoustic sensing (SAS) approach for ASAC systems.

- Developed and demonstrated a new SFAEST feedforward controller, which exhibits, improved convergence speed and attenuation

- Developed and demonstrated a new decoreallation filter for pre-processing multiple reference control signals that are a partially correlated. The pre-processor gives improved convergence speed and attenuation of feedforward controllers when multiple noise sources are present.

- Developed and successfully tested a new nonvolumetric eigenassigment design approach for ASAC and active skin systems.

- Developed and successfully tested a new split level modal optimization technique for realistic ASAC systems.

- Demonstrated that the double amplifier piezoelectric actuator can be used as a component of the active skin approach.

- Developed and tested a FEM/BEM numerical model of the piezoelectric double amplifier actuator and integrated skin. Successfully used the numerical model for optimal design of the system.

- Demonstrated that an active skin consisting of piezoelectric double amplifier cells and integrated SAS sensing can be used to controlling broad band sound radiation from structures over a wide frequency range under realistic disturbances.

- Successfully demonstrated the active skin concept of decoupling structural vibration from the radiation field rather than directly controlling structural normal motion.

- Developed and successfully tested a prototype active-passive insert for reducing power flow in structures.

- Developed and successfully tested a distributed active passive vibration absorber (DAVA) for controlling global vibration and/or sound over a wide frequency range with low control power.

- Successfully demonstrated the active-passive concept in reducing control complexity at high frequencies and control power requirements at low frequencies.

7. MAJOR LESSONS LEARNED

Even though the work of this project was considered a resounding success in achieving its major goals there were a number of important lessons learned during the course of the work. In the aim of helping future devotees of active noise control research these are listed below;

- The amount of required actuator stroke at low frequencies(<200Hz) was consistently underestimated. The reasons for this are not clear but it should be taken into account in future related work.
- The effective weight per unit area of the active skin was often underestimated by ignoring the power supplies required. Large actuator stroke often implies high control voltages and thus heavy and expensive power supplies. A trade-off decision must be made.
- The original approach to dealing with structures with a complex response is to simply add more channels of control. However this approach was found, when the number of channels became large, to lead to control convergence and instability problems. In addition the DSP

cost rises rapidly. New control approaches which are less complex and more cost effective are needed. Simply increasing the number of control channels without limit will not be an effective solution.

- Perception of the active noise control effect was found to be a problem. Even with around 10dB of total attenuation it appears that the listener adjusts his perception to judge that the controlled sound is still loud. Perhaps this is related to the fact that, in contrast to passive control, the user has the ability to turn the noise control on and off at will.
- A development logistic challenge was communication between the different technology elements of the project team (i.e. in materials, structural acoustics, signal processing, power supplies etc.) This was due to active noise control being multi-disciplinary and different disciplines using different languages. A significant amount of time was expended on overcoming this.
- In transitioning the technology to commercial use the major limitations were found to be; (1) complexity which reduced the cost effectiveness by increasing the manufacturing requirements and (2) lack of structural robustness which decreased the customer acceptance due to perceptions of damage problems etc. Work must be directed towards decreasing the complexity, increasing the cost effectiveness and increasing structural robustness.

8. CONCLUSION

The work of this project summarized above has demonstrated the large potential of an active skin for reducing structurally radiated sound. A suitable cell element of the actuator component of the skin based upon a double amplifier configuration of piezoelectric elements has been successfully developed and tested. Two summary papers have been given (Appendices 34 and 35) which delineate the capabilities which have been generated for flat panel acoustic control. During the course of theses studies it was necessary to explore the behavior of the soft piezoelectric ceramic materials under high sinusoidal drive fields. Consideration of this data suggests an extension from the current Rayleigh law description which is discussed in more detail in Appendix 36.

Radiation sensing approaches which can be integrated into the skin have been developed and implemented. New robust feedforward control approaches and optimal design methodology have been developed and used to synthesize the components into an integrated active skin approach. The use of the integrated skin on controlling broadband sound radiation from structures has been successfully shown. Promising new active-passive approaches have been developed. The general work has been summarized in a number of keynote survey papers and chapters of Refs. 36-40.

9. PERSONNEL

- The Pennsylvania State University program element was under the direction of Professor L. Eric Cross, Evan Pugh Professor of Electrical Engineering.

PSU faculty on the program were Prof. L. Eric Cross, Dr. Qiming Zhang, Assistant Professor of Electrical Engineering and Ms. Shoko Yoshikawa, Senior Research Assistant in the Materials Research Laboratory.

PSU Post Doctoral Fellows working on the program were Drs. Valery Kugel, Baomin Xu, Ruibin Liu, and Catherine Elissalde.

PSU Graduate Assistants were Sanjay Chandran, MS in Materials, graduated in 1997 and Qing-Ming Wang, PhD in Materials, graduated in June 1998.

An associate program element from Penn State was with the Materials Systems Inc (MSI) in Boston. MSI was funded by purchase order to supply ceramic piezoelectric materials for the bending mode and pseudo-shear mode driving devices.

- The Virginia Tech program element was under the direction of Professor Chris. R. Fuller, Roanoke Electric Steel Professor of Mechanical Engineering.

Va Tech faculty on the program were Dr. Chris Fuller, Roanoke Electric Steel Professor of the Mechanical Engineering Department and Dr. Ricardo Burdisso, Associate Professor of the Mechanical Engineering Department.

Va Tech Post doctoral Research Associates working on the program were Drs. Marcus Bronzel, Michael Wenzel and Catherine Guigou.

Mr. Steve Booth worked on the Va Tech program as a Research Associate who provided manufacturing and technical support. Mrs. Dawn Bennett of Va Tech provided overall grant and subcontract administration support and program coordination.

Va Tech Graduate students were Zhonglin Li, Ph.D. graduated in October 1997, Julien Maillard, Ph.D. graduated in February 1997, Pierre Cambou, M. S. graduated September 1998, Brody Johnson, M. S. graduated July 1997, and Yi Feng Tu, M. S. graduated March 1997.

- The University of Washington/Hood Technology Corp program was a small subcontract from Va Tech and under the direction of Professor Juris Vagners of the Dept of Aero/Astro, University of Washington in Seattle.

UW/Hood faculty on the program were Professor Juris Vagners and Andreas von Flotow, Affiliate Associate Professor/President of Hood Technology Corp.

UW Graduate students on the program were Douglas Thayer, completed Ph.D in Aeronautics and Astronautics, Spring 1998 and Kalev Sepp, Ph.D candidate in Electrical Engineering to complete in June 1999.

10. HONOURS AND AWARDS

Name of Person Receiving Award	Recipients Institution	Name, Sponsor, and Purpose of Award
L. Eric Cross	Penn State	IEEE Distinguished UFFC Lecturer for 1994-95
L. Eric Cross	Penn State	UFFC 1996 Achievement Award
L. Eric Cross	Penn State	Dow Lecture, Northwest University
Chris R. Fuller	Virginia Tech	Alumni Award for Excellence in Research, 1997, Virginia Tech
Chris R. Fuller	Virginia Tech	Group Achievement Award, NASA, 1997

11. BOOKS AND PATENTS

A number of books, book chapters and patents were generated as a result (or partially as a result) of the work of this project as listed below;

Books

1. “Active Control of Vibration”, C.R. Fuller, S.J. Elliott and P.A. Nelson, *Academic Press*, London (1996).
2. “Active Control of Vibration”, C.R. Fuller, S.J. Elliott and P.A. Nelson, *Academic Press*, London, Vol. 2(1997).
3. “Active Vibration Control”, C.R. Fuller, Chapter 72 of *Encyclopedia of Acoustics*, John Wiley and Sons, New York (1997).

Patents

1. " A Distributed Active Vibration Absorber", C.R. Fuller and P. Cambou, *US Patent Application*, (submitted June 1998).
2. " A New type of Psuedo Shear Mode Piezoceramic Actuator" , L.E.Cross, Q. M.Wang and J.Chirevella, *US Patent Application*, (submitted March , 1998).

12. TRANSITION OF TECHNOLOGY

An important part of the project was to vertically integrate and transition the resultant technology of this project to commercial and military practical use. To this end a coordinated program was undertaken with Material Systems Inc. and Hood Technology Corp. Evolving actuator and active skin technology was shared with MSI and they are now involved in the fabrication of commercially available, cost effective, injection molded acoustic panels for industrial applications. The technology of this project has been transitioned into an ONR funded SBIR project at MSI on using active skins composed of PANEL like actuators to actively control interior noise in automobiles and transformer radiated noise. Preliminary results have demonstrated the potential of the technology and MSI is now involved in increasing the robustness and reducing the price aspect by developing efficient and automated manufacturing techniques. Hood Technology was involved in the project for the purpose of determining realistic commercial application and performance requirements by surveying various market applications relative to the active skin and active-passive approaches.

APPENDICES

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5. "Dynamic Characteristics of Rainbow Ceramics," C. Elissalde and L.E. Cross. *J. Am. Ceram. Soc.* **78** (8), 2233-2235 (1995).

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7. "Structural-Property Relations in a Reduced and Internally Biased Oxide Wafer (RAINBOW) Actuator Material," C. Elissalde, L.E. Cross, and C.A. Randall. *J. Am. Ceram. Soc.* **8**, 2041-2048 (1996).

8. "Determination of the Young's Modulus of the Reduced Layer of a Piezoelectric RAINBOW Actuator," Q.-M. Wang and L.E. Cross. *J. Appl. Phys.* **83** (10), 5358-5363 (1998).

9. "Caterpillar-Type Piezoelectric d_{33} Bimorph Transducer," V.D. Kugel, S. Chandran, and L.E. Cross. *Appl. Phys. Lett.* **69** (14), 2021-2023 (1996).

10. "Characteristics of Shear Mode Piezoelectric Actuators," Q.-M. Wang, B. Xu, V.D. Kugel, and L.E. Cross. *Proc. of Tenth IEEE International Symposium on Application of Ferroelectrics* **2**, 767-770 (1996).

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13. "Behavior of Soft Piezoelectric Ceramics Under High Sinusoidal Electric Fields," V.D. Kugel and L.E. Cross. *J. Appl. Phys.* **84** (5), 2815-2830 (1998).

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19. "Comparison of Two Structural Sensing Approaches for Active Structural Acoustic Control," J. P. Maillard and C. R. Fuller submitted to *J.Acoust. Soc. Amer.* (1997).

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